Multi-Generational Flavour Physics

Jonas Rademacker (University of Bristol)

3 generations of quarks
2 generations of experiments

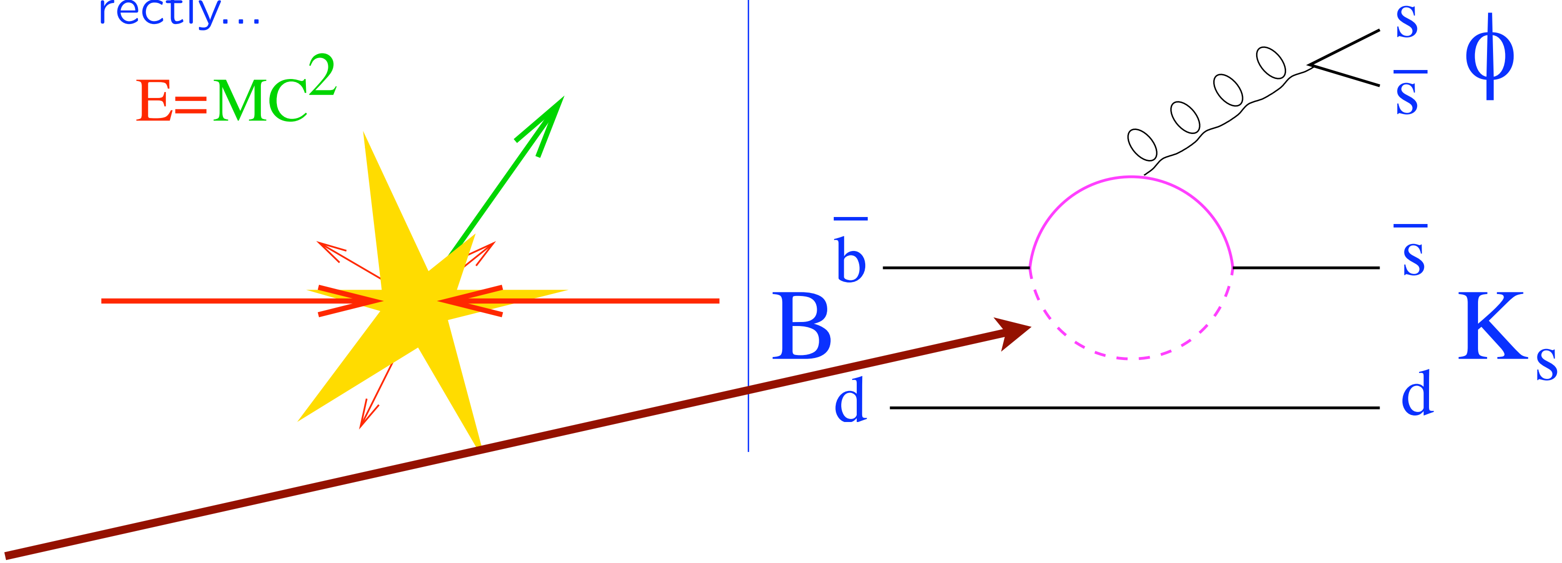
Two Roads to New Physics

Direct Observations

Particles with $MC^2 > E$ cannot be produced directly...

Indirect effects

... but they can have an effect as virtual particles, especially in loops.



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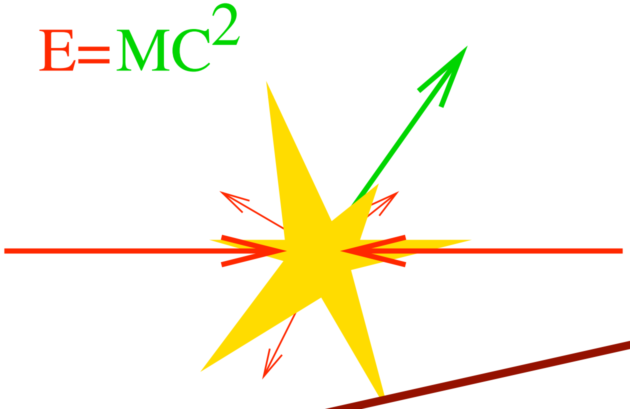

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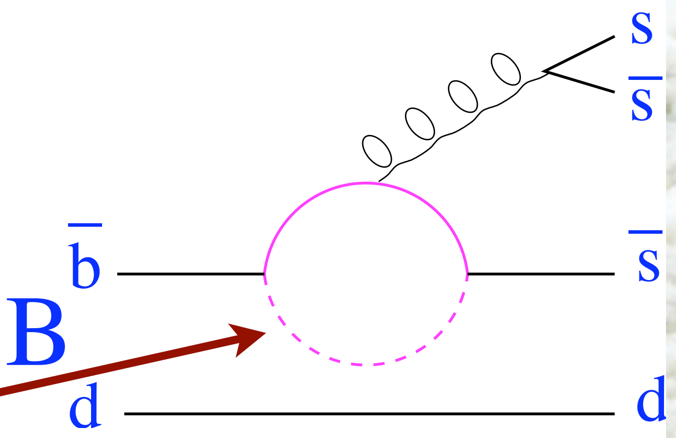

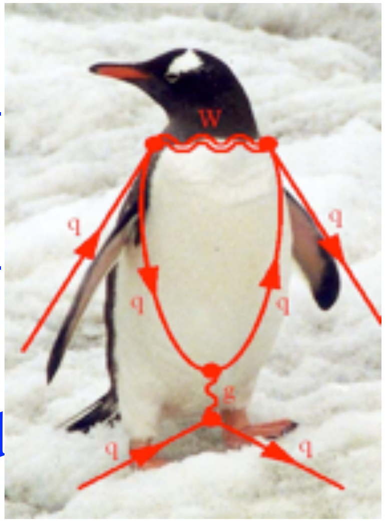

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CP violation and the creation of the universe

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Bang!!

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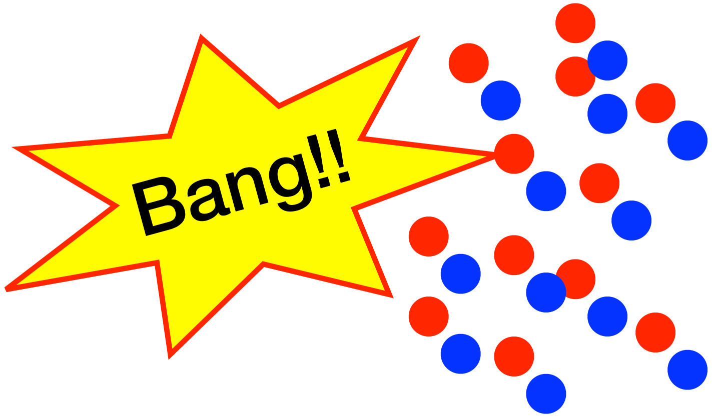

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matter and
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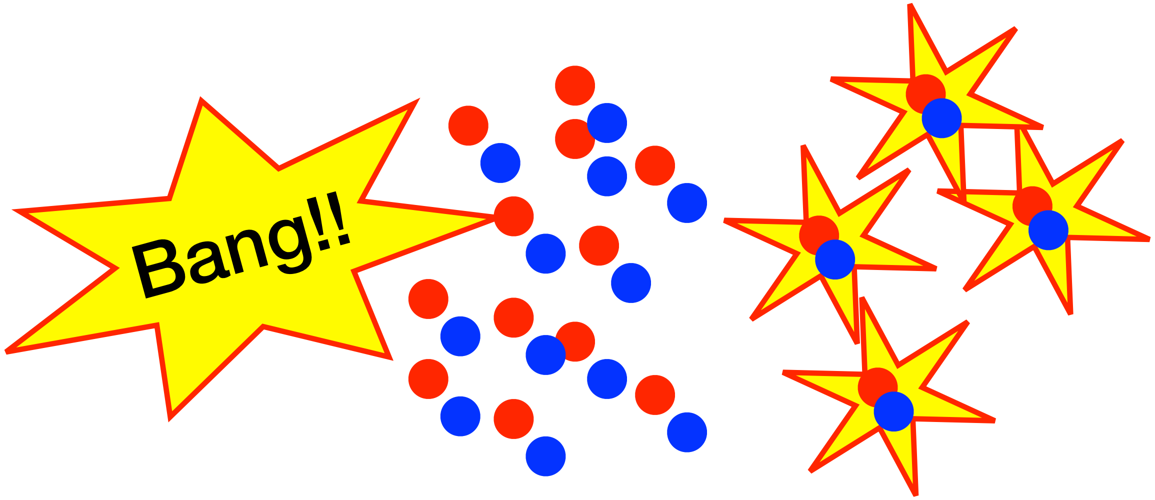

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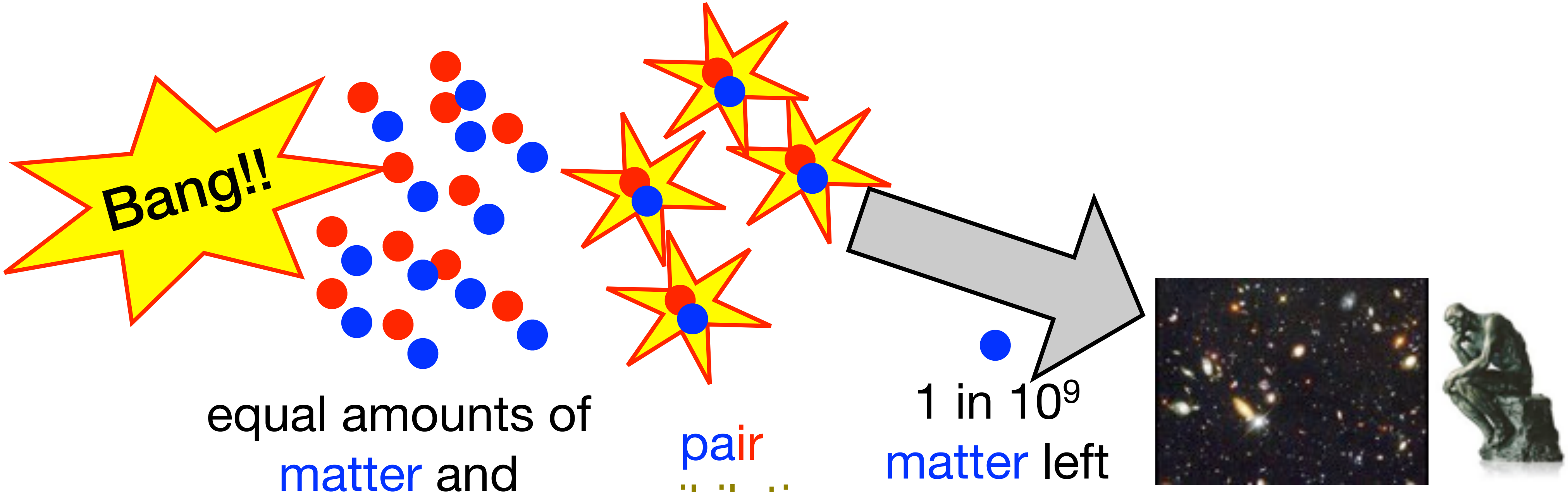

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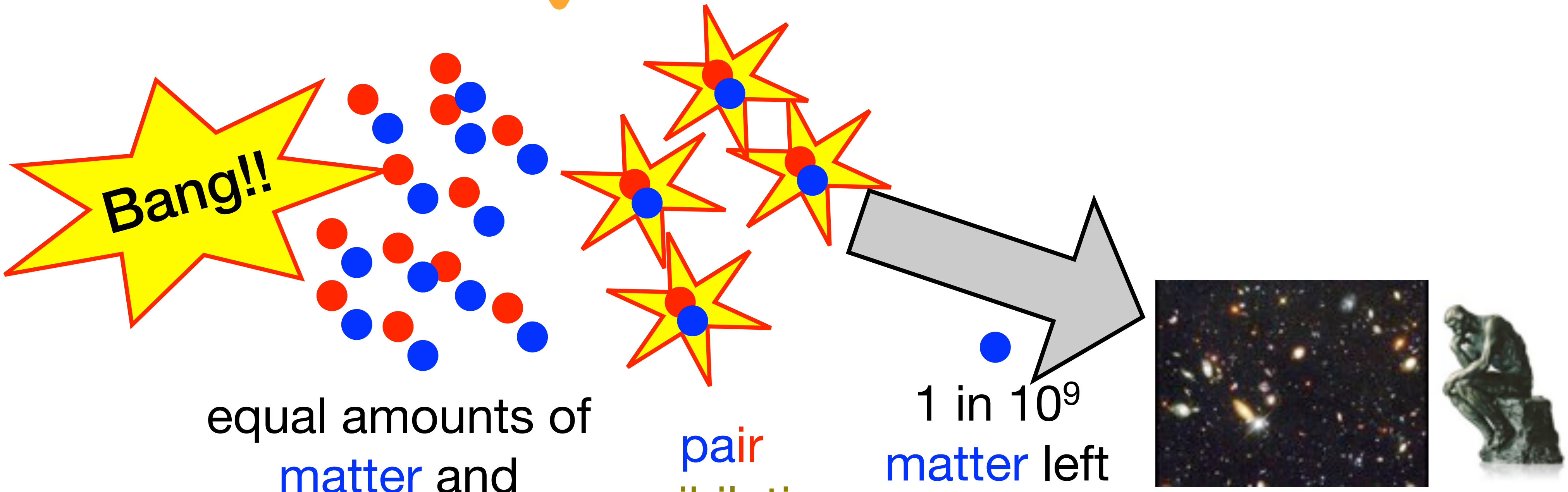

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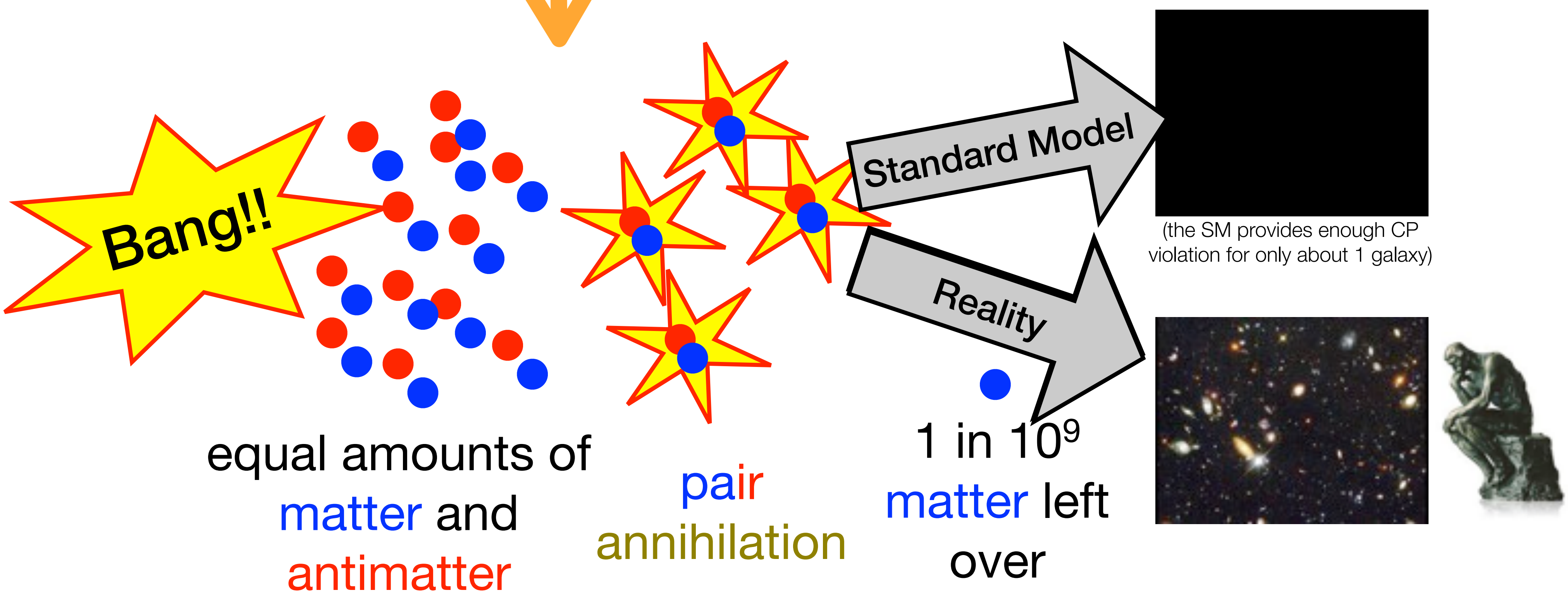

(the SM provides enough CP violation for only about 1 galaxy)

equal amounts of matter and antimatter

pair annihilation

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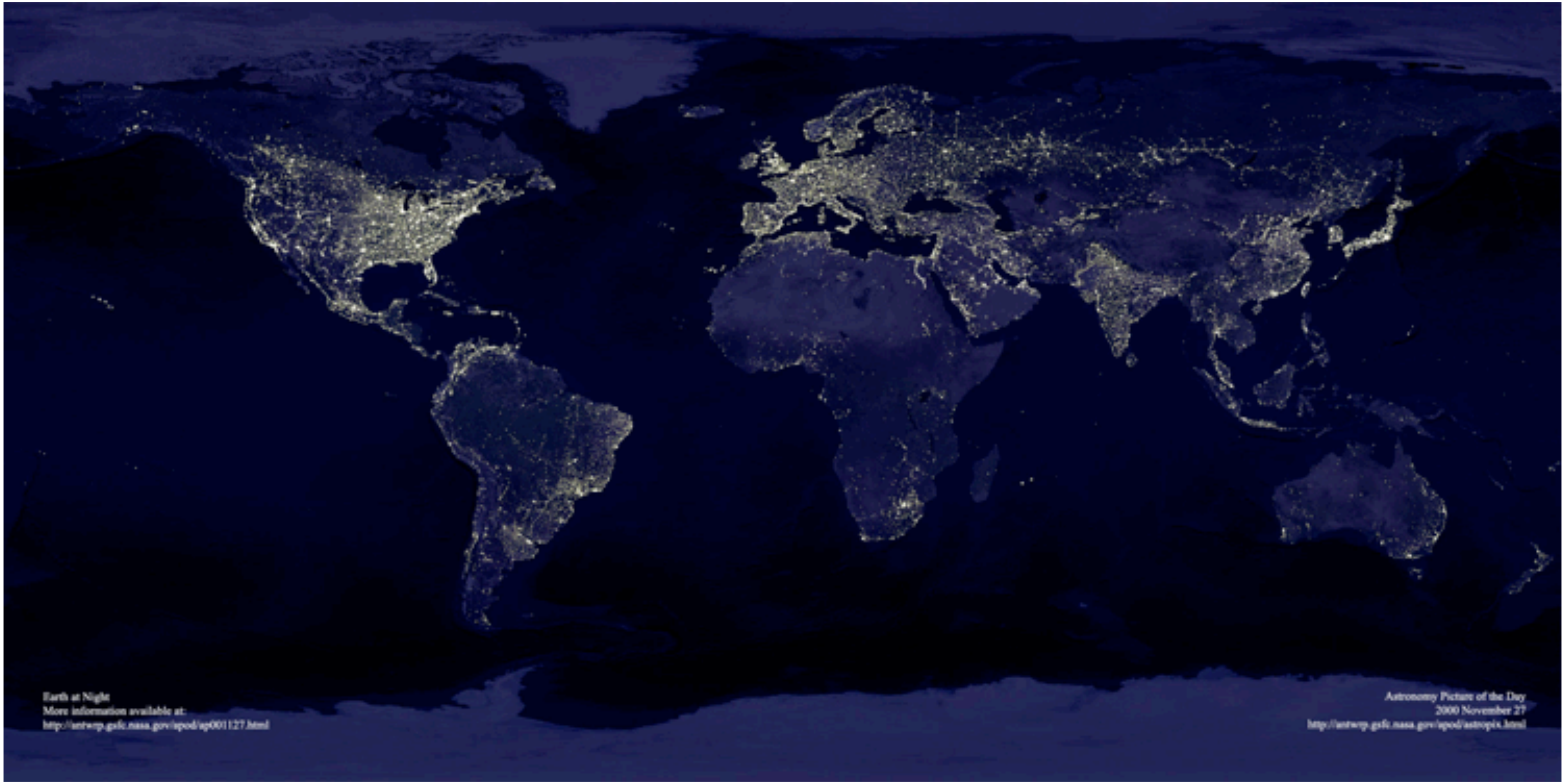
This wouldn't be here if the Standard Model were complete.



Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap001127.html

Astronomy Picture of the Day
2000 November 27
http://antwrp.gsfc.nasa.gov/apod/astropix.html

Flavour physics, CP violation and New Physics

- Quark Flavour physics is the precision study of quark transitions - the only known source of CP violation.
- Sensitive to new particles that can be much heavier than those directly produced (i.e. lie beyond the energy frontier).
- Very successful in the past:
  - Charm quark predicted based on the suppression of s→d transitions
  - Top/bottom quark predicted based on the observation of CP violation.

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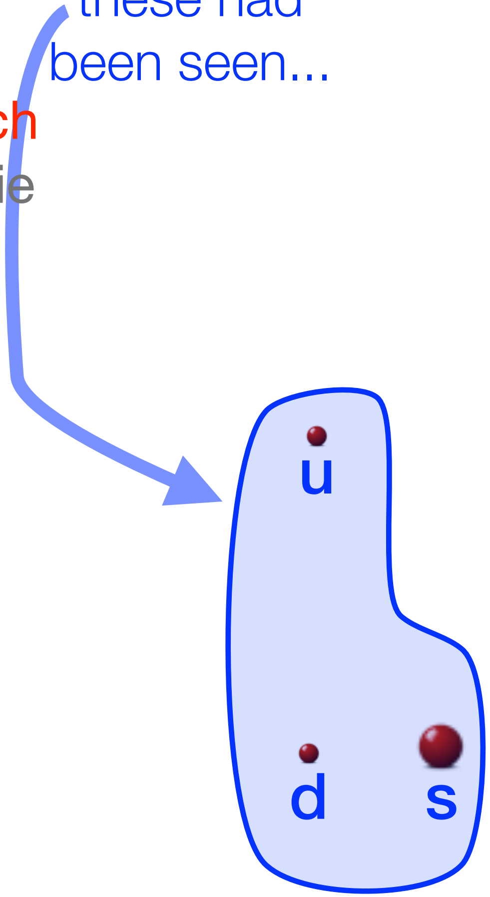

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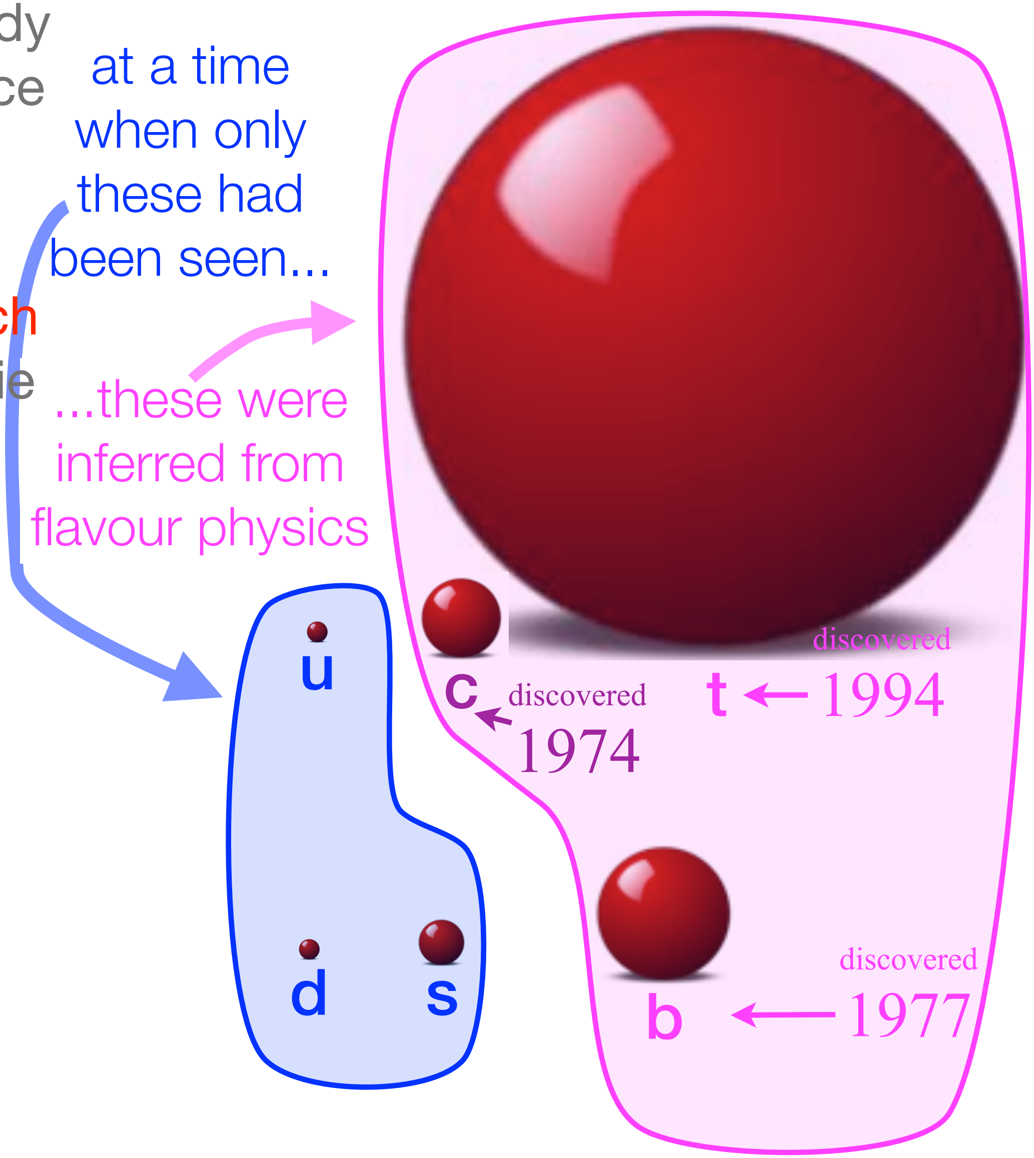

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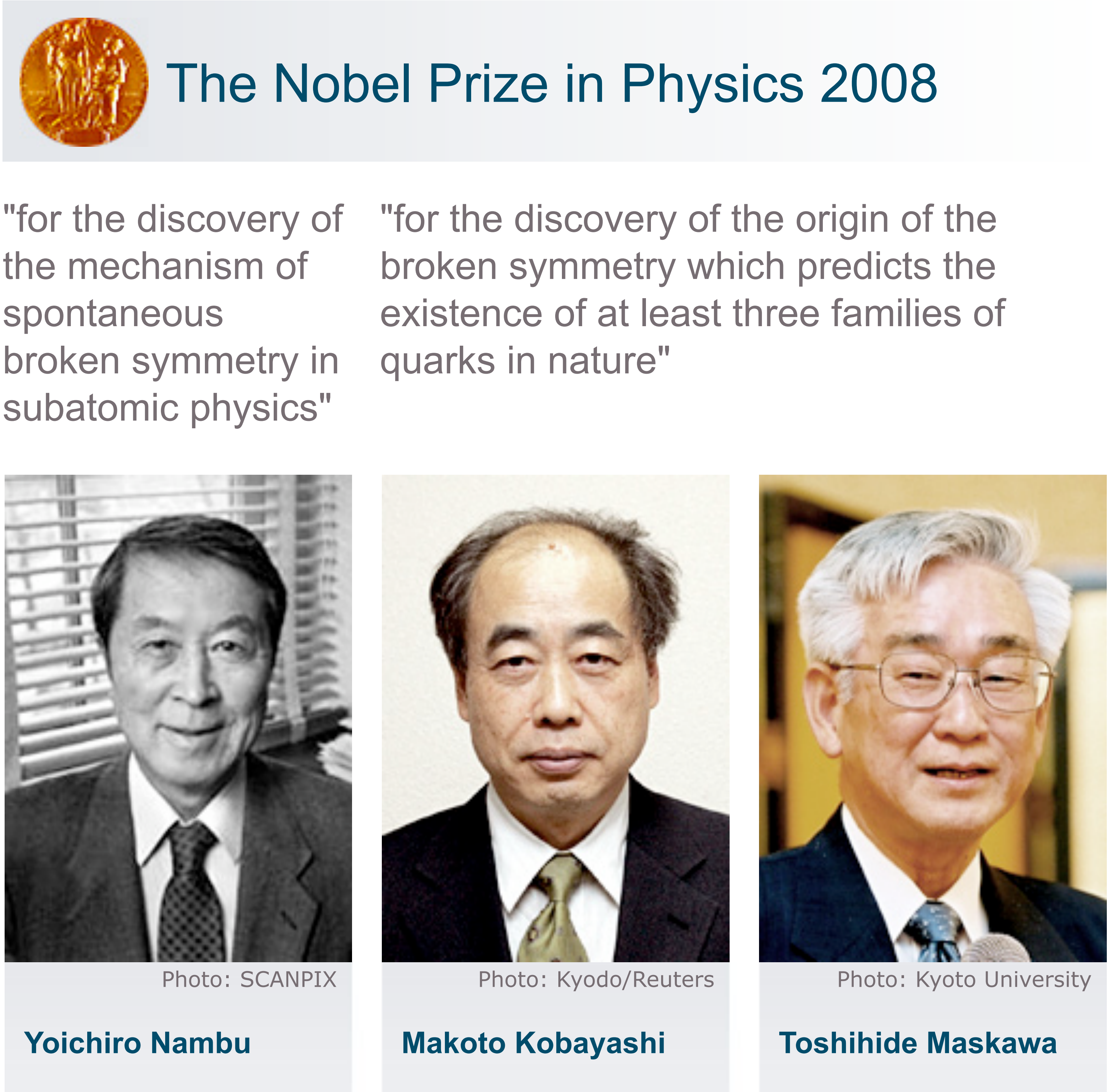
...these were inferred from flavour physics

N



The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

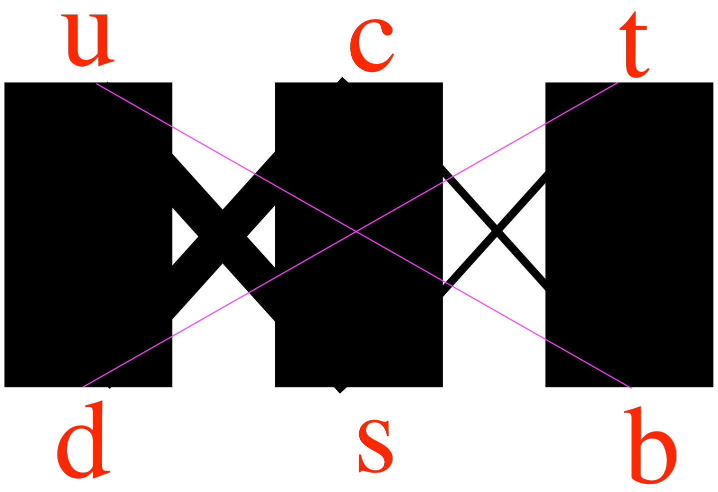
Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

CKM matrix, CP violation



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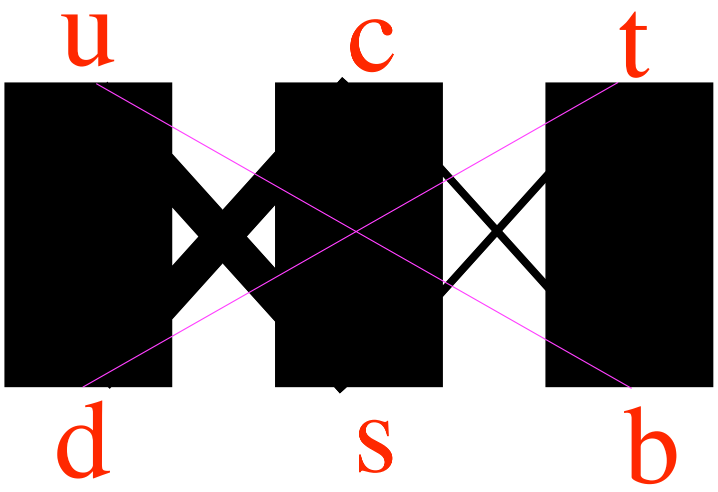
where $\lambda=0.22$

structure of the quark mixing matrix

CKM matrix, CP violation



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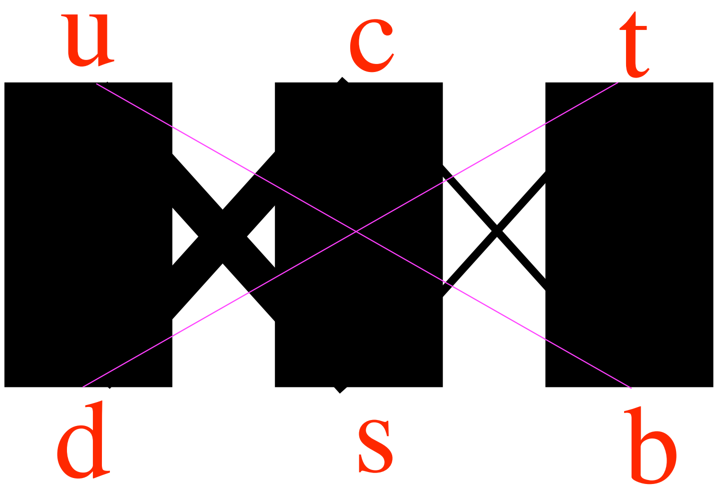

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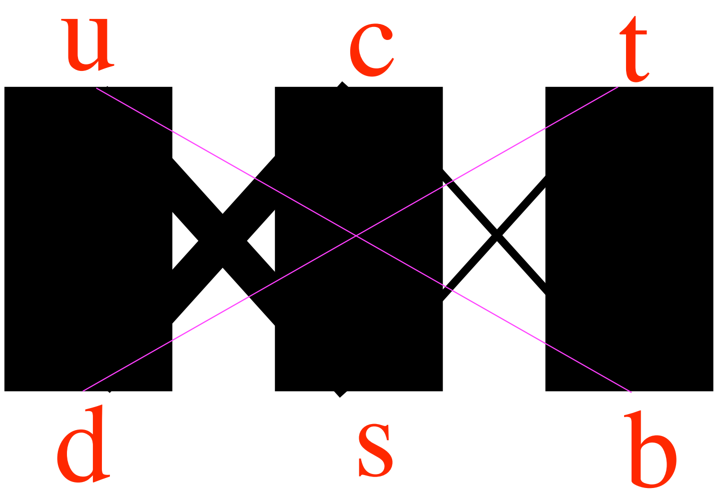

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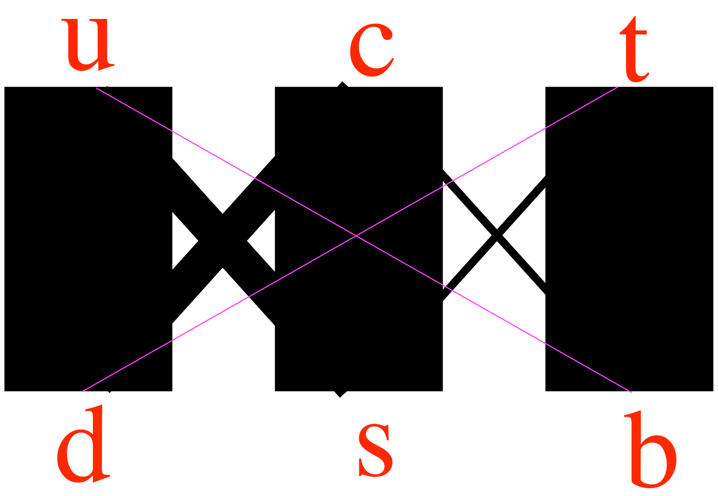
- Turns out: Only possible with at least three generations of quarks.

CKM matrix



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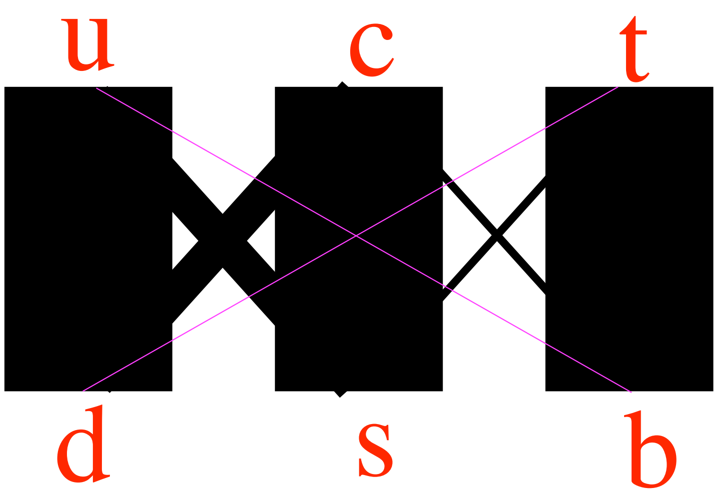

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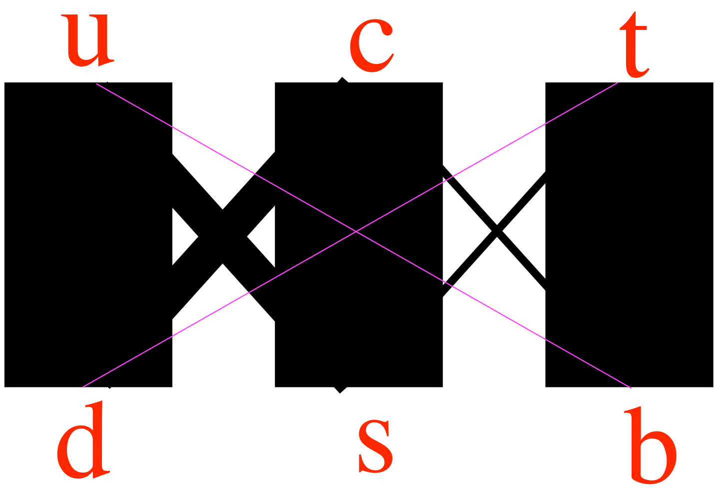

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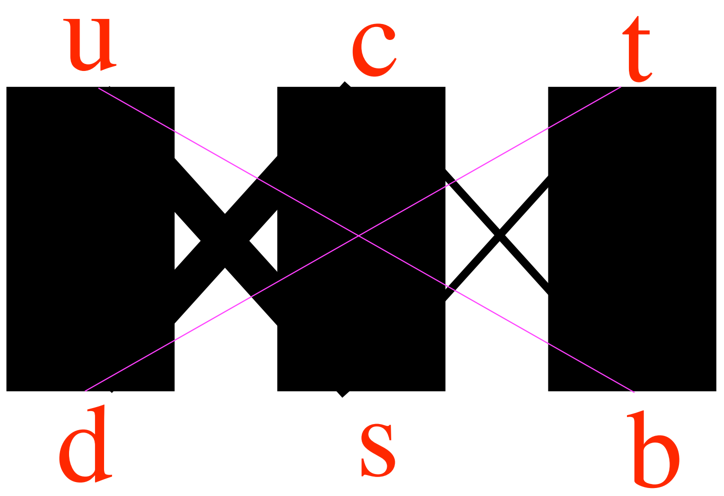

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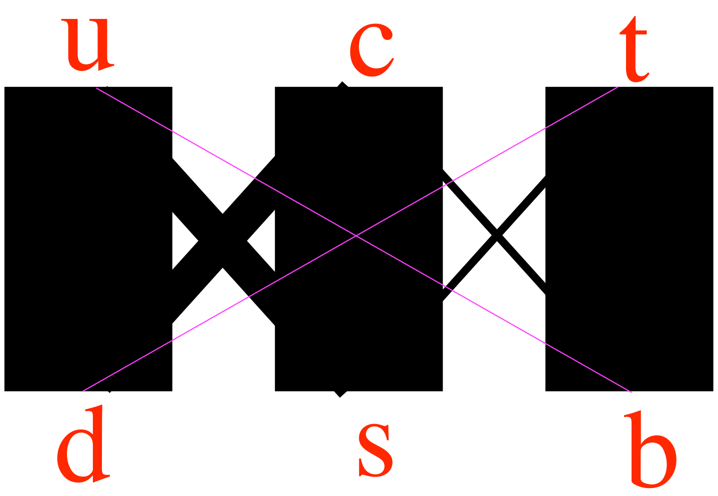

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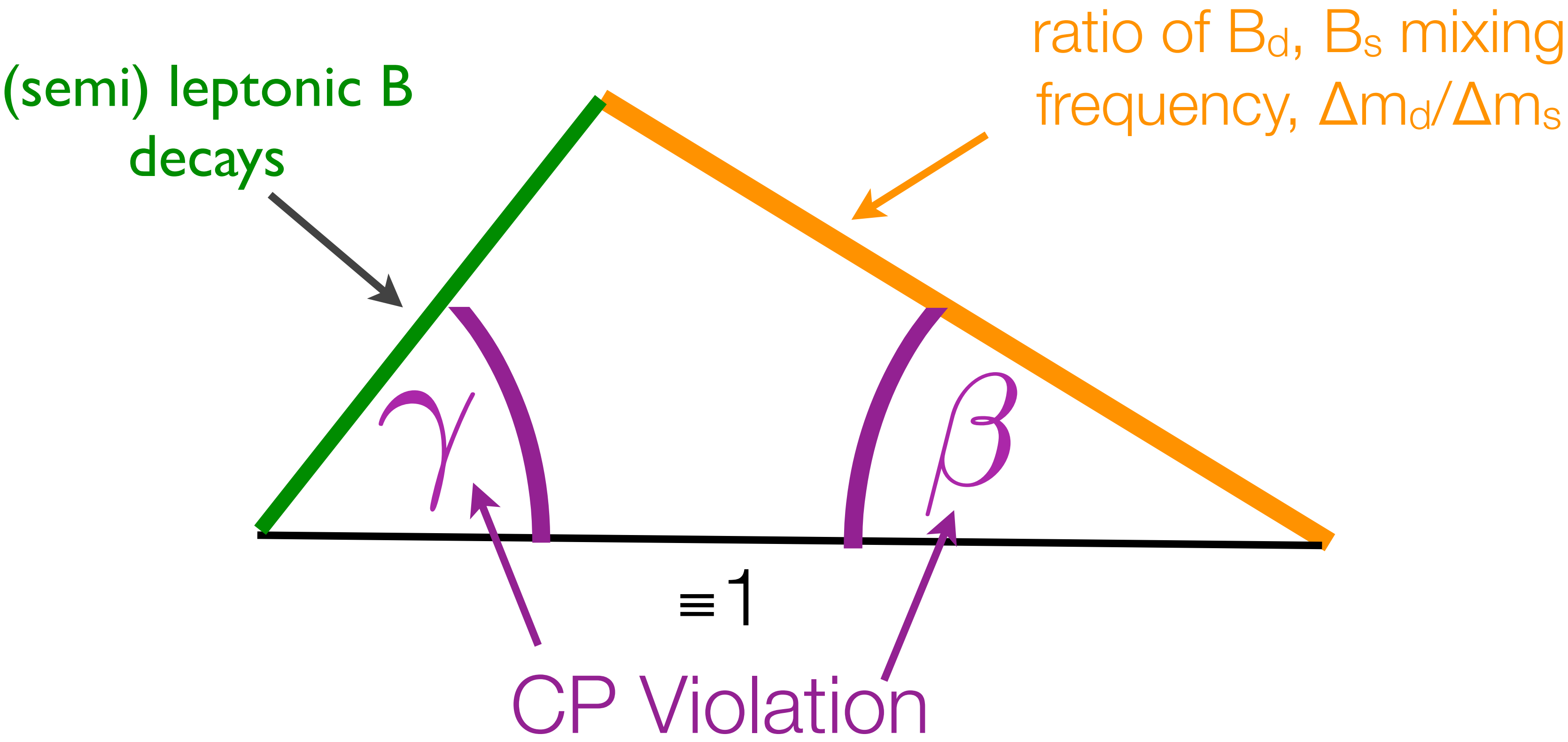
Unitarity Triangle

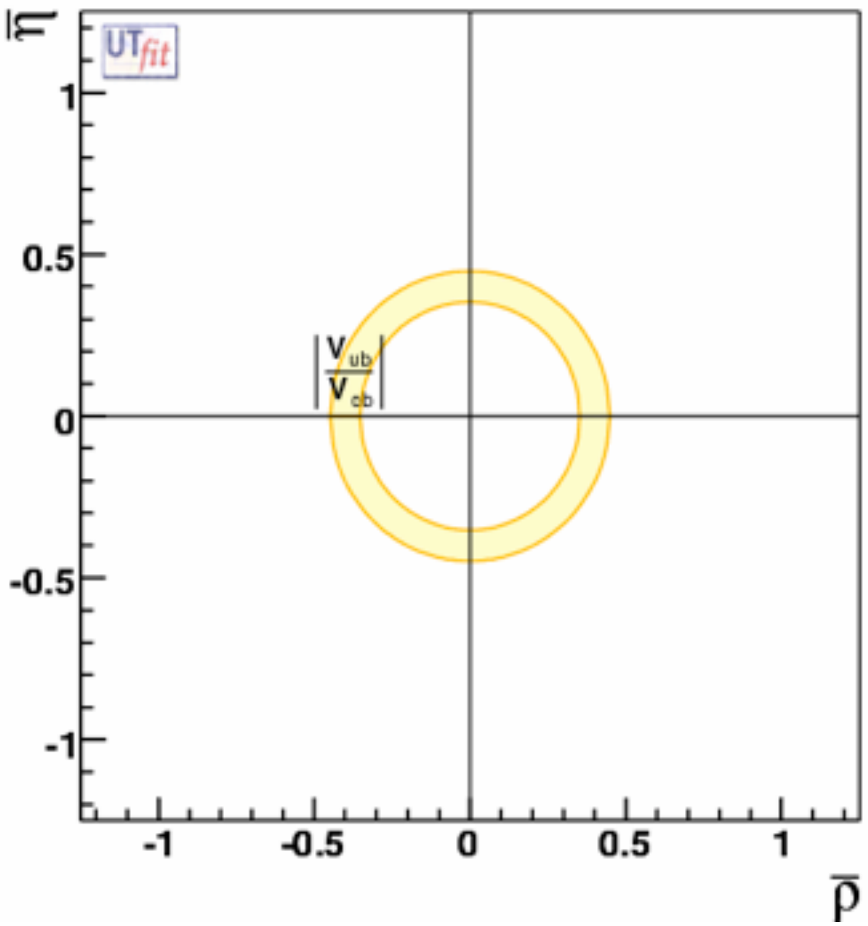


ratio of B_d, B_s mixing frequency, $\Delta m_d/\Delta m_s$

(semi) leptonic B decays

CP Violation

Current constraints on the apex of the UT



The flavour puzzle

- The Standard Model description of quark flavour physics has been confirmed to about 10%
- Many of the measurements constraining the UT are loop diagrams, sensitive to New Physics
- If there are really all these new particles out there, the Standard model description should fail.
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So far, all we got is this:

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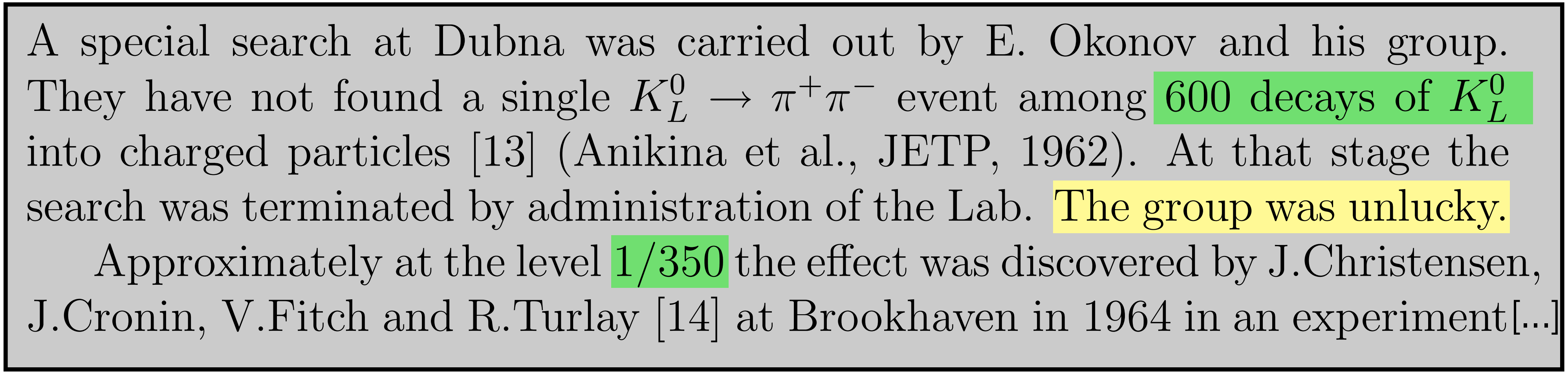

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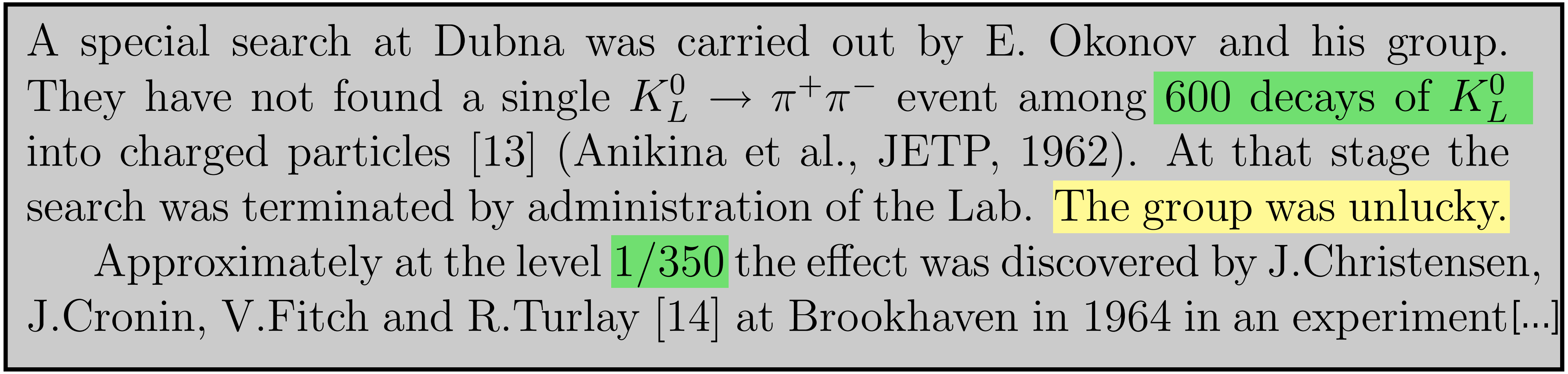

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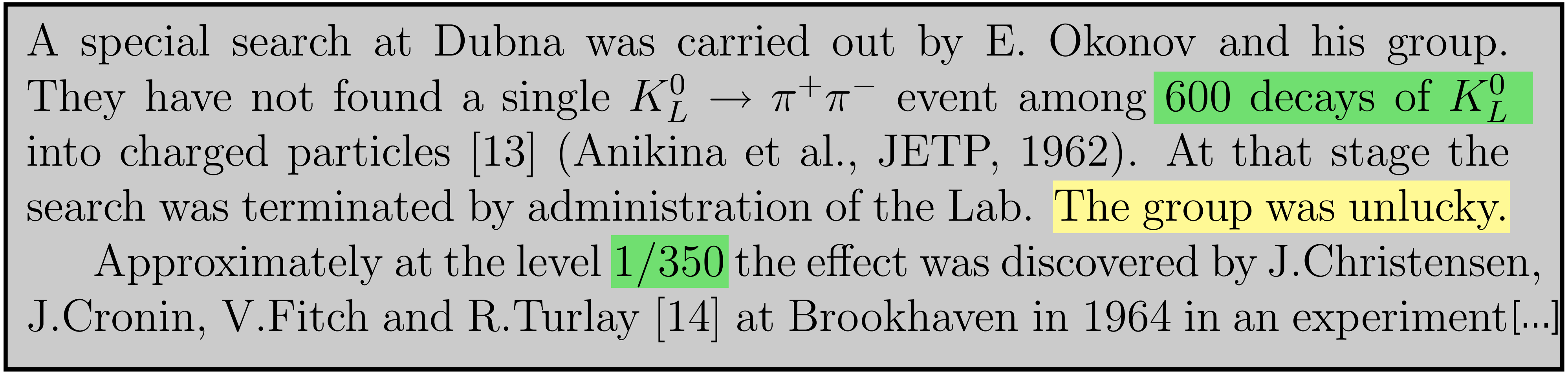

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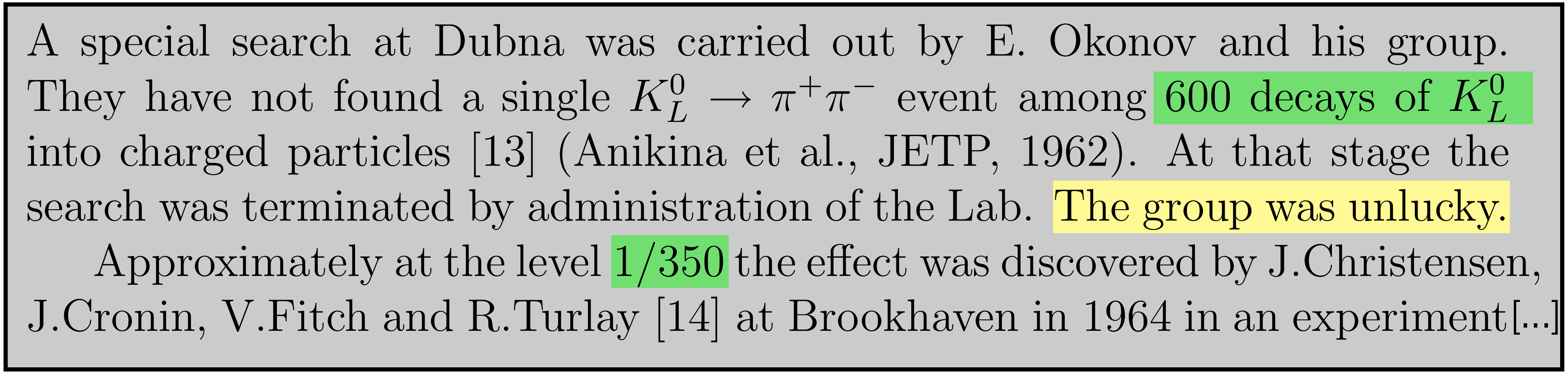

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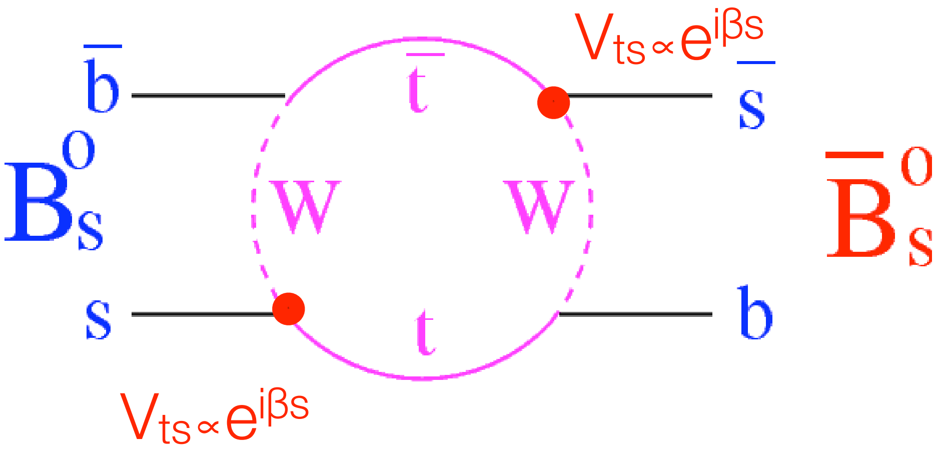
- Global symmetries are usually broken (C, P, CP,... MFV?)

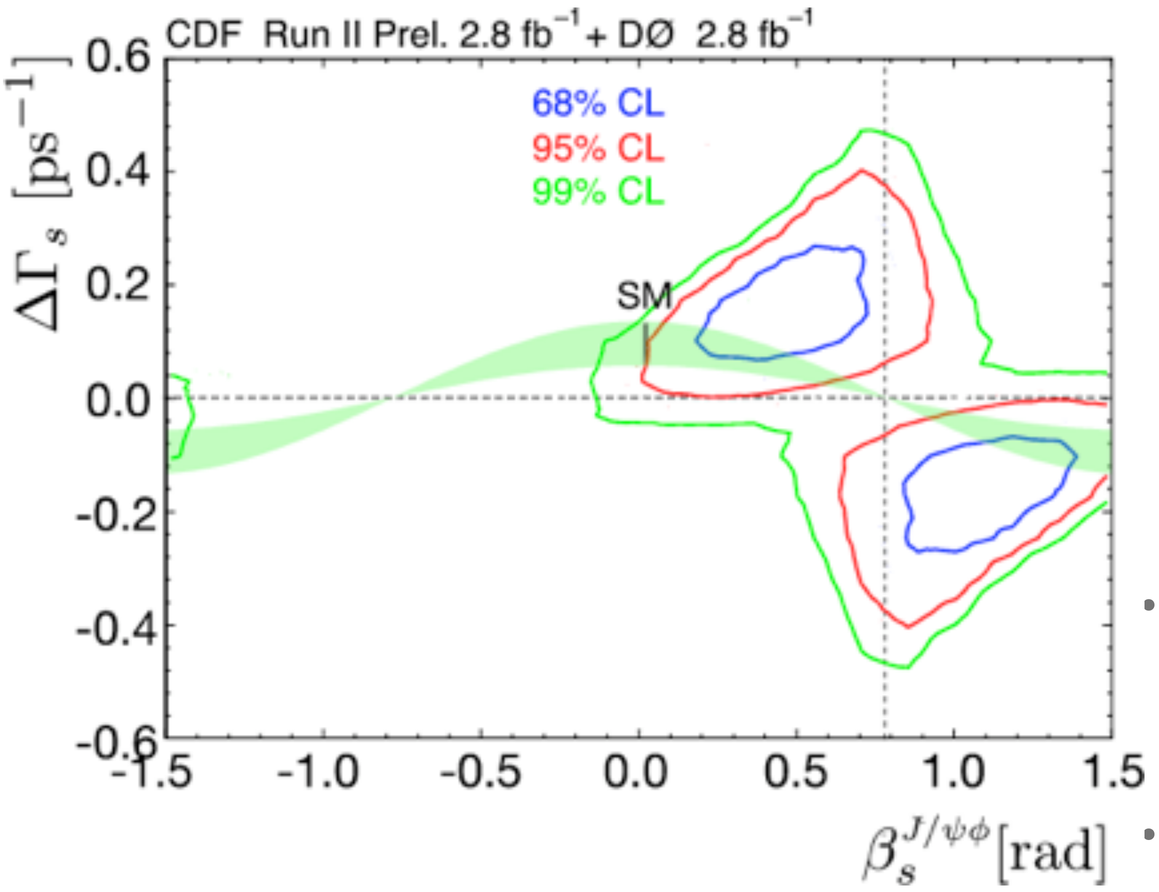
Example: Bs oscillations

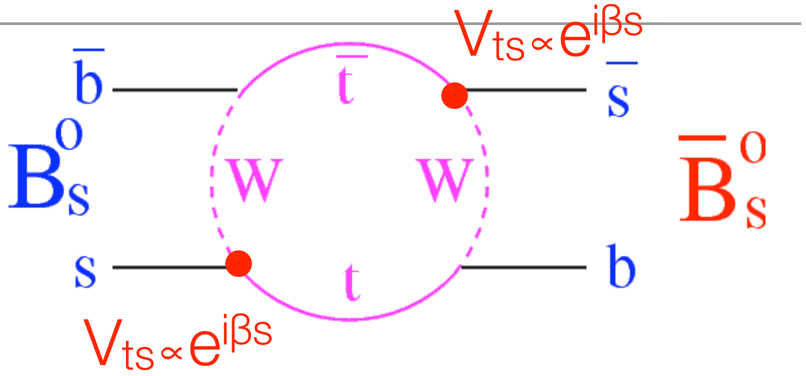


$$M(B_s \to \bar{B}_s) \sim \frac{(y_t V_{tb}^* V_{ts})^2}{16\pi^2 M_W^2} + \frac{c_{NP}}{\Lambda^2}$$

- Bs - like other neutral mesons - continually transform into their own antiparticle and back (“mixing”).
- Bs mesons do this approximately 3,000,000,000,000 times per second. First observed at the Tevatron in 2006.
- Can measure mixing frequency (done) and phase. Both sensitive to New Physics. The more precise the measurements, the higher the mass scale we can access.

New Physics hints in Bs mixing at Tevatron





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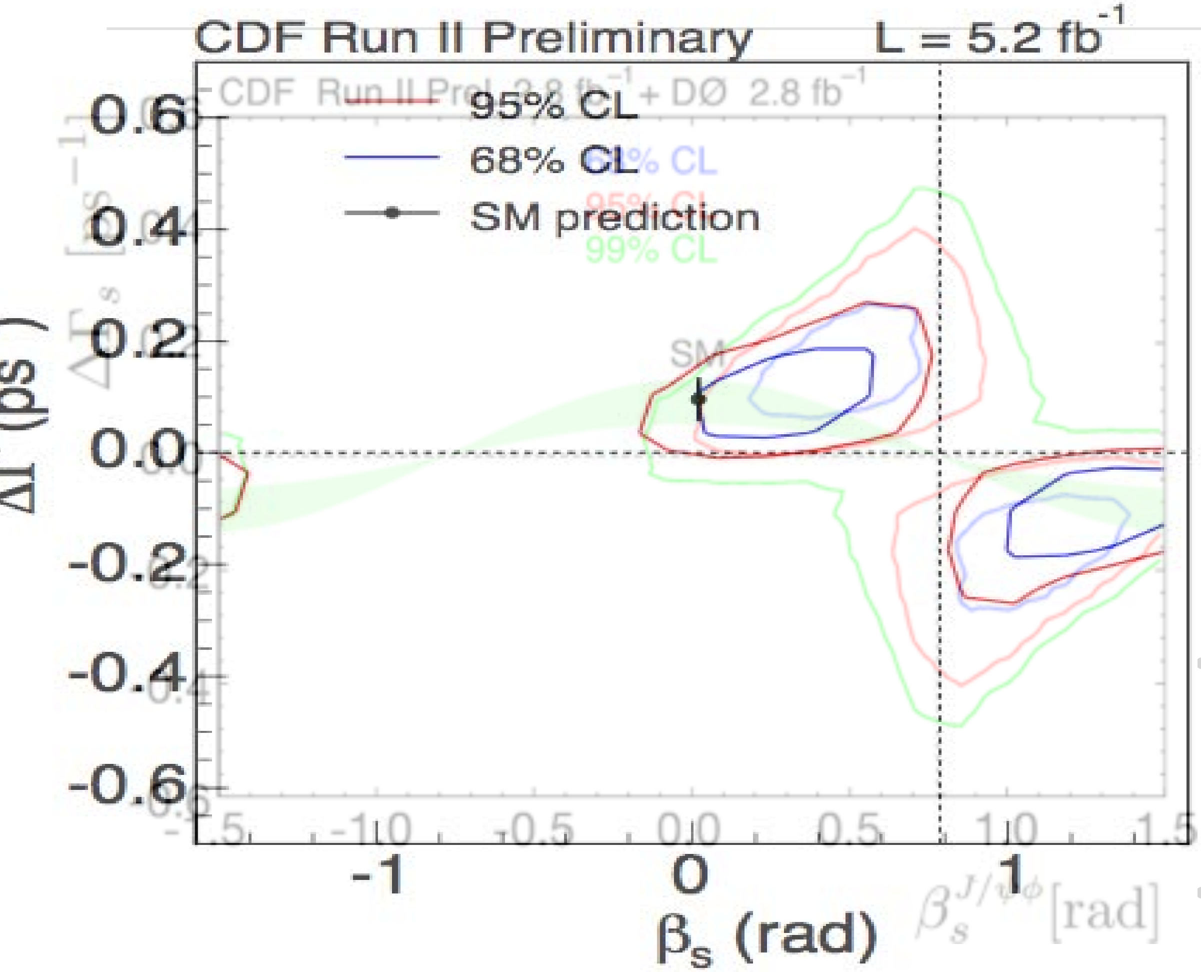
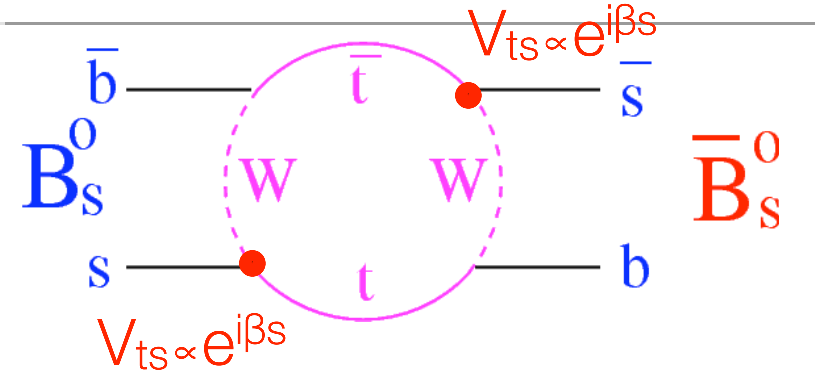
- Bs mixing diagram with CP-violating phase β_s that is ~0 in SM
- Tevatron data hint at non-zero β_s^{NP} (2.1σ).
- LHCb will resolve this very quickly.

$$\begin{aligned} \Delta\Gamma_s(\text{meas}) &= \Delta\Gamma_s^{SM} \cos\phi_s^{NP} \\ \sin(2\beta_s^{J/\psi\phi})(\text{meas}) &= \sin(2\beta_s^{SM} - \phi_s^{NP}) \end{aligned}$$

New Physics hints in Bs mixing at Tevatron



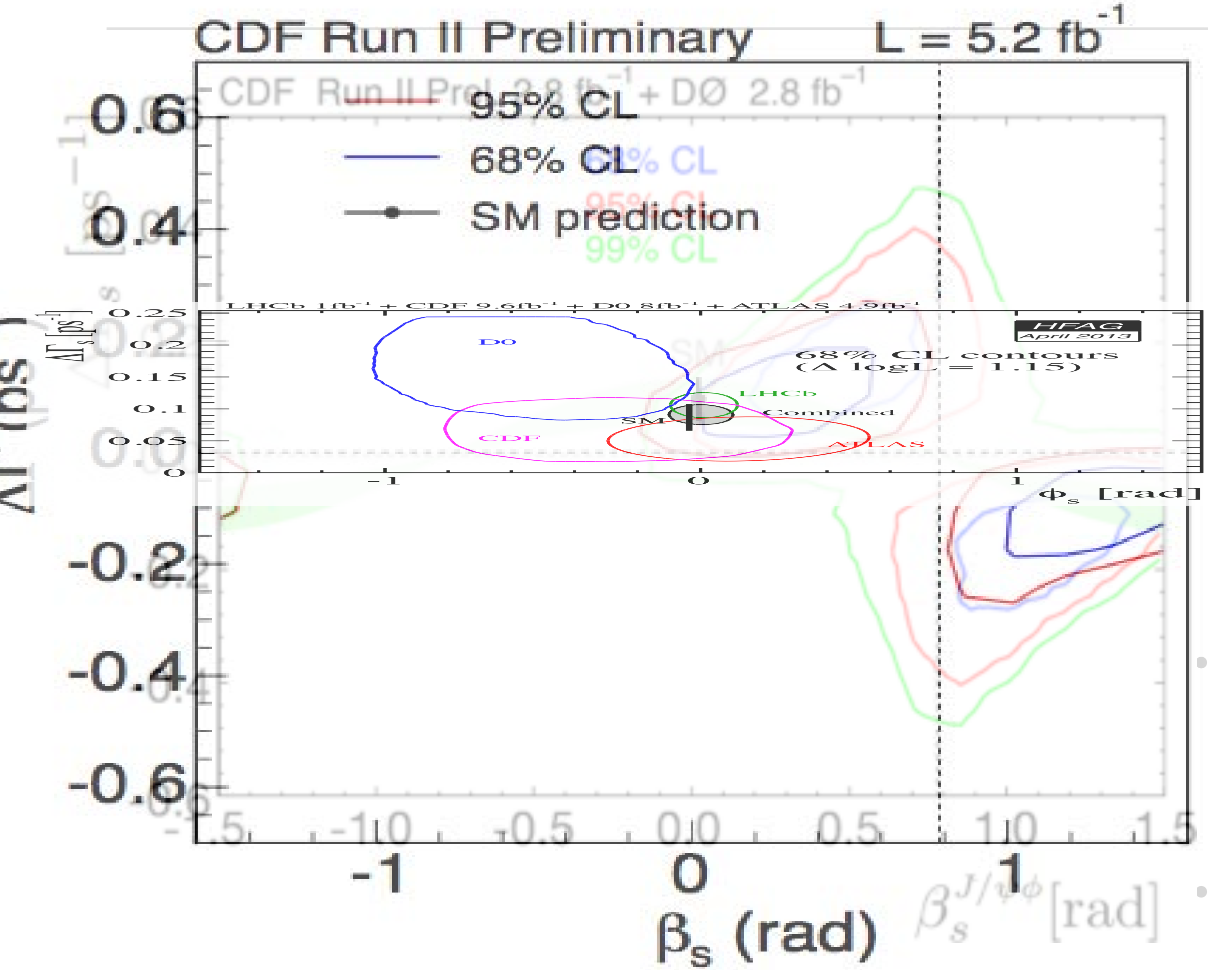
$$\begin{aligned}\Delta\Gamma_s(\text{meas}) &= \Delta\Gamma_s^{SM}\cos\phi_s^{NP}\\ \sin(2\beta_s^{J/\psi\phi})(\text{meas}) &= \sin(2\beta_s^{SM}-\phi_s^{NP})\end{aligned}$$



$$M(B_s \to \bar{B}_s) \sim \frac{(y_t V_{tb}^* V_{ts})^2}{16\pi^2 M_W^2} + \frac{c_{NP}}{\Lambda^2}$$

- Bs mixing diagram with CP-violating phase βs that is ~0 in SM
- Tevatron data hint at non-zero β_s^{NP} (2.1σ).
- LHCb will resolve this very quickly.

New Physics hints in Bs mixing at Tevatron



$$\Delta\Gamma_s(\text{meas}) = \Delta\Gamma_s^{SM} \cos\phi_s^{NP}$$

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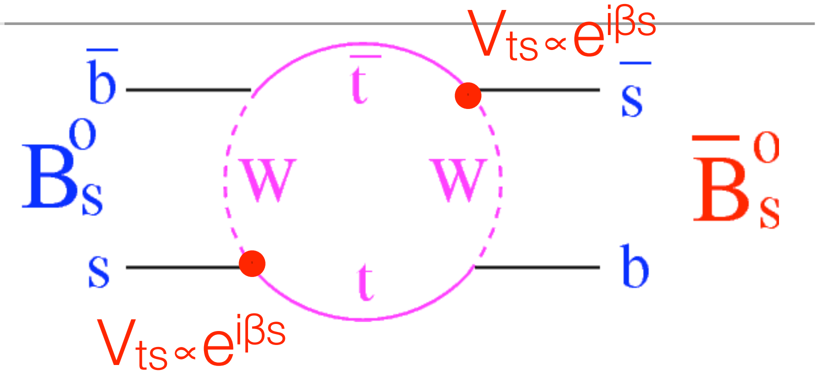

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- Bs mixing diagram with CP-violating phase β_s that is ~0 in SM
- Tevatron data hint at non-zero β_s^{NP} (2.1σ).
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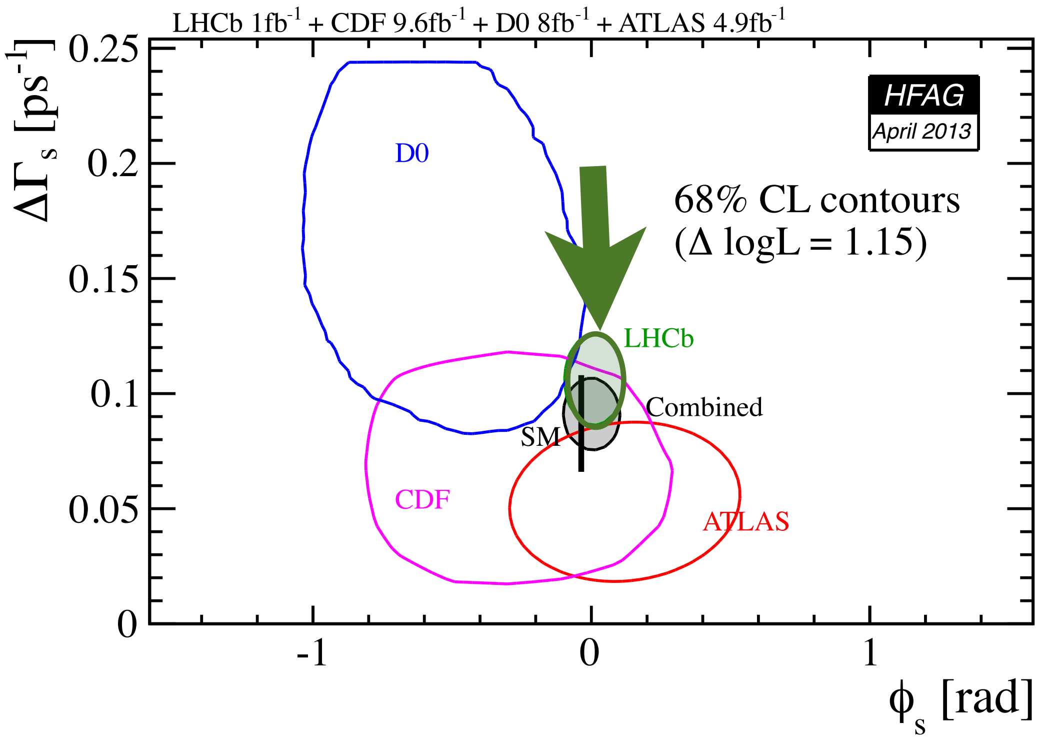
Combined $B_s \to J/\psi\, KK$ and $B_s \to J/\psi\, \pi\pi$ for ϕ_s



arXiv:1304.2600 (2013)
supersedes previous results:
Phys. Rev. Lett. 108 (2012) 101803
Physics Letters B 713 (2012) 378

ϕ_s very sensitive to NP. But no NP effects seen, yet...

$\Delta\Gamma_s$ less sensitive to NP ($\propto\cos(\phi^{new})$), but impressive validation of HQE calculation.

SM: $\phi_s^{SM} = -0.036 \pm 0.002$ rad

LHCb:
$$
\begin{aligned}
\phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad},\\
\Gamma_s \equiv (\Gamma_{\mathrm{L}} + \Gamma_{\mathrm{H}})/2 &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}\\
\Delta\Gamma_s \equiv \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1}
\end{aligned}
$$

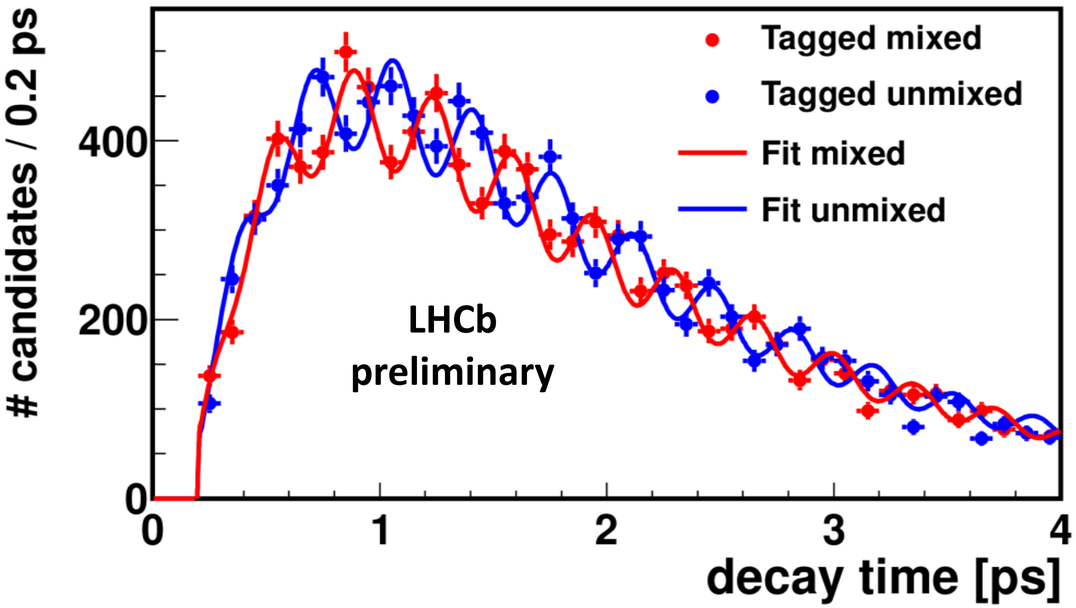
B_S-mixing frequency Δm

- Bs mixing frequency - most precisely measured by LHCb (LHCb-PAPER-2013-006), first measured at Tevatron in 2006 [latest update: Phys.Rev.Lett.97:242003,2006]

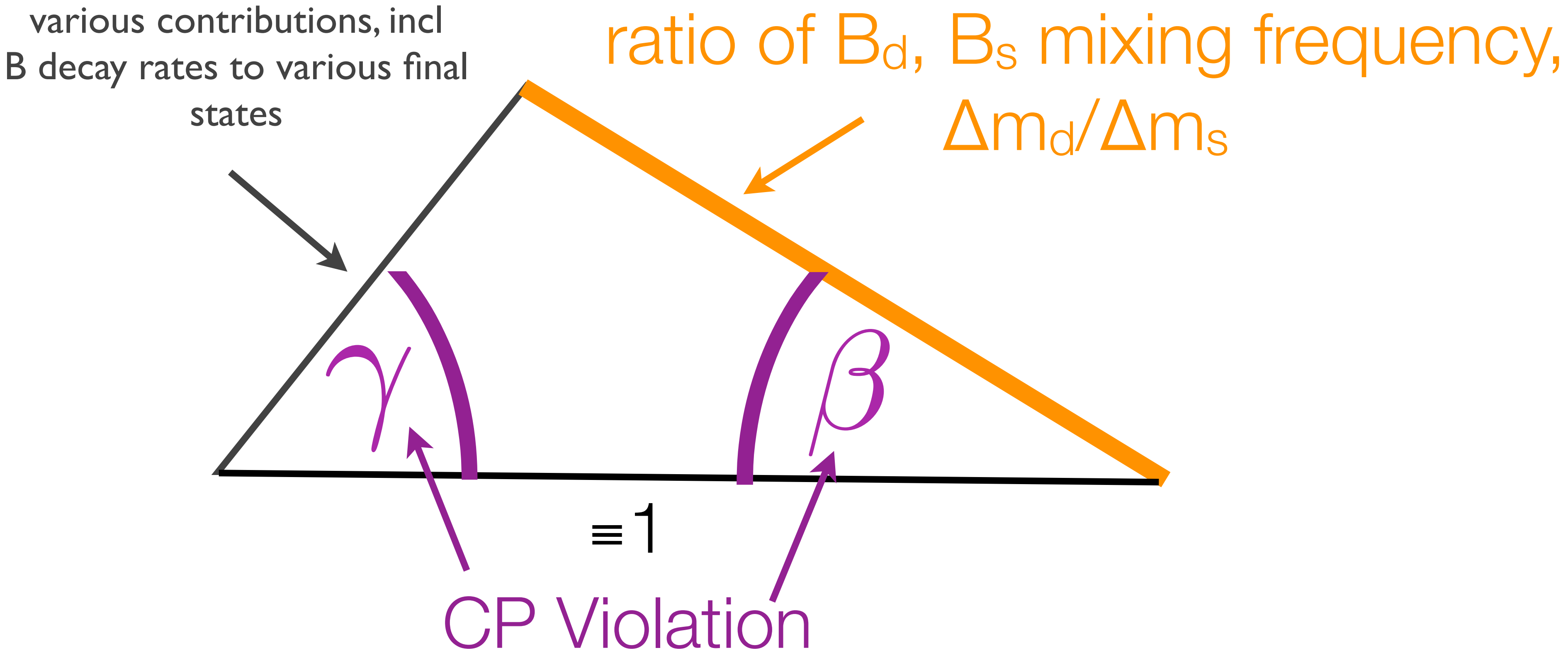
- Result: 2.82 ps^{-1}, (Δm=17.8 ps^{-1}) in line with SM expectations

- So no New Physics...

.... or is there?



Have we seen New Physics w/o realising it?



various contributions, incl
B decay rates to various final
states

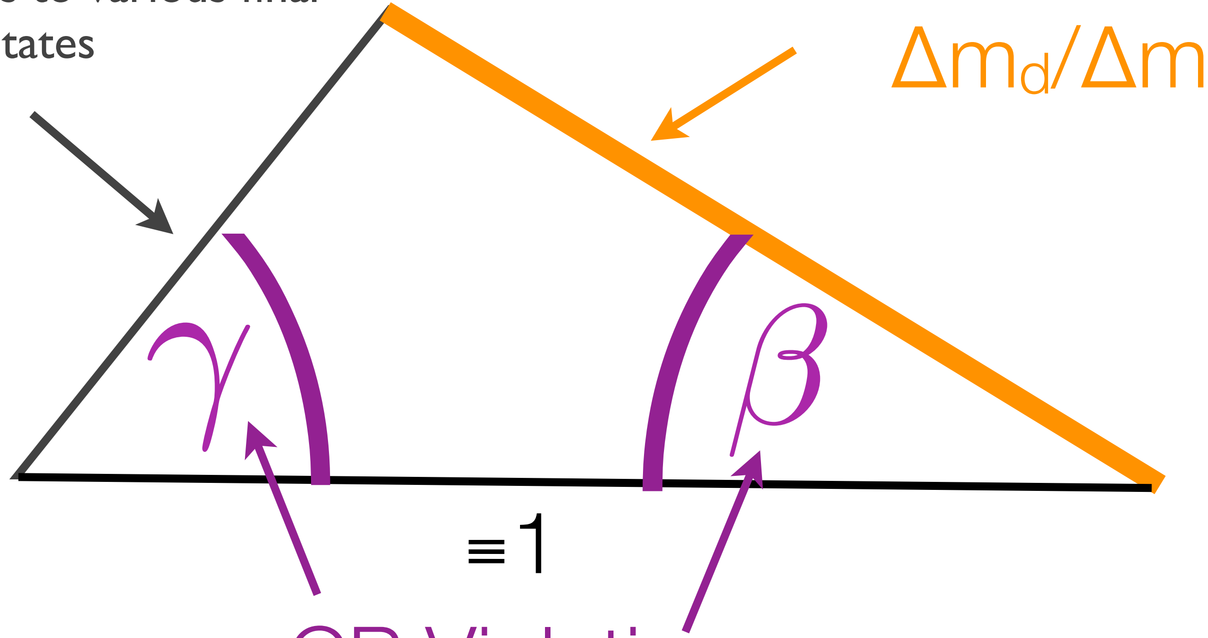
ratio of B_d, B_s mixing frequency,
$\Delta m_d/\Delta m_s$

$\equiv 1$

CP Violation

- Need Standard Model γ to see if mixing frequency is New Physics or not!

Have we seen New Physics w/o realising it?



various contributions, incl
B decay rates to various final
states

ratio of B_d, B_s mixing frequency,
$\Delta m_d / \Delta m_s$

γ

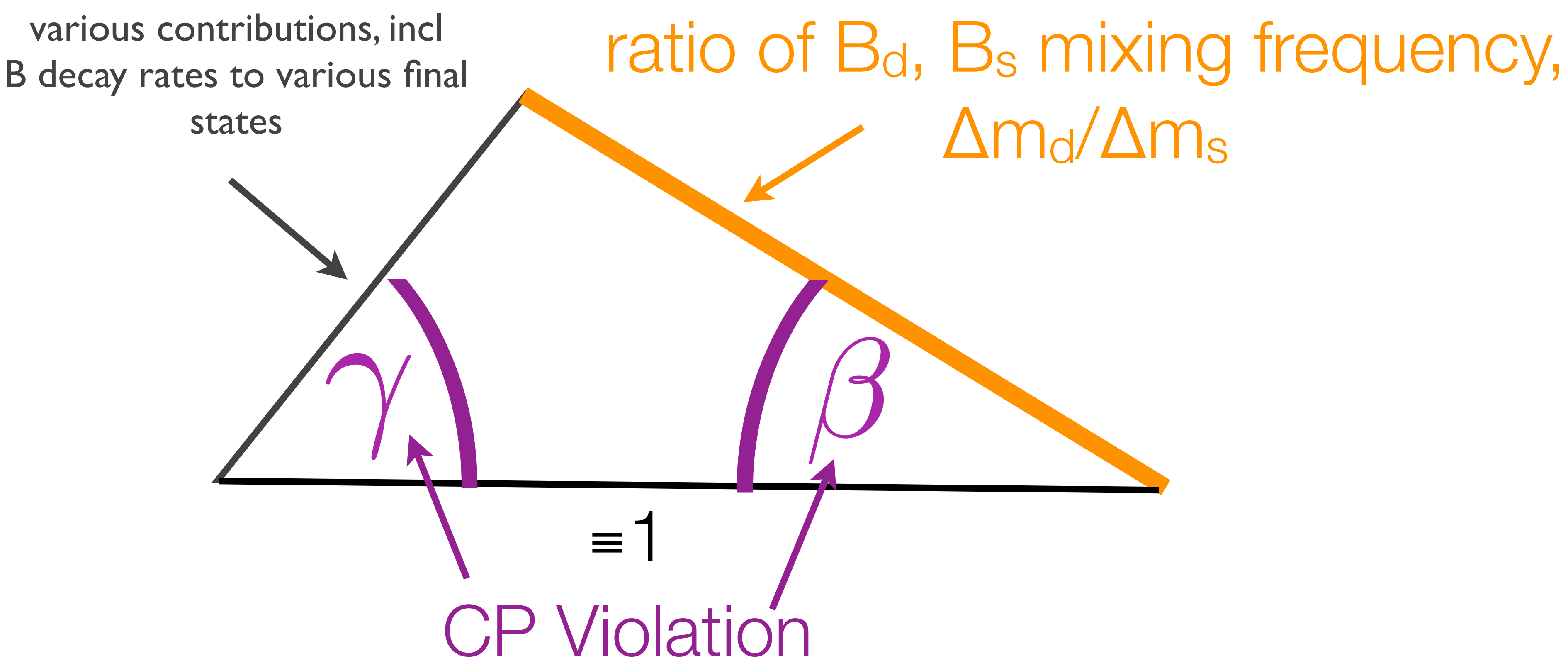
β

$\equiv 1$

CP Violation

- Need Standard Model γ to see if mixing frequency is New Physics or not!

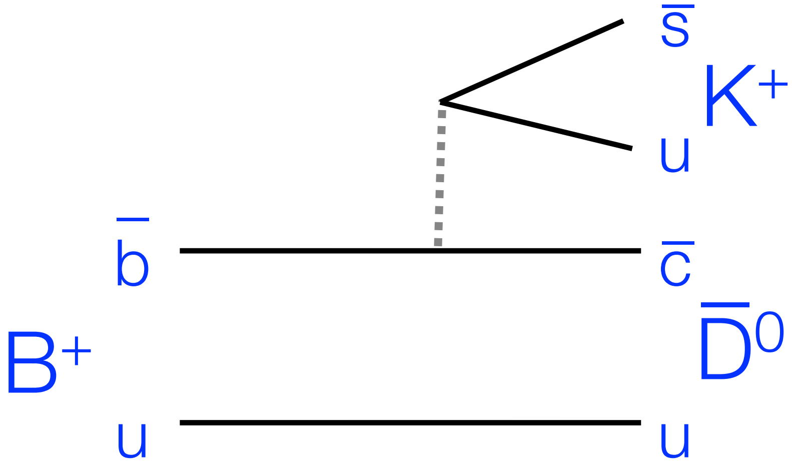
Have we seen New Physics w/o realising it?

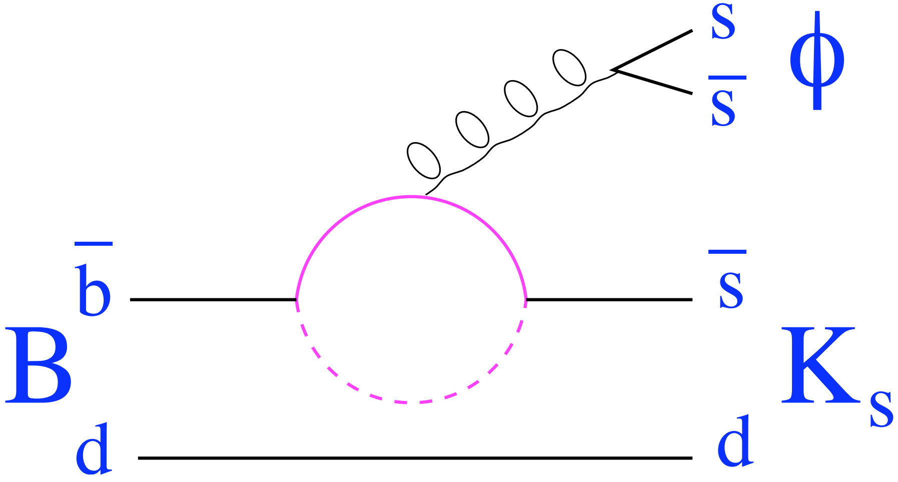


- Need Standard Model γ to see if mixing frequency is New Physics or not!

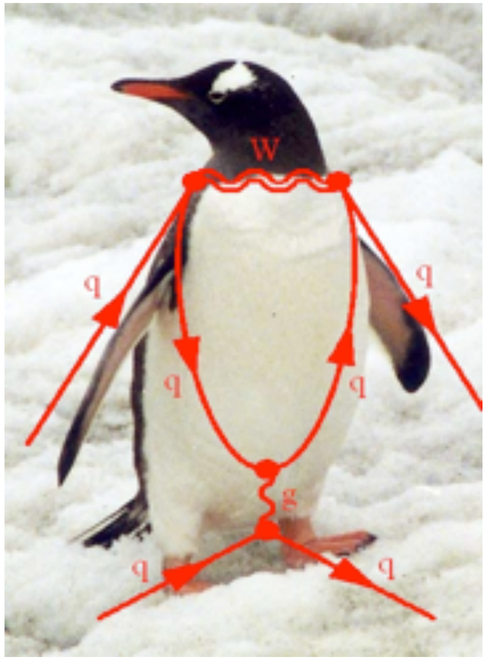
Loops vs Trees

- Expect no New Physics in Trees
- New Physics in loops?





Can penguins be bad?



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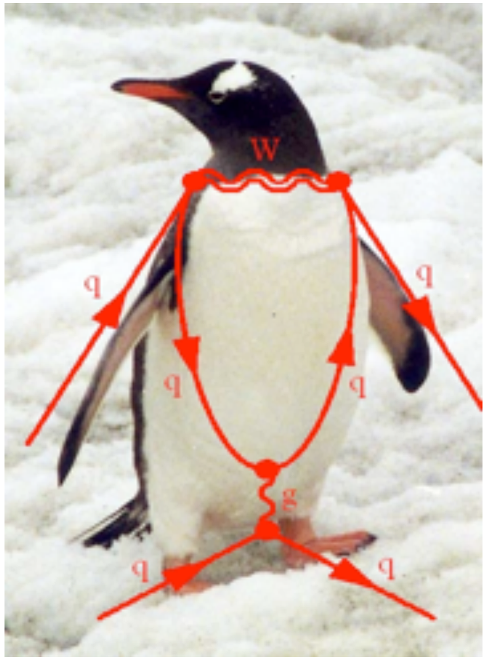

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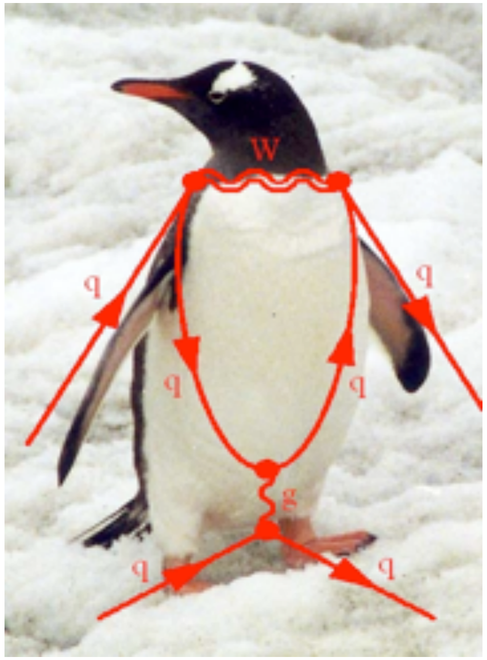
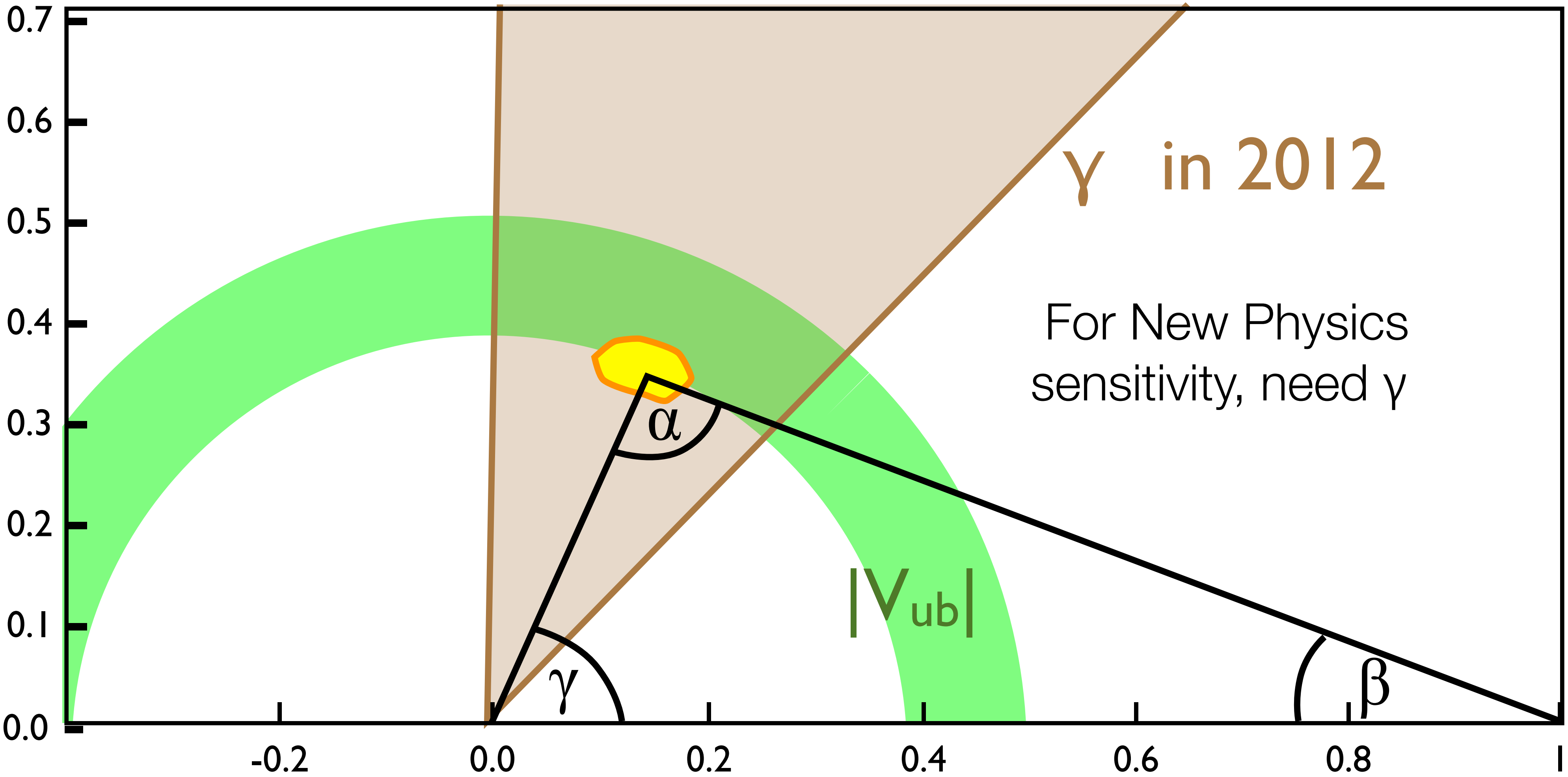


They can.

The “Unitarity Triangle” represents key parameters of the Standard Model description of CP violation.

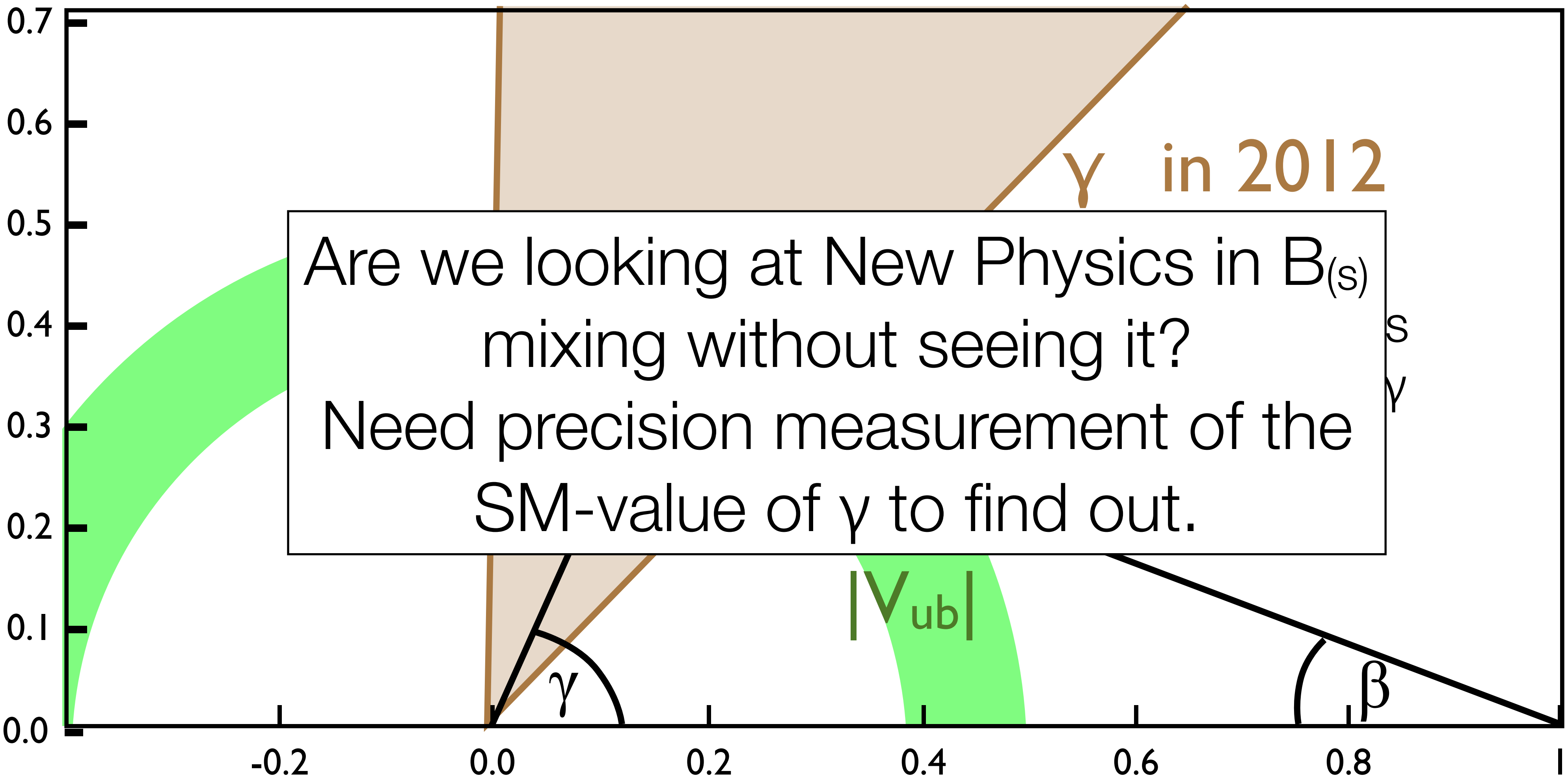
If the Standard Model is correct, we should get consistent constraints on the apex of the triangle. Shaded areas identify constraints from different sources (95% CL). (Yellow: “loops”, others “trees”.)



For New Physics sensitivity, need γ

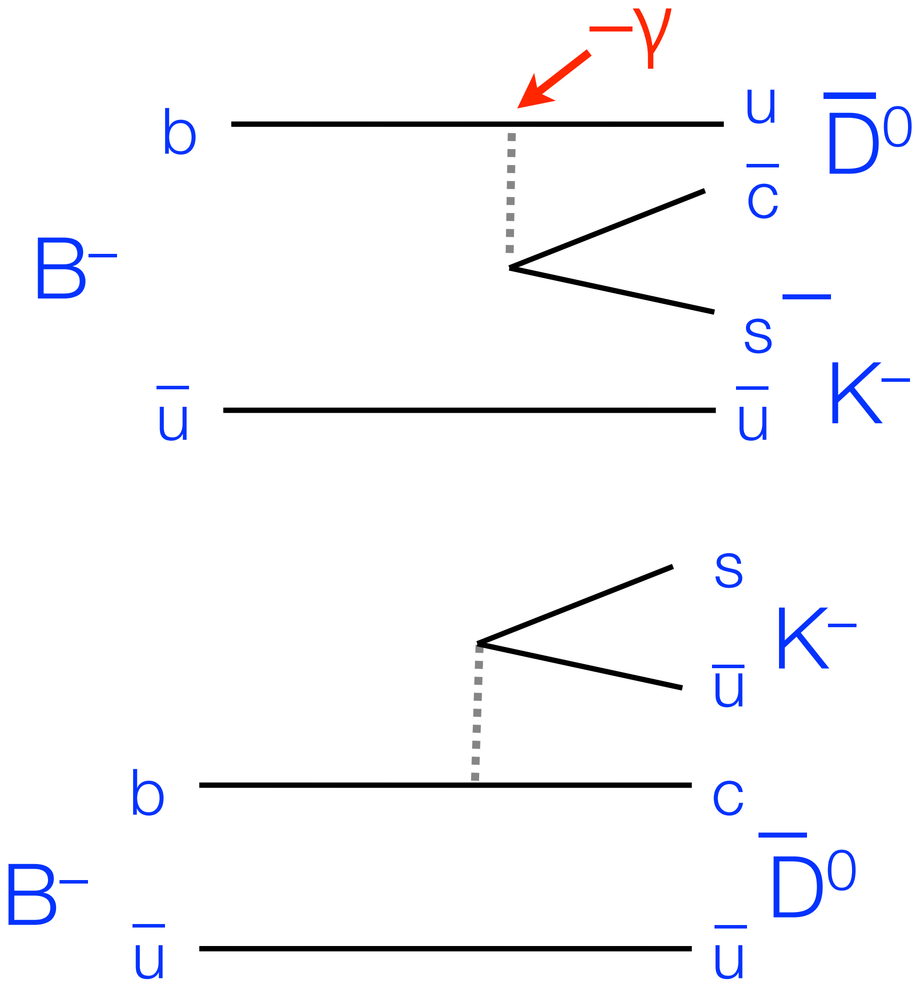
The “Unitarity Triangle” represents key parameters of the Standard Model description of CP violation.

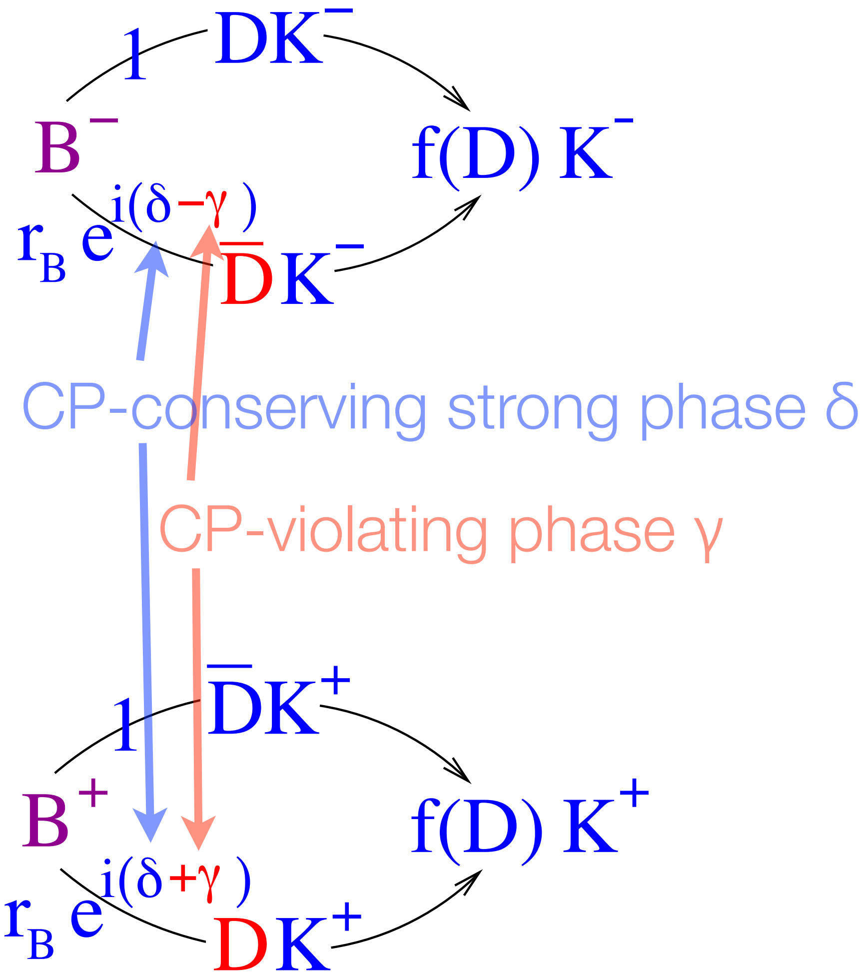
If the Standard Model is correct, we should get consistent constraints on the apex of the triangle.
Shaded areas identify constraints from different sources (95% CL). (Yellow: “loops”, others “trees”.)



Are we looking at New Physics in $B_{(s)}$ mixing without seeing it?
Need precision measurement of the SM-value of γ to find out.

$B^\pm \to DK^\pm$



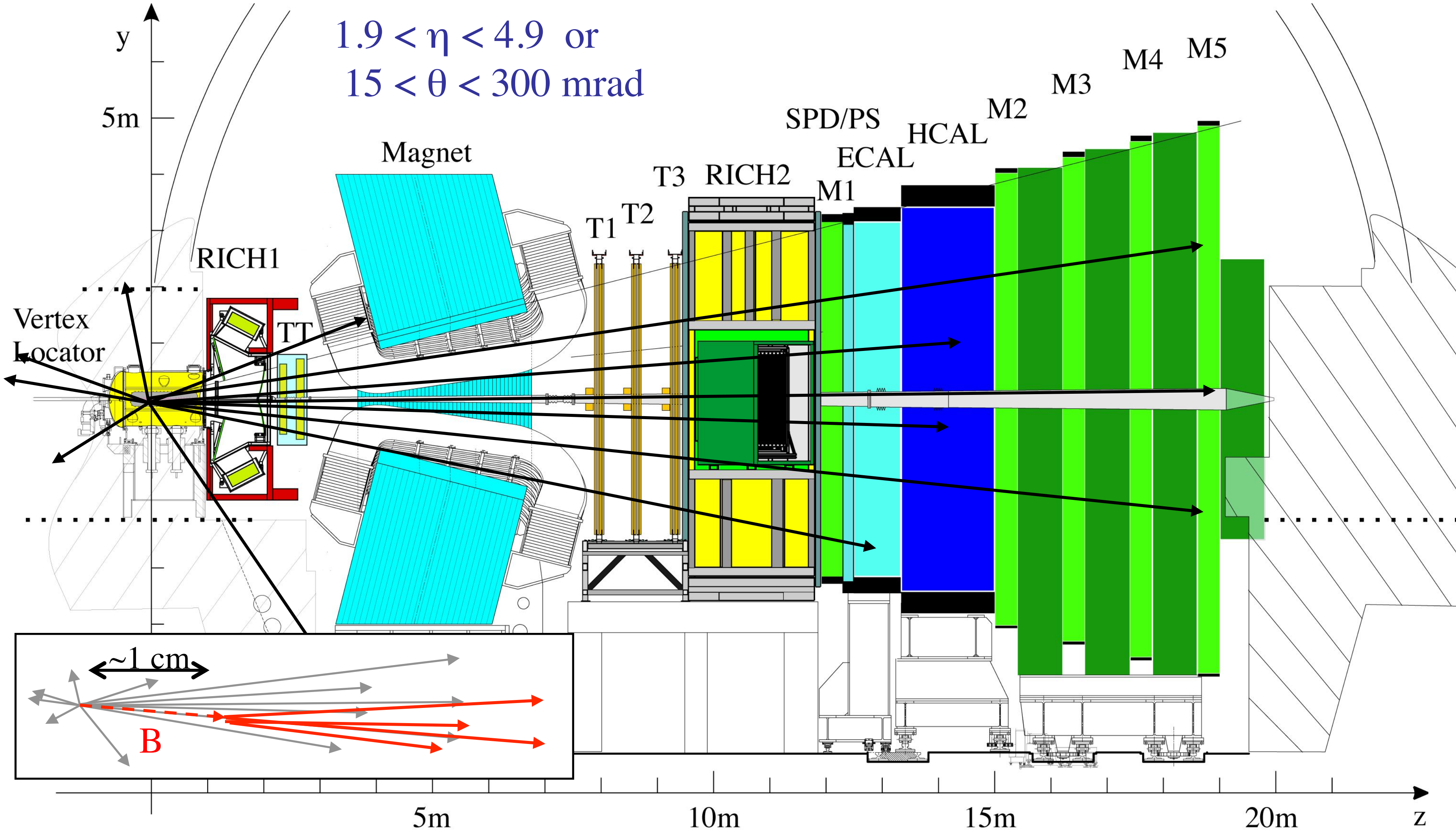


CP-conserving strong phase δ

CP-violating phase γ

Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

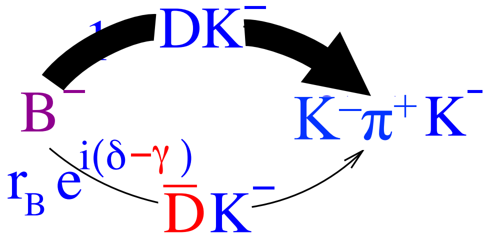
The LHCb Detector



$1.9 < \eta < 4.9$ or

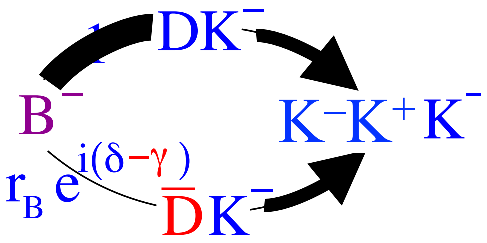
$15 < \theta < 300$ mrad

CP violation in 2-body modes.



B^- DK^- $K^-\pi^+K^-$

$r_B e^{i(\delta-\gamma)}$ $\bar{D}K^-$



B^- DK^- $K^-K^+K^-$

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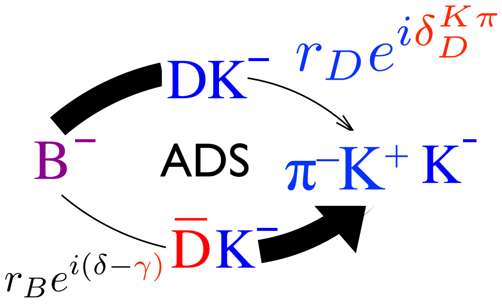
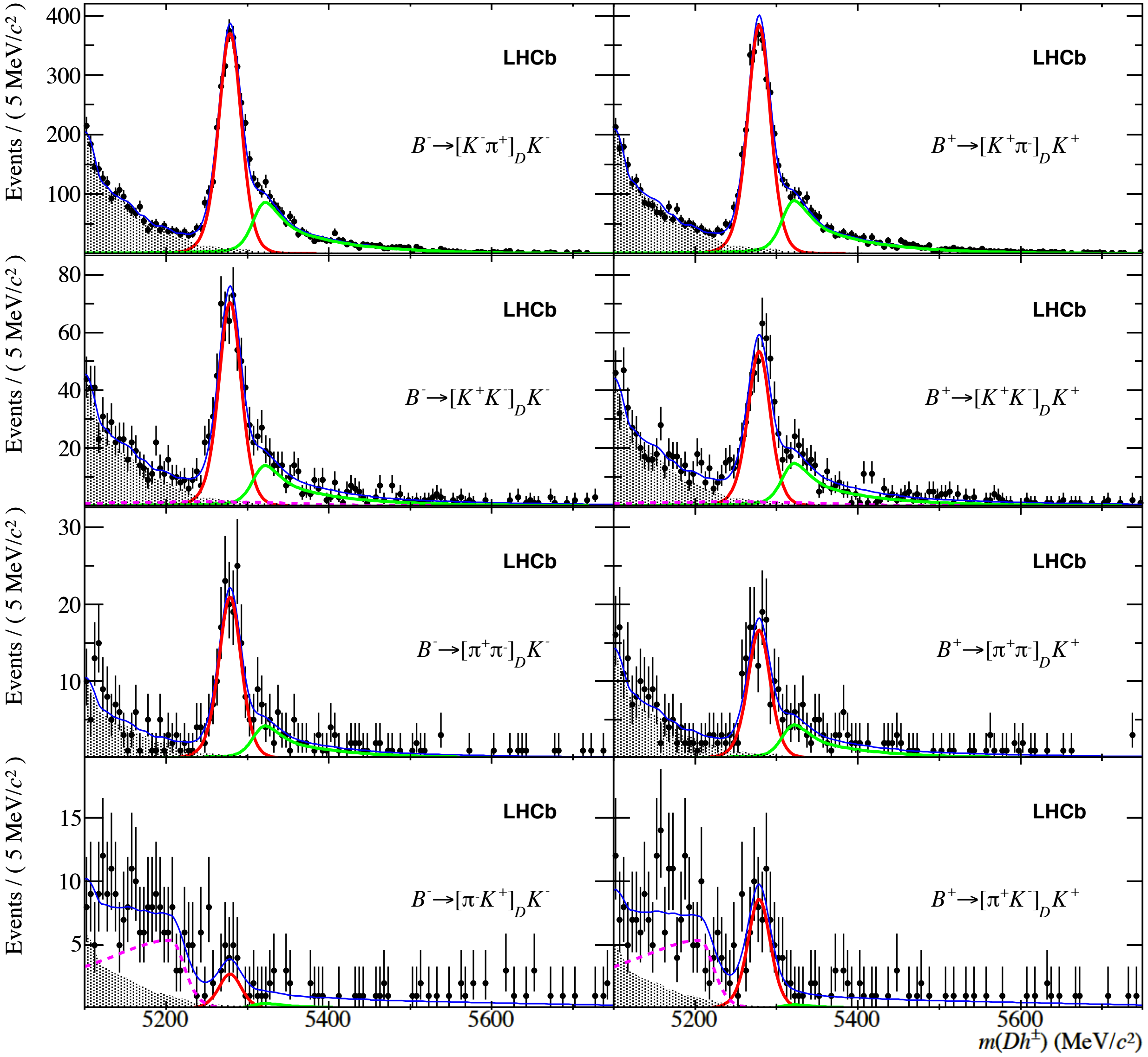


$r_D e^{i\delta_D^{K\pi}}$

B^- DK^- ADS $\pi^-K^+K^-$

$r_B e^{i(\delta-\gamma)}$ $\bar{D}K^-$



3-body D decays and Dalitz Plots

There are many paths from
$\mathrm{D^o}$ to $\mathrm{K_s}\pi\pi$

$\mathrm{D}^0 \rightarrow$

Intermediate state	Amplitude $\|c_j\|$	Phase δ_j (°)
$K^*(892)^+\pi^-$	1.656 ± 0.012	137.6 ± 0.6
$K^*(892)^-\pi^+$	$(14.9 \pm 0.7) \times 10^{-2}$	325.2 ± 2.2
$K_0^*(1430)^+\pi^-$	1.96 ± 0.04	357.3 ± 1.5
$K_0^*(1430)^-\pi^+$	0.30 ± 0.05	128 ± 8
$K_2^*(1430)^+\pi^-$	1.32 ± 0.03	313.5 ± 1.8
$K_2^*(1430)^-\pi^+$	0.21 ± 0.03	281 ± 9
$K^*(1680)^+\pi^-$	2.56 ± 0.22	70 ± 6
$K^*(1680)^-\pi^+$	1.02 ± 0.2	103 ± 11
$K_S\rho^0$	1.0 (fixed)	0 (fixed)
$K_S\omega$	$(33.0 \pm 1.3) \times 10^{-3}$	114.3 ± 2.3
$K_S f_0(980)$	0.405 ± 0.008	212.9 ± 2.3
$K_S f_0(1370)$	0.82 ± 0.10	308 ± 8
$K_S f_2(1270)$	1.35 ± 0.06	352 ± 3
$K_S\sigma_1$	1.66 ± 0.11	218 ± 4
$K_S\sigma_2$	0.31 ± 0.05	236 ± 11
non-resonant	6.1 ± 0.3	146 ± 3

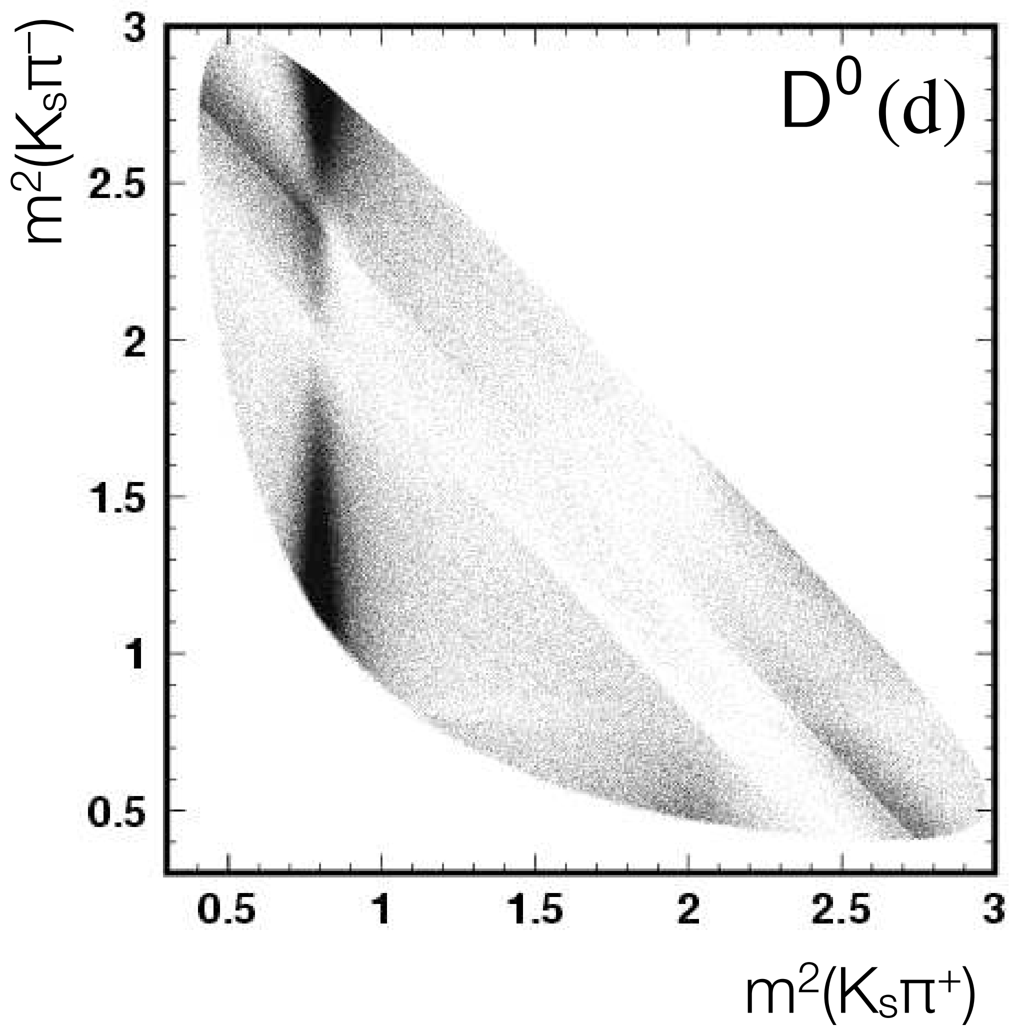
$\rightarrow \mathrm{K_s}\pi\pi$

$D \rightarrow K_S\pi^+\pi^-$ Dalitz Plot

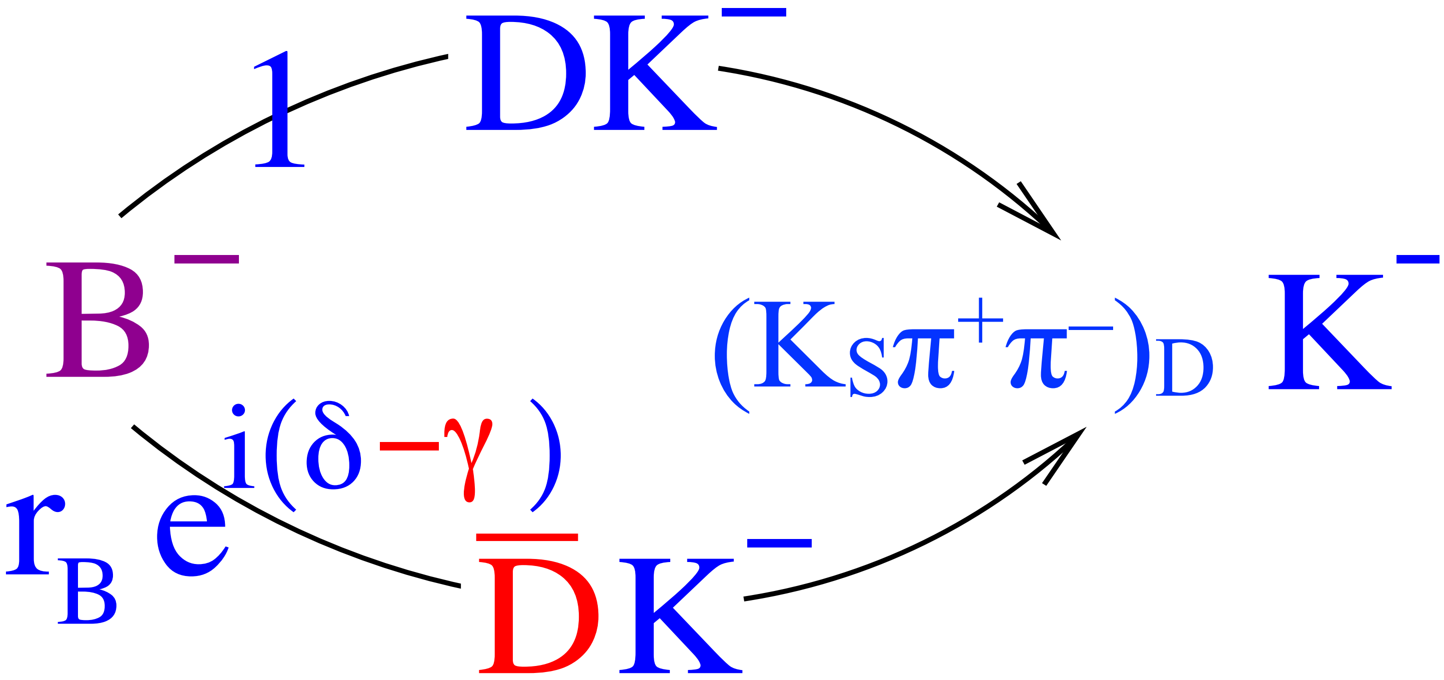
- Entire decay kinematics down to two variables.
- Choose:

  $m^2(K_S\pi^+)$, $m^2(K_S\pi^-)$

- Each point in plot = one event (BaBar) (have many, many more D than B)



CP violation is an interference effect



DK^-

1

B^-

$(K_S\pi^+\pi^-)_D\ K^-$

$r_B\, e^{i(\delta-\gamma)}$

$\bar{D}K^-$

Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 **(GLW)** Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

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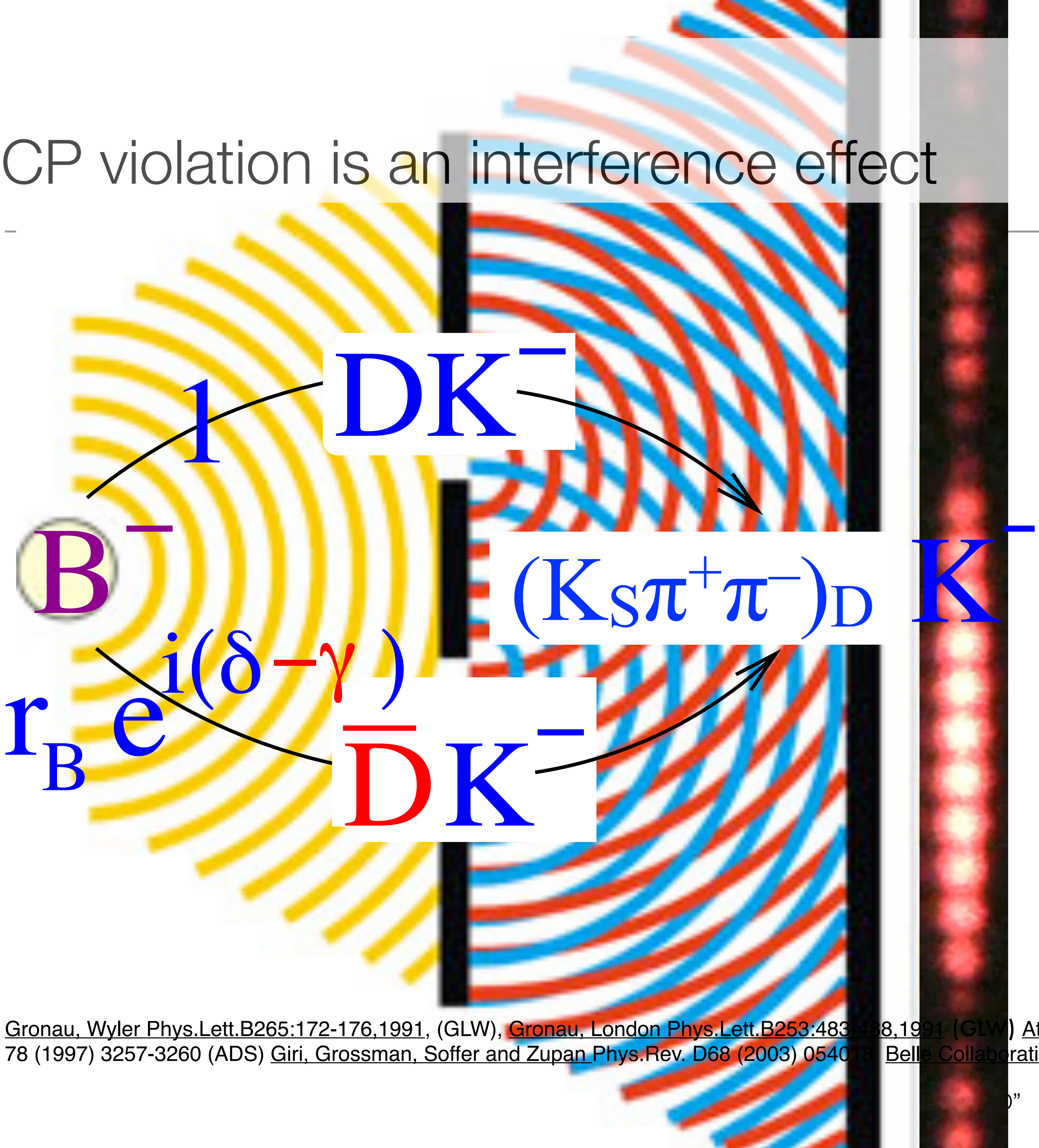

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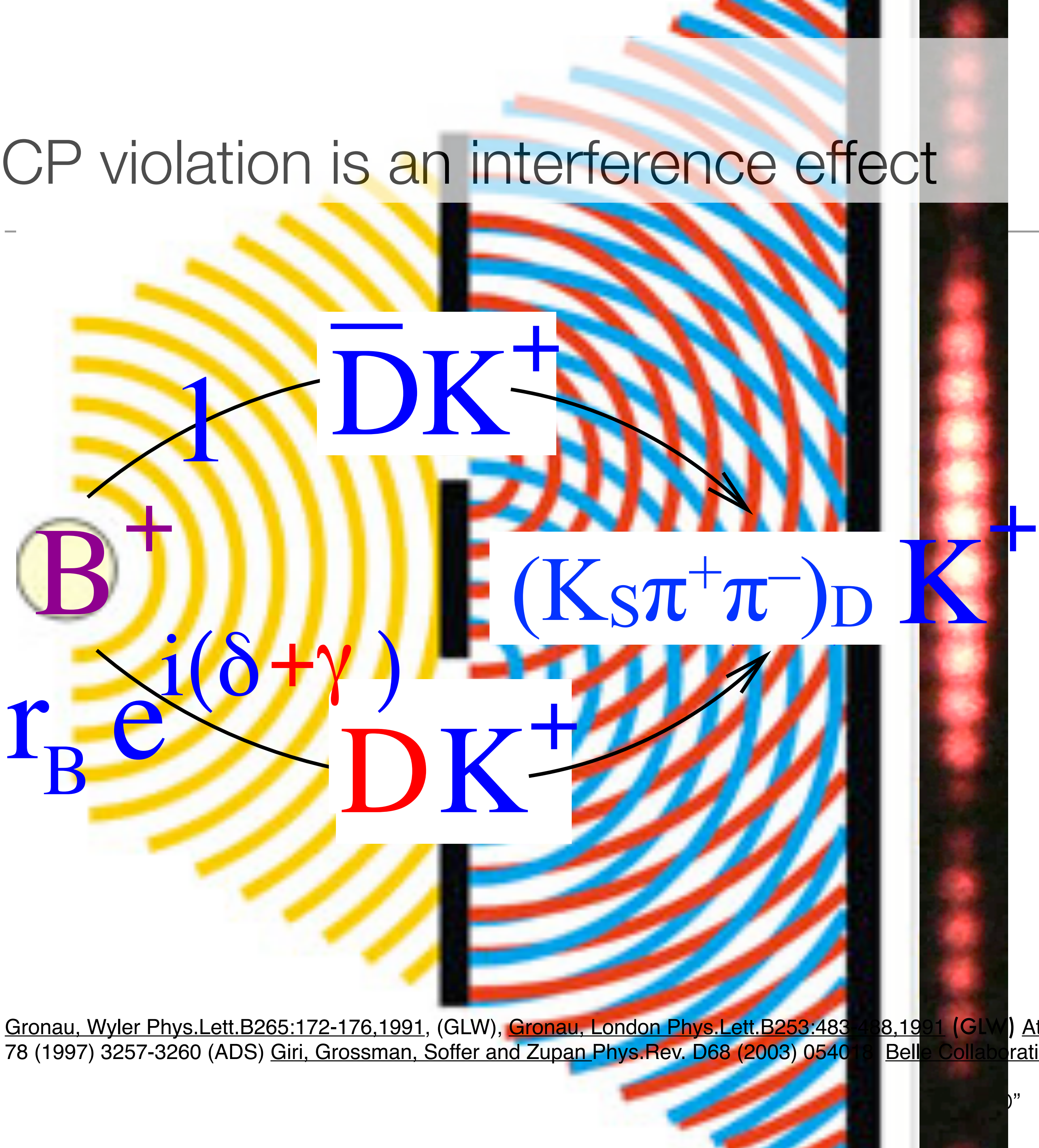

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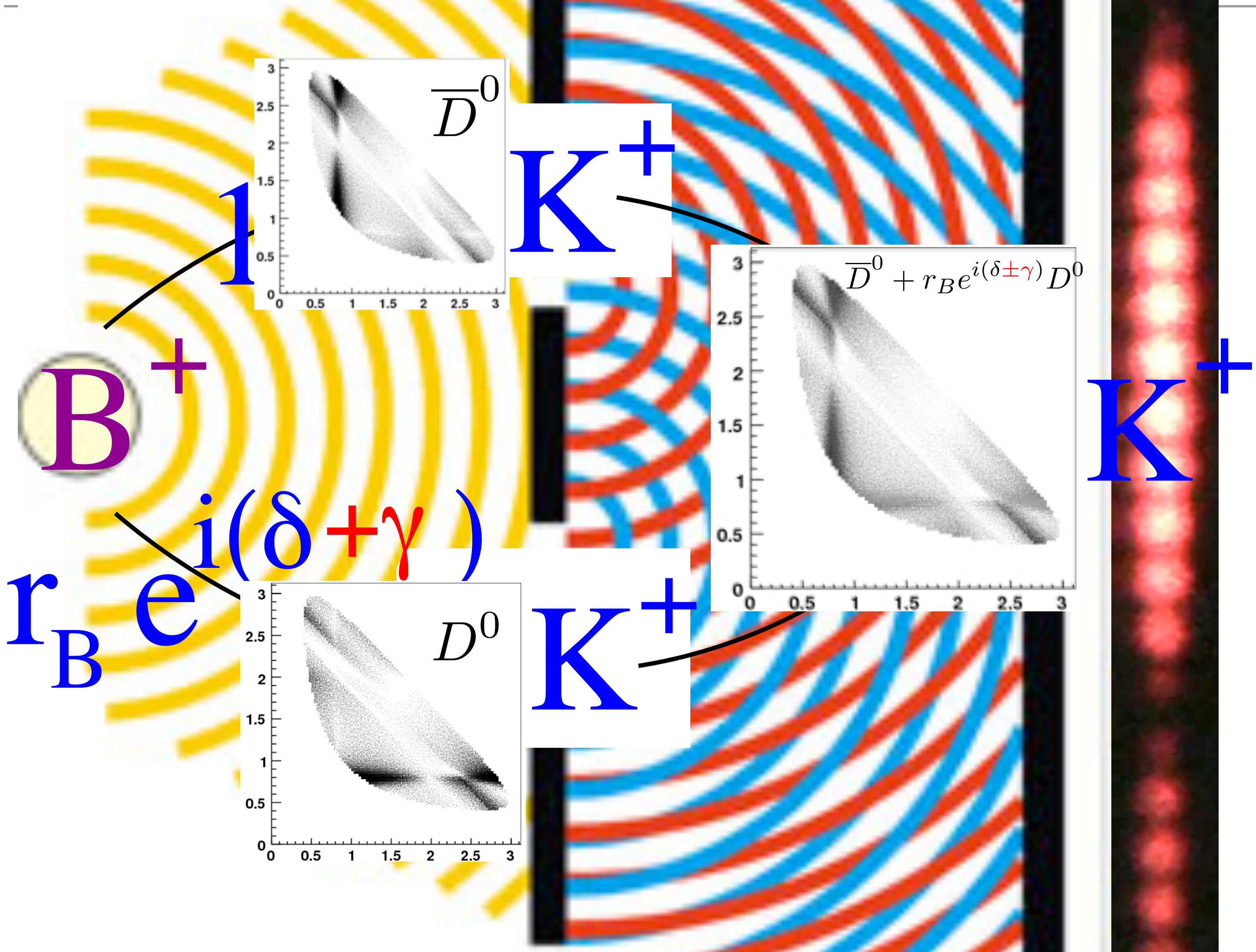
CP violation is an interference effect



- For D→3-body decays, the interference takes place in an abstract 2-D space (Dalitz plot)
- Analysing the Dalitz plot of the D decay, in D's that come from B±'s, gives access to γ

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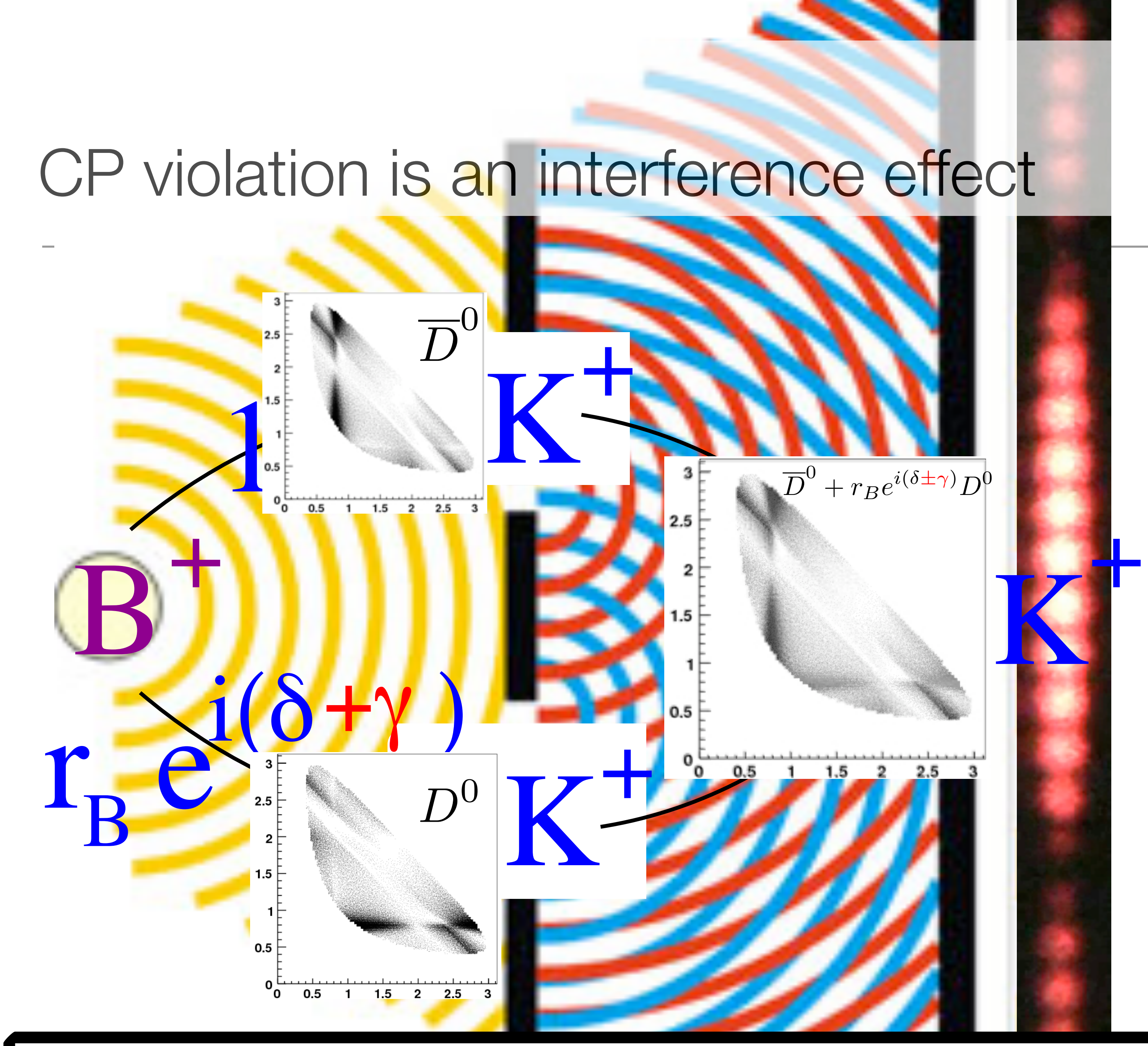
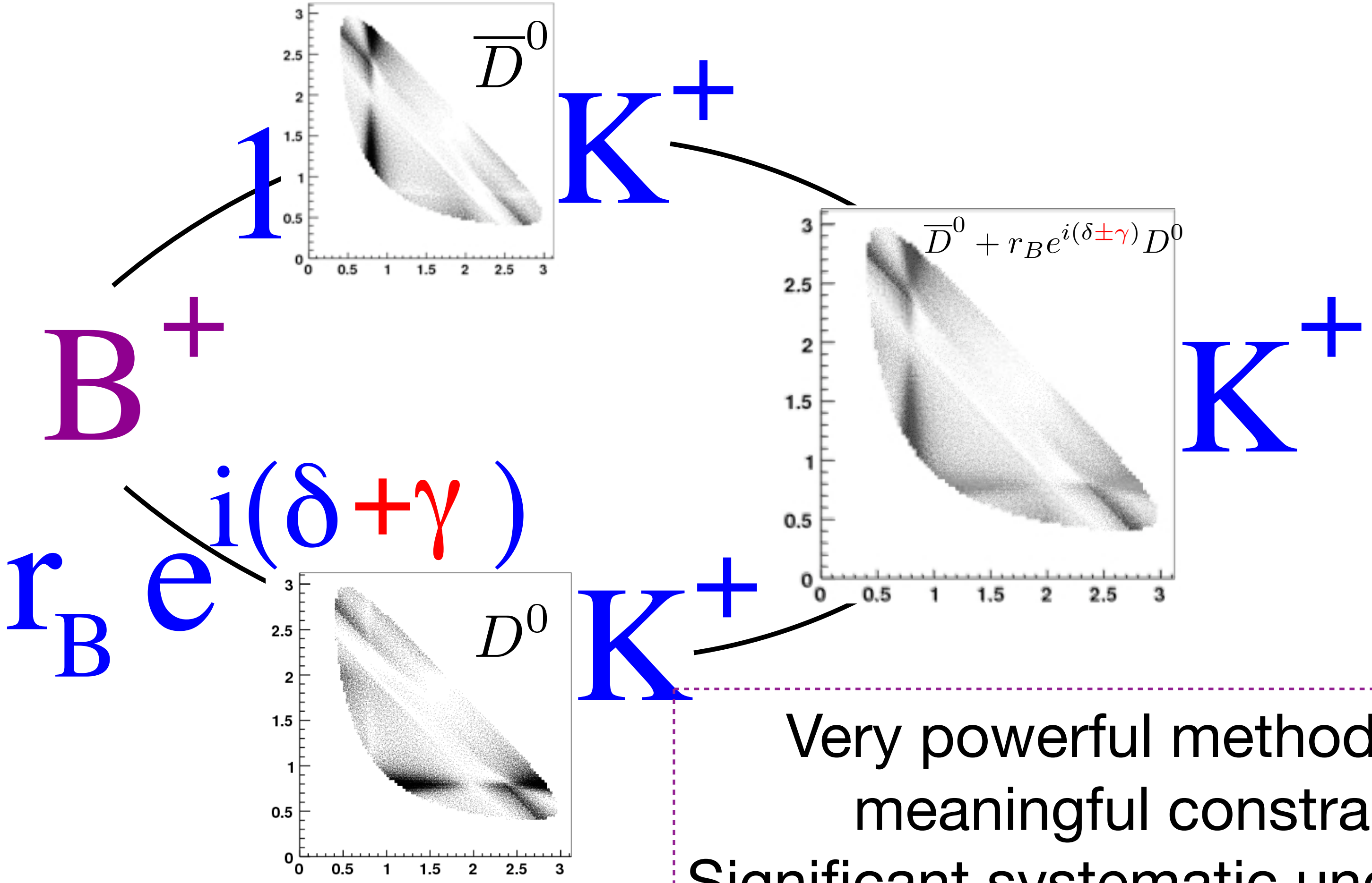


- For D→3-body decays, the interference takes place in an abstract 2-D space (Dalitz plot)
- Analysing the Dalitz plot of the D decay, in D's that come from $B^{\pm}$'s, gives access to γ

This is the best method we know to measure γ. The only meaningful constraints on γ are based on it. We will improve it a lot!

γ from B→DK with D→$K_S\pi\pi$



Very powerful method, led to first meaningful constraints on γ.
Significant systematic uncertainty (4°-9°) due to Dalitz model dependence.

Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 **(GLW)** Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

Multi-Generational Flavour Physics

Edward V. Brewer (1883 – 1971)

Multi-Generational Flavour Physics

Edward V. Brewer (1883 – 1971)

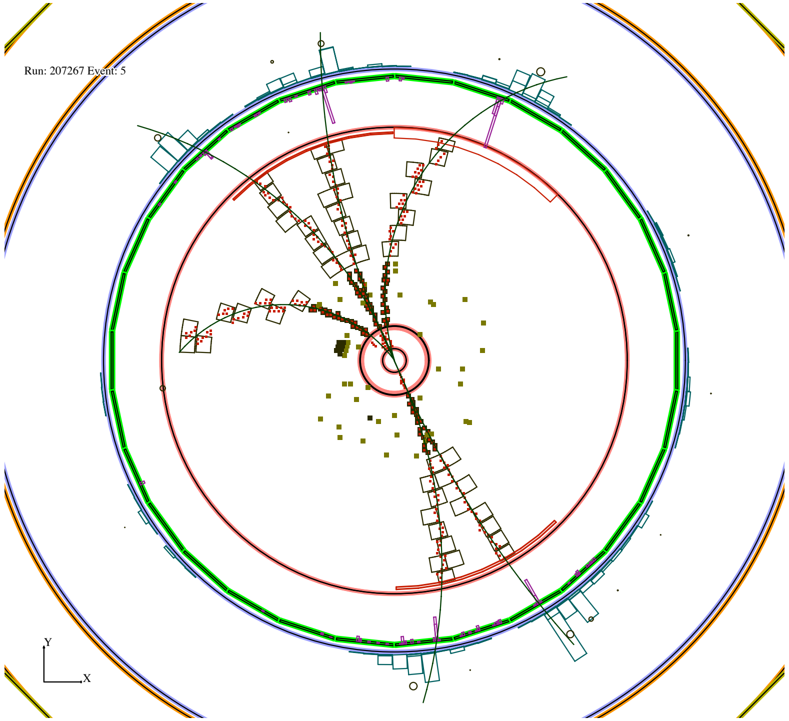
Regrettably, CLEO recently deceased - but her data live on.

CLEO-c

$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

CLEAN-c

- Threshold production of correlated DD.
- Final state must be CP-even with L=1: D mesons must have opposite intrinsic CP.
- Final state is also flavour-neutral.
- That gives us access to both amplitude and phase across the Dalitz plot.



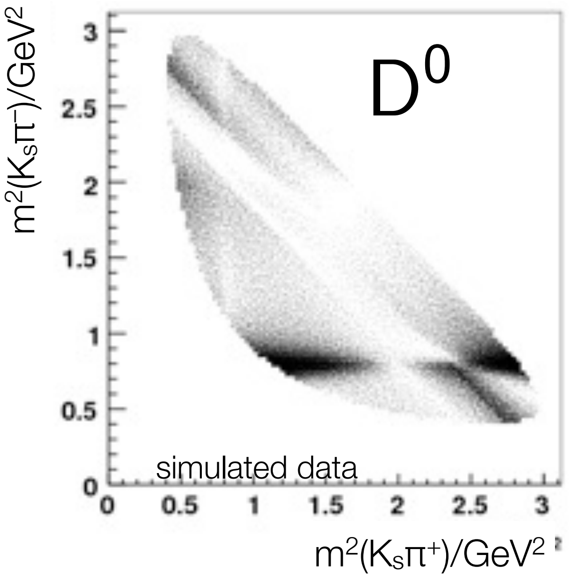
$$\psi(3770) \rightarrow D^0(K_S\pi^+\pi^-)\bar{D}^0(K^+\pi^-)$$

CP and flavour tagged D°

ψ''

$\rightarrow \bar{D}_{\mathrm{flavour}} \rightarrow K^{+}e^{-}\,\nu_{e}$

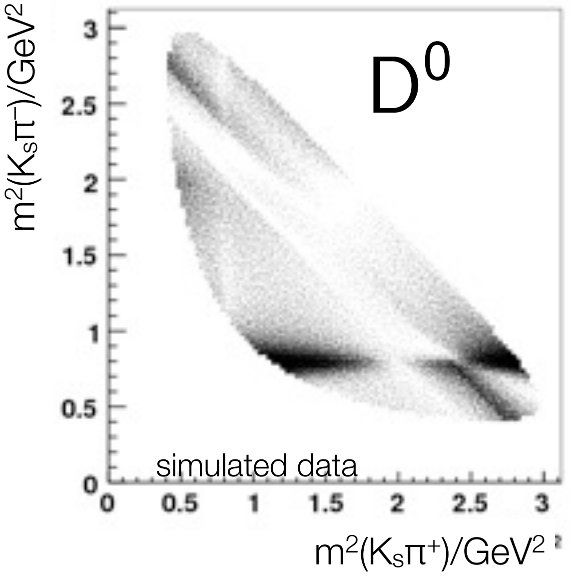
$\rightarrow D_{\mathrm{flavour}} \rightarrow K_{S}\pi^{+}\pi^{-}$

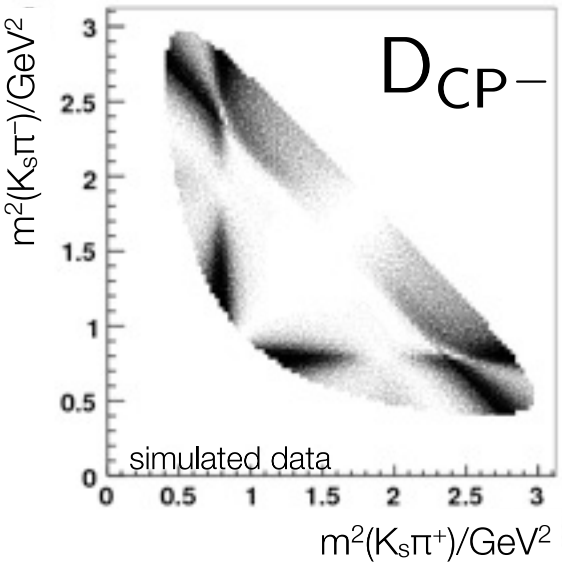


CP and flavour tagged D°

$$\psi'' \to \begin{cases} \bar{D}_{\text{flavour}} \to K^+ e^- \nu_e \\ D_{\text{flavour}} \to K_S \pi^+ \pi^- \end{cases}$$

$$\psi'' \to \begin{cases} D_{CP+} \to KK \\ D_{CP-} \to K_S \pi^+ \pi^- \end{cases}$$





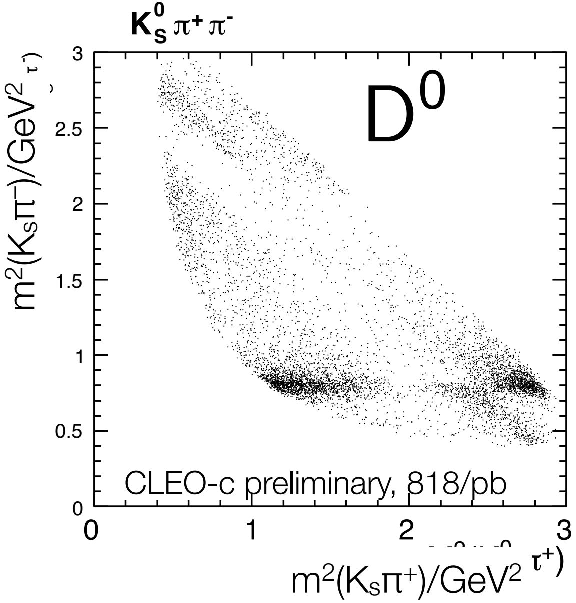
CP and flavour tagged D^o at CLEO

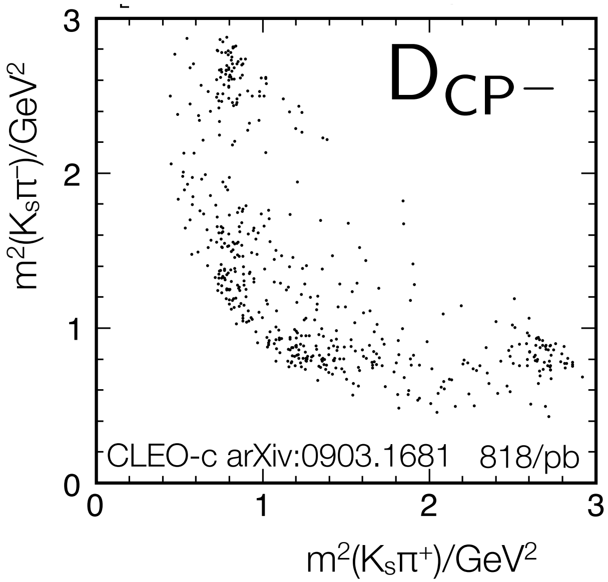
$$\psi'' \rightarrow \bar{D}_{\text{flavour}} \rightarrow K^+ e^- \nu_e$$

$$\psi'' \rightarrow D_{\text{flavour}} \rightarrow K_S \pi^+ \pi^-$$

$$\psi'' \rightarrow D_{CP+} \rightarrow KK$$

$$\psi'' \rightarrow D_{CP-} \rightarrow K_S \pi^+ \pi^-$$





Model independent γ fit

Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).

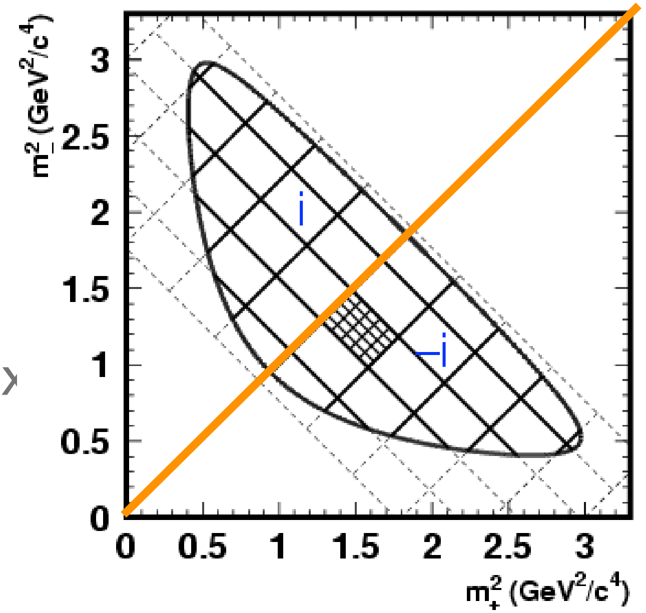
- Binned decay rate:

$\mathcal{T}_i$ known from flavour-specifc D decays (e.g. D*)

$$\Gamma\left(B^\pm \to D(K_s\pi^+\pi^-)K^\pm\right)_i = \mathcal{T}_i + r_B^2\mathcal{T}_{-i} + 2r_B\sqrt{\mathcal{T}_i\mathcal{T}_{-i}}\left\{c_i\cos\left(\delta\pm\gamma\right)+s_i\sin\left(\delta\pm\gamma\right)\right\}$$

(weighted) average of cos(δ_D) and sin(δ_D) over bin i, where δ_D = phase difference between D→Ksππ and Dbar→Ksππ

- Binning such that such that $c_i = c_{-i}$, $s_i = -s_{-i}$
- Distribution sensitive to c_i, s_i, r_B, δ and γ.
- To extract γ from realistic numbers of B events need ex input from CLEO's quantum-correlated DDbar pairs.



CLEO-c’s input to γ

- CLEO-c’s input is concerned with δ_D, the phase difference between

  $A(D^o \to K_S\pi^+\pi^-)$ and $A(\overline{D}^o \to K_S\pi^+\pi^-)$

  at each point on the Dalitz plot.

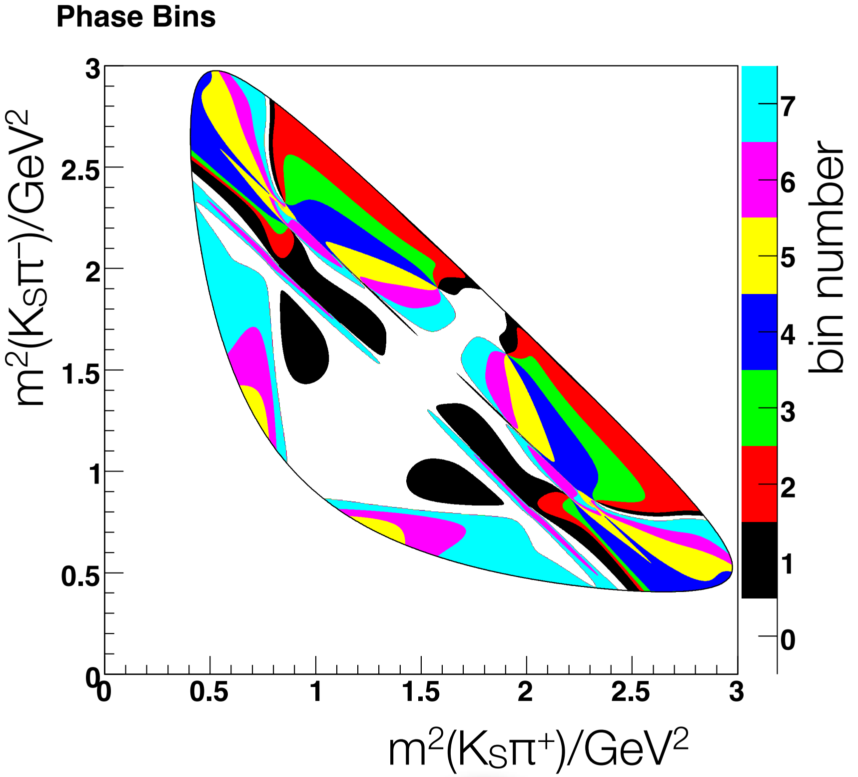
- Measure the cosine and sine of this phase, averaged over bins:

  $c_i = \langle\cos(\delta_D)\rangle_i$, $s_i = \langle\sin(\delta_D)\rangle_i$

- This input allows model-independent γ measurement.

Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).

Binning used at CLEO-c*



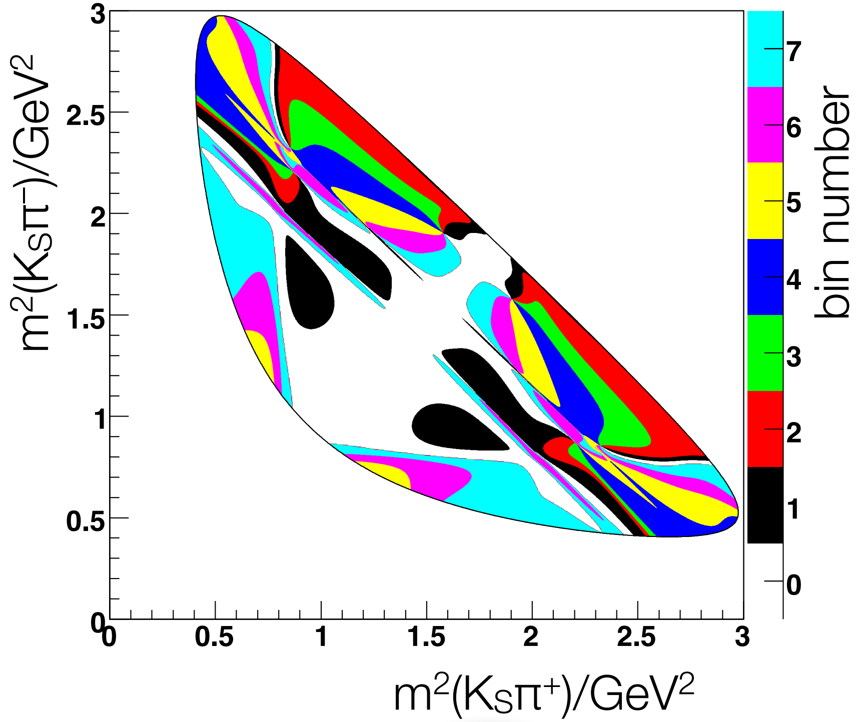
CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

*bin width uniform in δ_D based on BaBar model PRL 95 (2005) 121802

Optimal binning

- Best γ sensitivity if phase difference δ_D is as constant as possible over each bin[1].
- Plot shows CLEO-c's 8 bins, uniform in δ_D, (based on BaBar isobar model*).
- Choice of model will not bias result. (At worst a bad model would reduce the statistical precision of the result.)

Binning at CLEO-c based on BaBar model*



CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

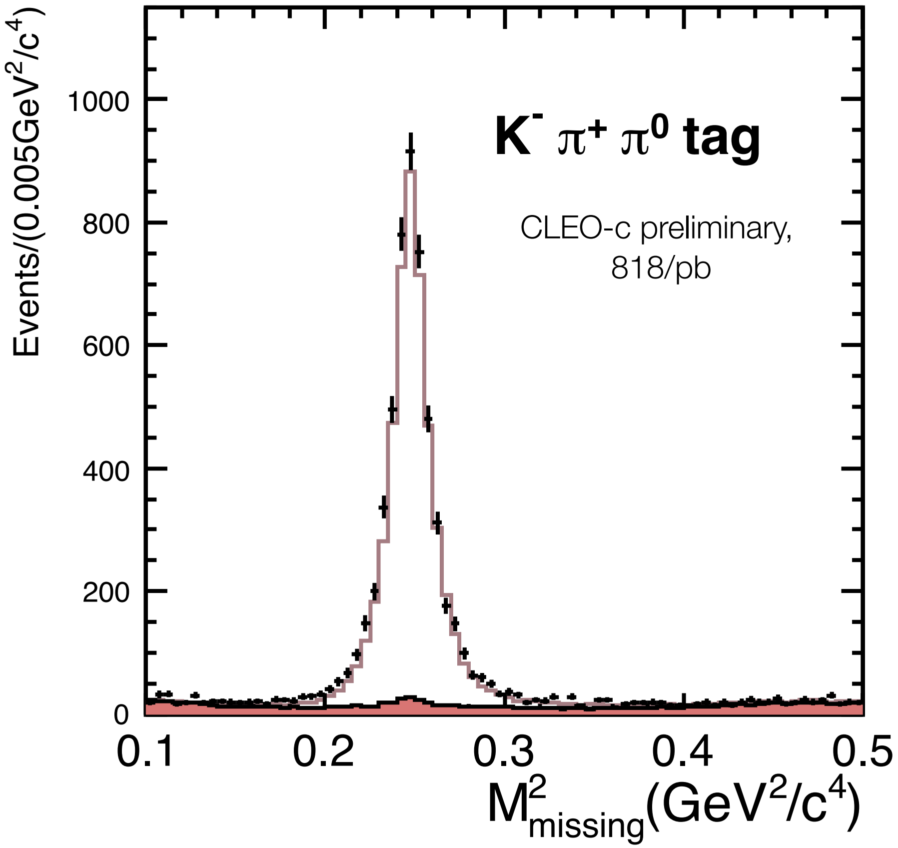
[1] Bondar, Poluektov hep-ph/0703267v1 (2007)

*model = BaBar PRL 95 (2005) 121802

CP-even $K_L\pi\pi \approx$ CP-odd $K_S\pi\pi$

- CLEO-c's clean environment allows the reconstruction of K_L from kinematic constraints.
- Significantly increases statistics.
- There is price to pay: A $\mathcal{O}(\tan^2\theta_C)$ model-dependent correction. Carefully evaluated (small) systematic uncertainty.

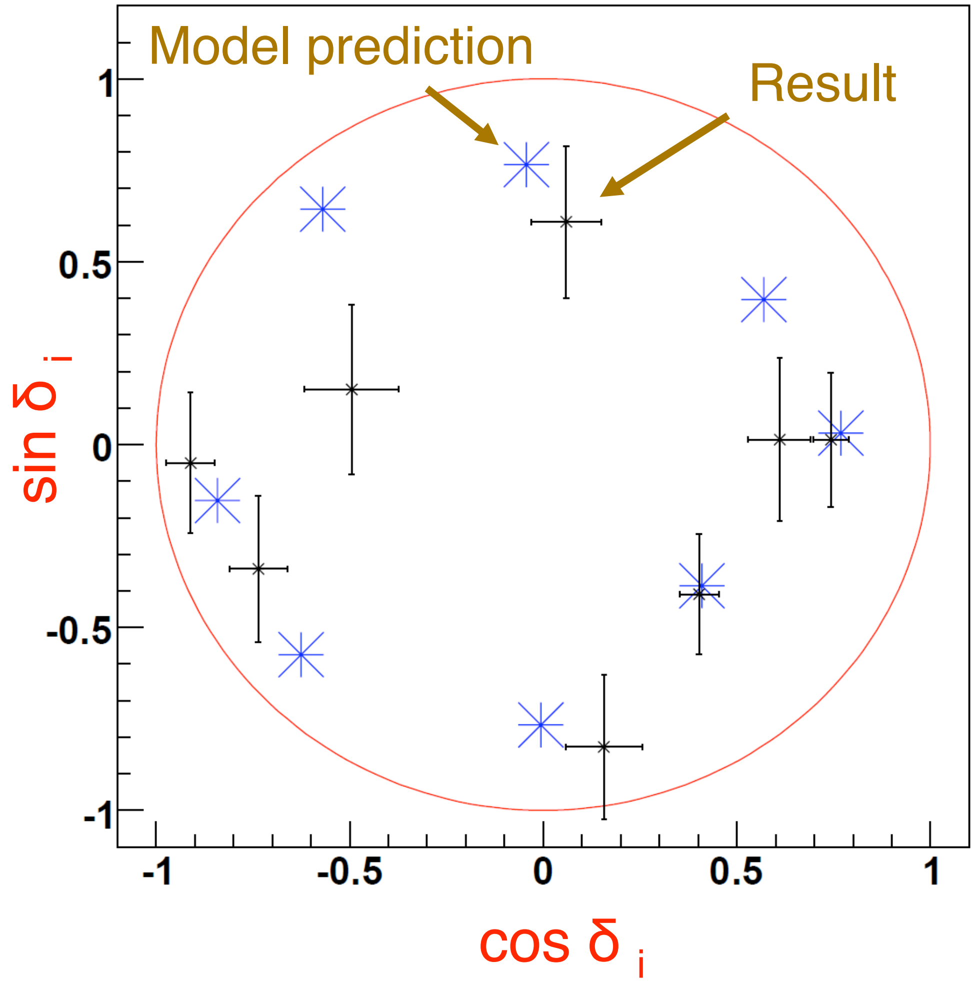
Overlaying Data (black) and MC (red) for missing M^2 in K_L reconstruction in $K_L\pi^+\pi^-$ vs $K^-\pi^+\pi^0$



CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

CLEO-c results

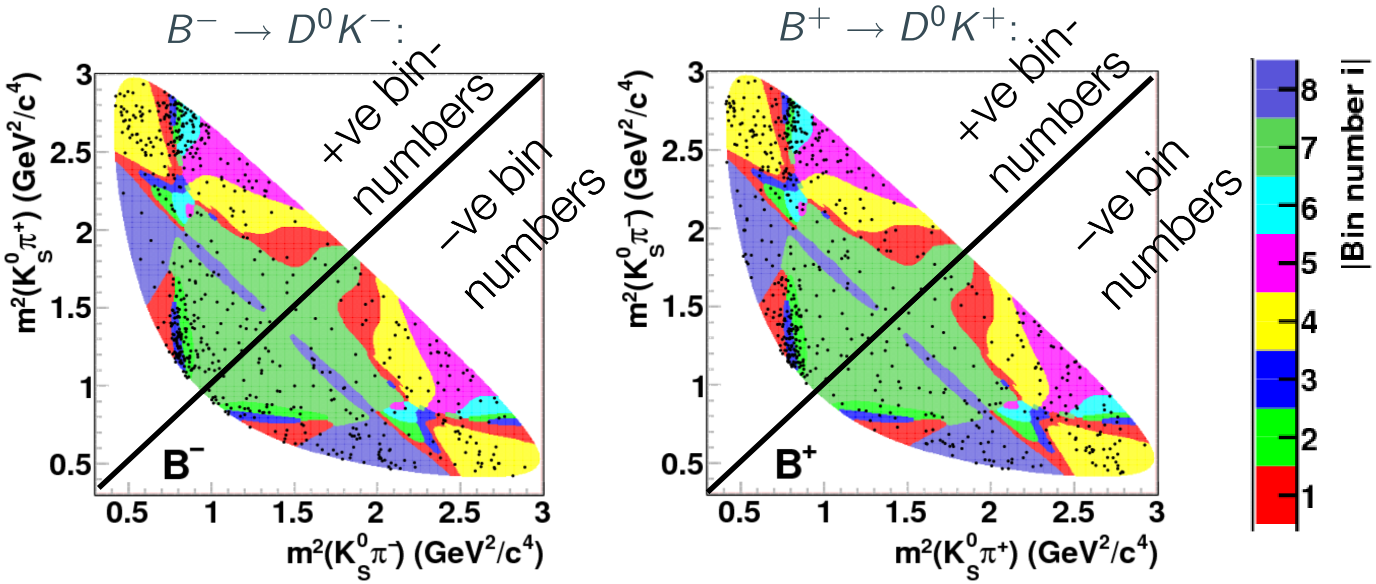
- 818/fb at CLEO-c
- 20k flavour tagged events (for magnitude of $A(D^0 \to K_S\pi^+\pi^-)$)
- 1.6 k CP-tagged events (for c_i extraction)
- 1.3k $K_{L,S}\pi\pi$ vs $K_S\pi\pi$ (for c_i and s_i extraction)
- S/B between 10 and 100, depending on tag mode.



Result: Phys.Rev.D80:032002,2009
model: BaBar PRL 95 (2005) 121802

First model-independent γ measurement (BELLE)

Flavour-tagged D→Kₛππ Dalitz plot

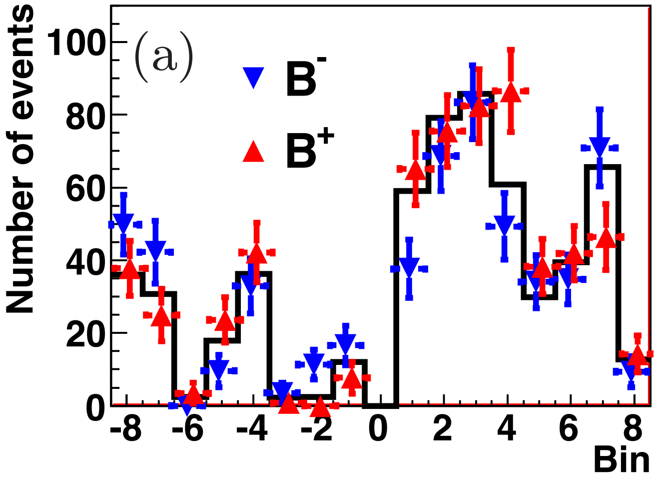


$$\gamma = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$$

$$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$$

$$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ,$$

where the last uncertainty on γ of 4.3° the former model uncertainty of 8.9°



BELLE: **arXiv:1106.4046**. See also Anton Poluektov's talk at Moriond EW 2011 (from which I lifted several of the plots shown here): http://belle.kek.jp/belle/talks/moriondEW11/poluektov.pdf

CLEO-c input:Phys.Rev.D82:112006,2010.

LHCb model-independent γ from $B^\pm \rightarrow (K_S\pi\pi)_D K$ and $B^\pm \rightarrow (K_S KK)_D K$

LHCb-CONF-2013-004

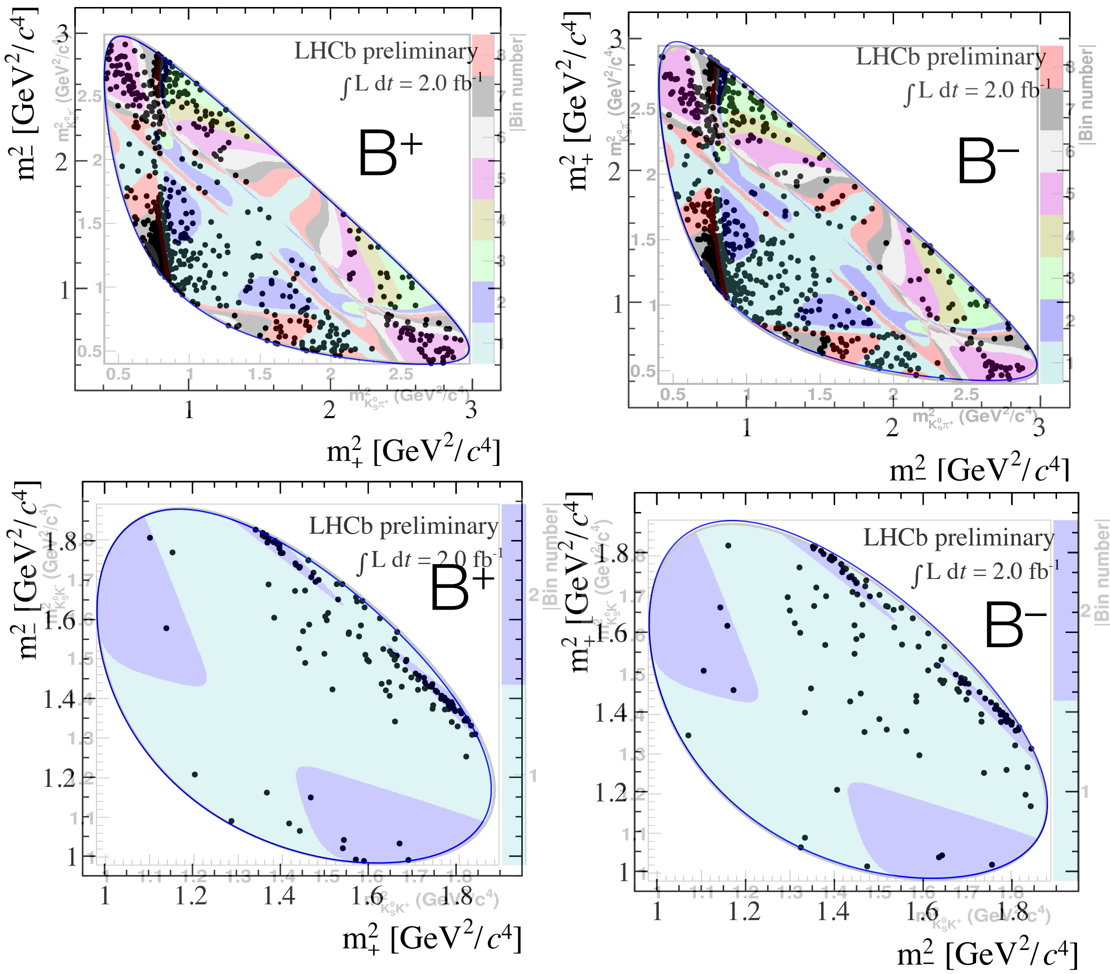
LHCb 2011 Result: Phys. Lett. B718 (2012) 43

- Binned, model-independent analysis using CLEO-c input. Phys. Rev. D 82 112006.
- Plots show LHCb 2012 data - the colours represent the bins, shaped to optimise sensitivity.
- Result of combined analysis (2011 & 2012 data, $K_S\pi\pi$ & $K_S KK$):

$$\gamma = (57 \pm 16)^\circ$$

$$\delta_B = (124^{+15}_{-17})^\circ$$

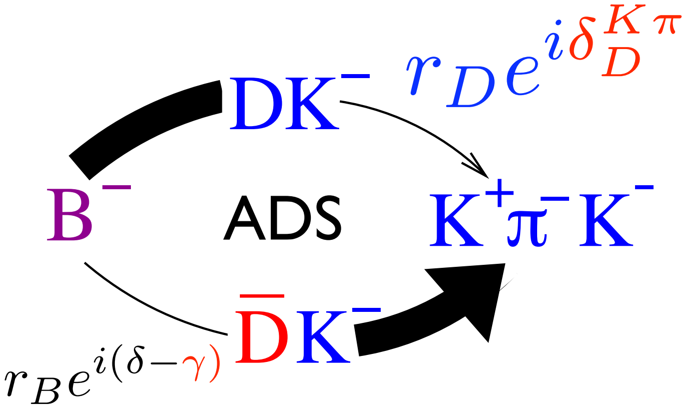
$$r_B = (8.8^{+2.3}_{-2.4}) \times 10^{-2}$$



CLEO-c input:: Phys. Rev. D 82 112006.
Model-independent method: Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).
Optimal binning: Bondar, Poluektov hep-ph/0703267v1 (2007)
BELLE’s first model-independent γ measurement: PRD 85 (2012) 112014

γ from 2-body decays, ADS

- Extract γ from 2-body decays[1]
- Particularly powerful: “ADS” modes with large interference terms (when r_D ~ r_B).



$$\Gamma(\mathrm{B}^- \rightarrow (\mathrm{K}^+\pi^-)_\mathrm{D}\mathrm{K}^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma)$$

$$\Gamma(\mathrm{B}^+ \rightarrow (\mathrm{K}^-\pi^+)_\mathrm{D}\mathrm{K}^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} + \gamma)$$

- CLEO-c’s provides as input: $\delta^{K\pi} = \left(18\,^{+11}_{-17}\right)^0$
- Also important input for D-mixing! *

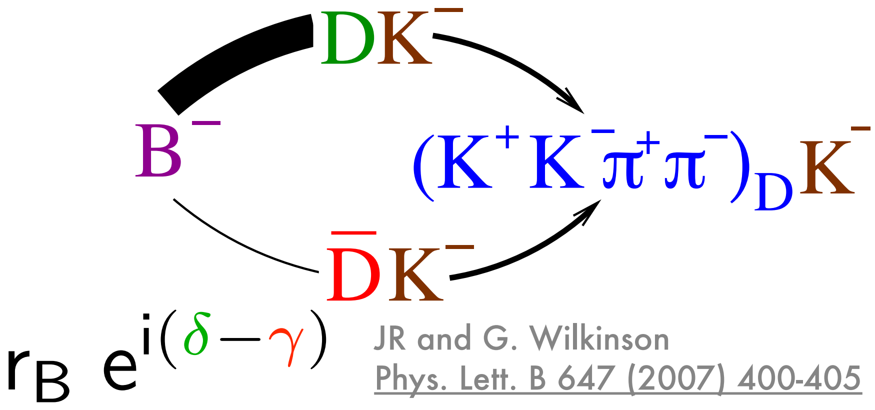
PRL 100, 221801 (2008),
PRD 78, 012001 (2008)
Phys.Rev. D86 (2012) 112001

* Result shown includes external input on y, y’ from mixing measurements. Without external inputs: $\left|\delta^{K\pi}\right| = \left(10\,^{+28}_{-53}\,^{+13}_{-0}\right)^0$.

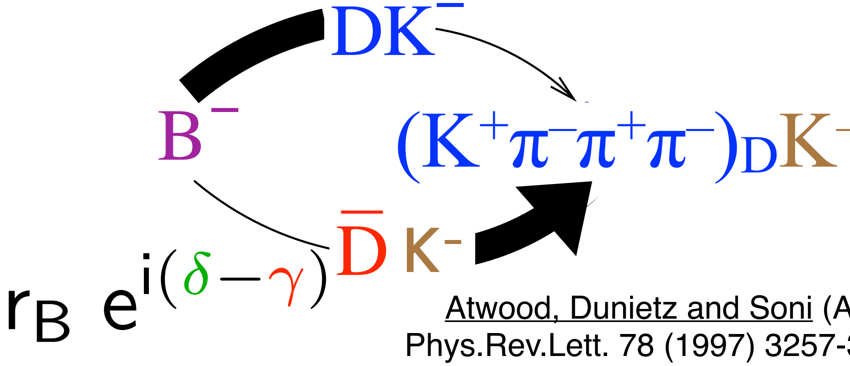
[1] Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

Why stop here

- Why stop at 3-body decays?
- 4-body amplitude analyses very promising for γ measurement at LHCb.
- First step: “quasi two body” (coherence factor) analysis. See next slide.



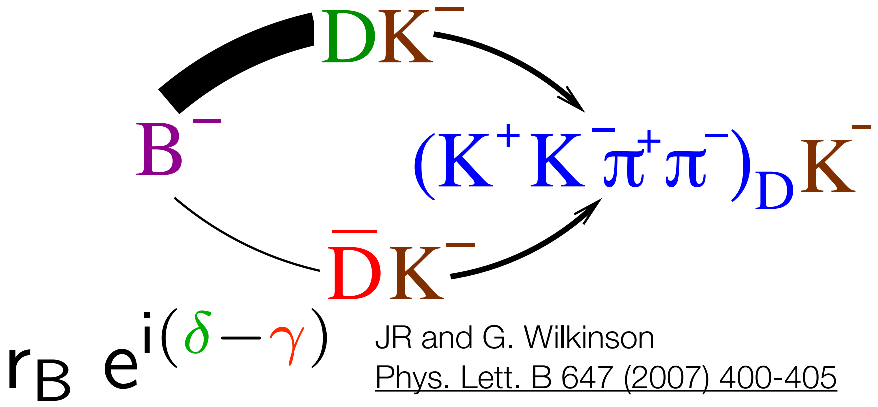
JR and G. Wilkinson
Phys. Lett. B 647 (2007) 400-405



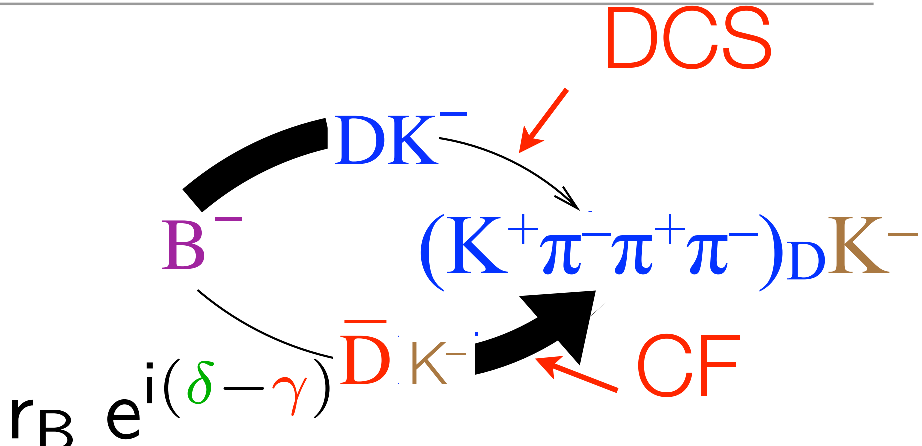
Atwood, Dunietz and Soni (ADS),
Phys.Rev.Lett. 78 (1997) 3257-3260

Atwood, Soni: Phys.Rev. D68 (2003) 033003

γ from 4-body Modes



JR and G. Wilkinson
Phys. Lett. B 647 (2007) 400-405



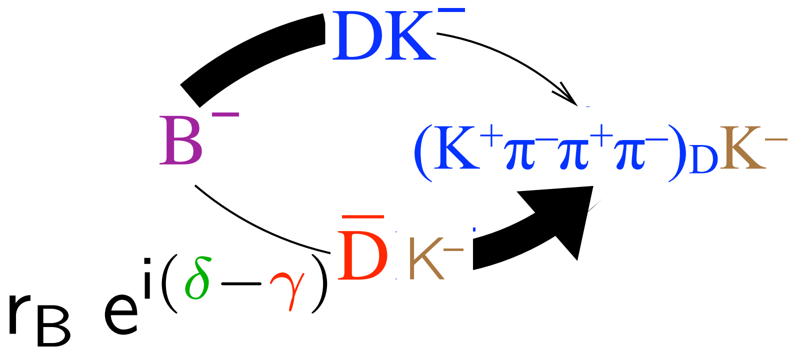
Atwood, Dunietz and Soni (ADS),
Phys.Rev.Lett. 78 (1997) 3257-3260
Atwood, Soni: Phys.Rev. D68 (2003) 033003

- KKππ: useful precision, similar ballpark as $K_S\pi\pi$, albeit somewhat worse (so far, only model-dependent study). See Andrew’s excellent thesis and LHCb note for details.

- Kπππ: Expect greater sensitivity due to “ADS” effect. Initial studies very promising.

- ππππ: recent toy study confirms that this is very promising (see later)

Coherence Factor Analysis of:

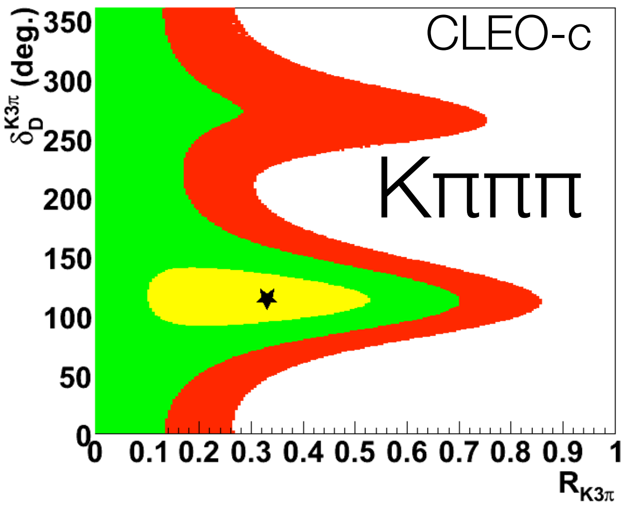


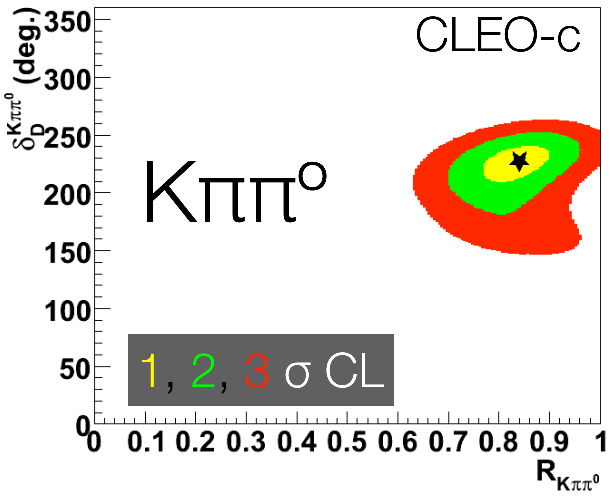
- Treat K3π like two-body decay with single effective strong phase δ_D.

- New parameter: Coherence factor R < 1.

$$\Gamma\left(B^- \to \left(K^+3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

- CLEO-c used coherent ψ(3770)→DD events to measure R, δ_D for Kπππ and Kππ°.

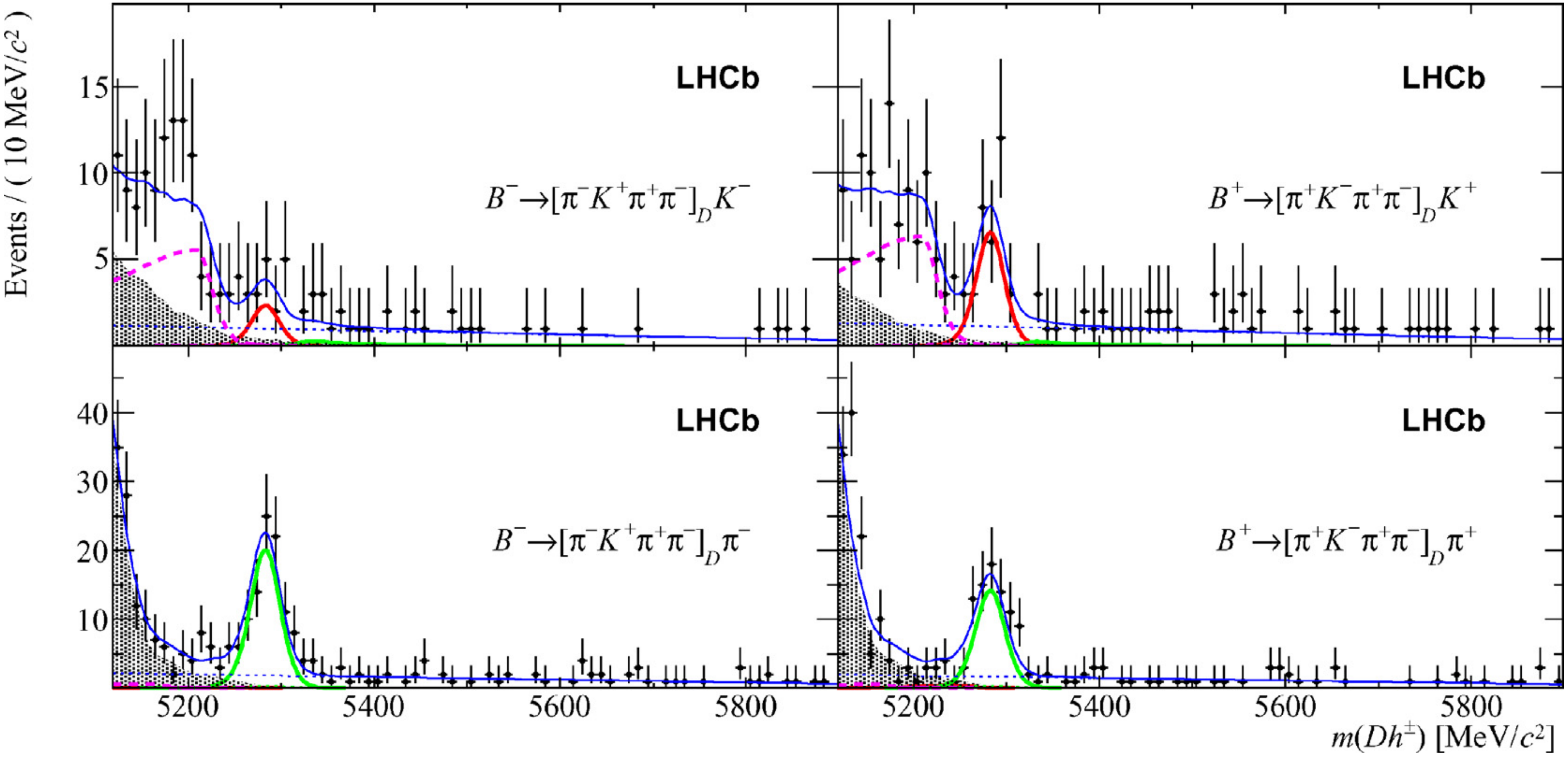




Theory:
Atwood, Soni: Phys.Rev. D68 (2003) 033003
CLEO-c input:
Phys.Rev.D80:031105,2009
LHCb CPV result:
Physics Letters B 723 (2013), 44

LHCb B± → D(Kπππ)K±

Physics Letters B 723 (2013), pp. 44-53



LHCb's γ combination

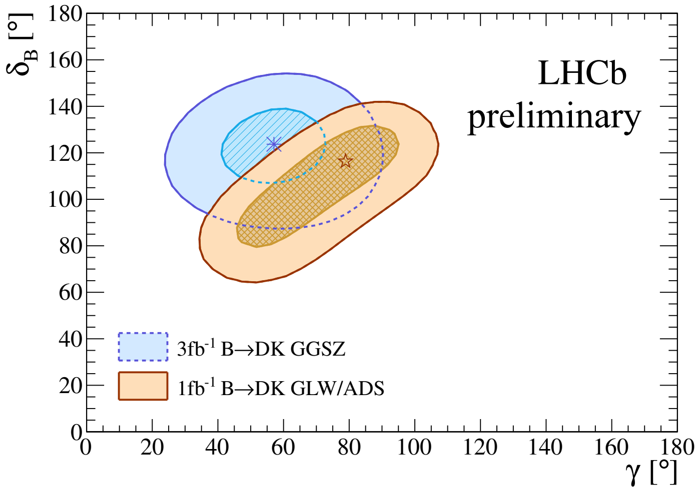
technique & 2011 results: arXiv:1305.2050 (2013)
2012 data: LHCb-CONF_2013-006) (in preparation)

- LHCb combines inputs from
  $B^\pm \to (hh')_D K^\pm$ (2011)
  $B^\pm \to (K_S\pi\pi)_D K^\pm$ (2012)
  $B^\pm \to (K_S KK)_D K^\pm$ (2012)
  $B^\pm \to (K\pi\pi\pi)_D K^\pm$ (2011)
- Result:

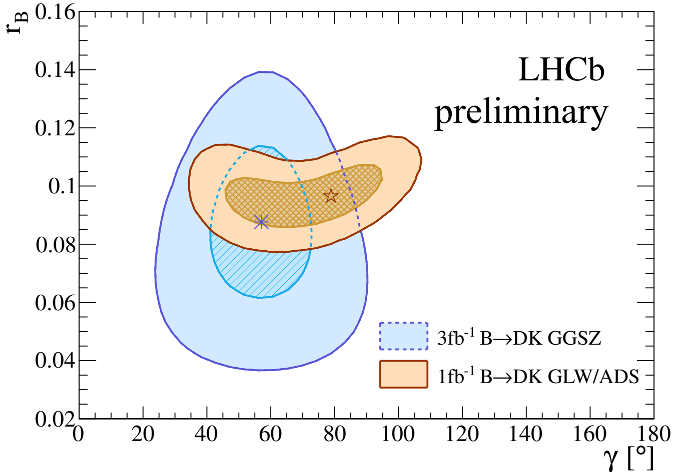
$$\gamma = (67.2 \pm 12)^o$$

- More channels and more data to be added, soon.

δ_B vs γ



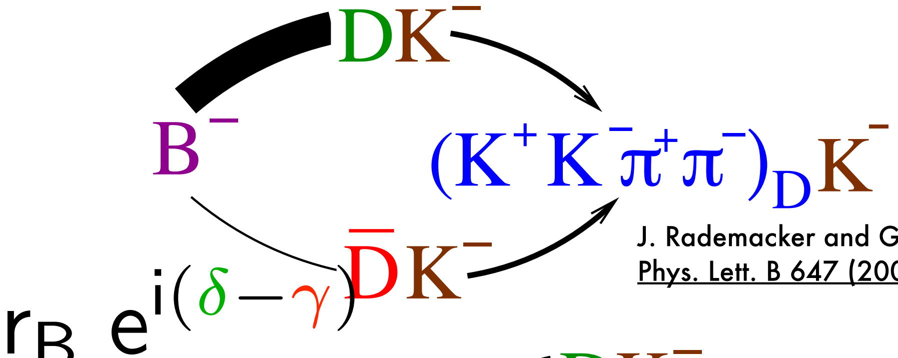
r_B vs γ



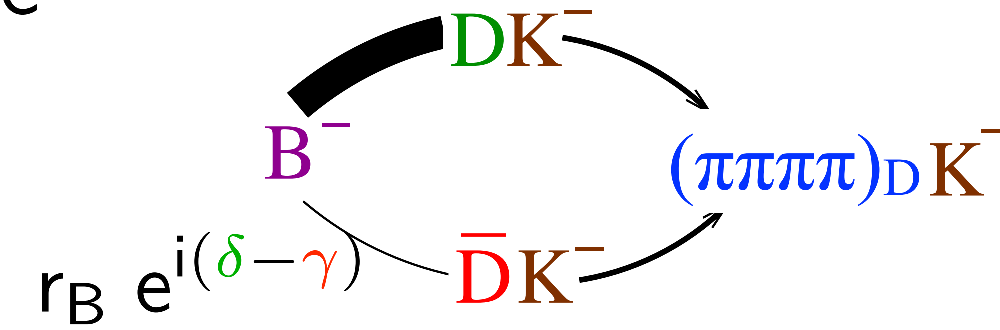
	best fit	68% CL	95% CL
δ_B	114.3°	$[101.7, 126.6]^\circ$	$[89.1, 136.5]^\circ$
r_B	0.0924	$[0.0847, 0.1004]$	$[0.0766, 0.1077]$
γ	67.2°	$[55.7, 79.6]^\circ$	$[44.6, 90.0]^\circ$

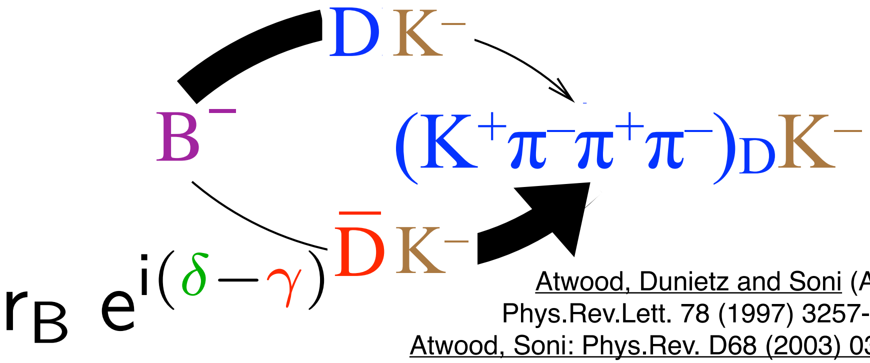
Exploiting the full 5-D phase space of 4-body D decays.

- Our studies indicate they 4-body the best sensitivity to γ.
- Challenging:
  2-dimensional Dalitz plot → 5-dimensional phase space
- Next slides: a few first steps



J. Rademacker and G. Wilkinson
Phys. Lett. B 647 (2007) 400-405





Atwood, Dunietz and Soni (ADS), Phys.Rev.Lett. 78 (1997) 3257-3260
Atwood, Soni: Phys.Rev. D68 (2003) 033003

Phys. Lett. B 647 (2007) 400-405
Phys. Rev. D 80, 031105 (2009)
arXiv:1201.5716 [hep-ex] (submitted to PRD)

γ from ππππ: toy MC study

- Model from FOCUS

Decay mode	Amplitude	Phase (degrees)
$a_1^+, a_1 \rightarrow \rho^0\pi^+, \rho^0 \rightarrow \pi^+\pi^-$ (S-wave)	1.0 (fixed)	0
$a_1^+, a_1 \rightarrow \rho^0\pi^+, \rho^0 \rightarrow \pi^+\pi^-$ (D-wave)	$0.241 \pm 0.033 \pm 0.024$	$82 \pm 5 \pm 4$
$a_1^+, a_1 \rightarrow \sigma\pi^+, \sigma \rightarrow \pi^+\pi^-$	$0.439 \pm 0.026 \pm 0.021$	$193 \pm 4 \pm 4$
$\rho^0\rho^0, \rho^0 \rightarrow \pi^+\pi^-$ (S-wave)	$0.157 \pm 0.027 \pm 0.020$	$120 \pm 7 \pm 8$
$\rho^0\rho^0, \rho^0 \rightarrow \pi^+\pi^-$ (P-wave)	$0.384 \pm 0.020 \pm 0.015$	$163 \pm 3 \pm 3$
$\rho^0\rho^0, \rho^0 \rightarrow \pi^+\pi^-$ (D-wave)	$0.624 \pm 0.023 \pm 0.012$	$357 \pm 3 \pm 3$
$f_0(980)\pi^+\pi^-, f_0(980) \rightarrow \pi^+\pi^-$	$0.233 \pm 0.019 \pm 0.015$	$261 \pm 7 \pm 4$
$f_2(1270)\pi^+\pi^-, f_2(1270) \rightarrow \pi^+\pi^-$	$0.338 \pm 0.021 \pm 0.016$	$317 \pm 4 \pm 4$
$\sigma\pi^+\pi^-, \sigma \rightarrow \pi^+\pi^-$	$0.432 \pm 0.027 \pm 0.022$	$254 \pm 4 \pm 5$

γ from ππππ

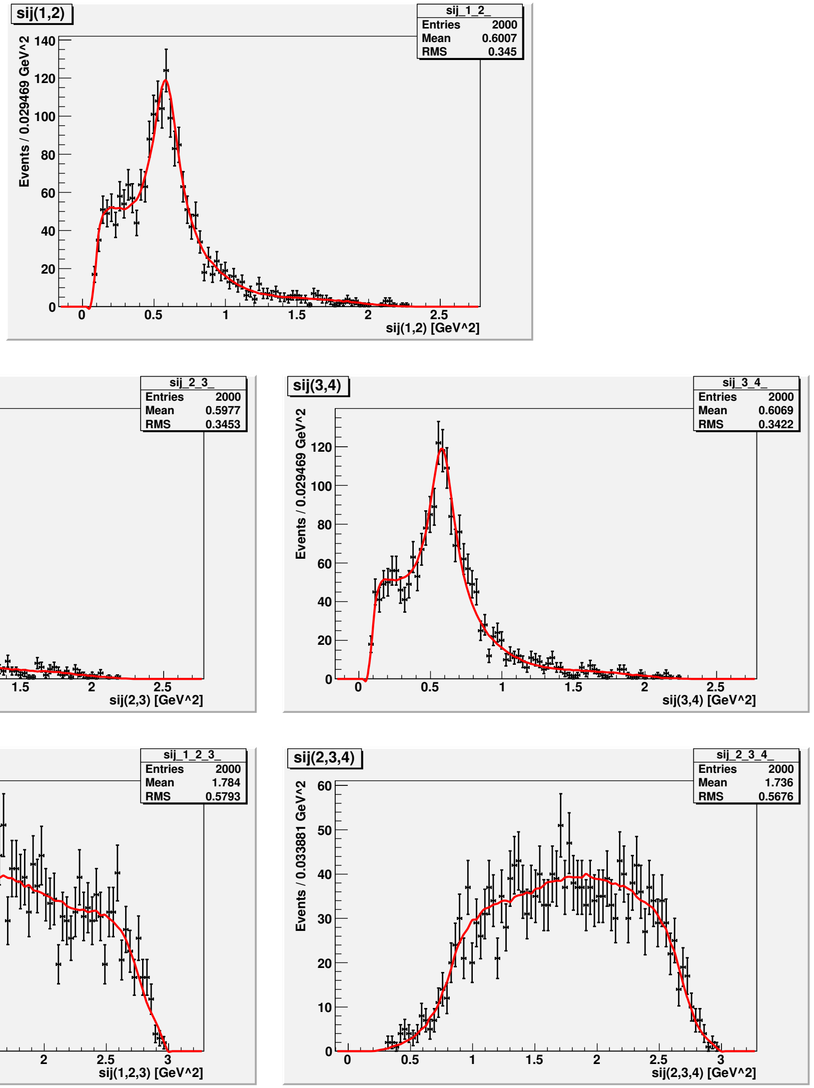


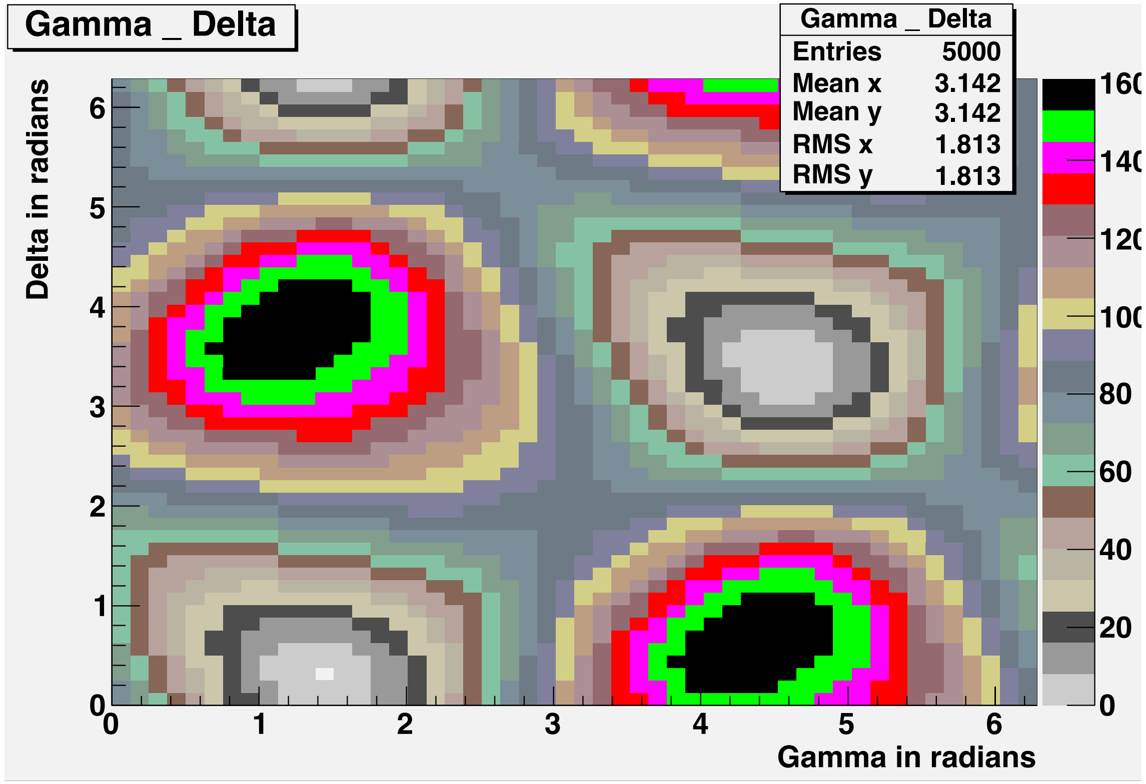
Figure 3: Shows five graphs displaying the results of 2000 simulated events for which the four body decay invariant masses have been fitted.Initial values of $\gamma = 60°, r_B = 0.10$ and $\delta_B = 0°$ were chosen.

Likelihood scan for 1000 B+ and 1000 B- events

Input: rB = 0.1 delta =0, gamma = 1.5

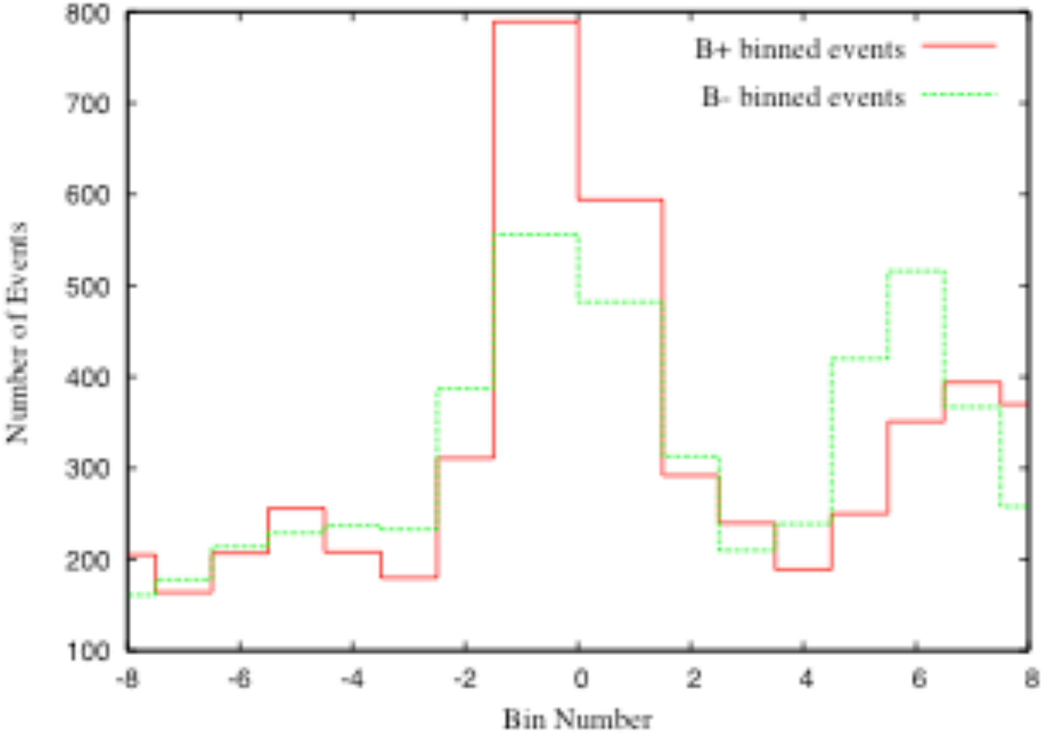
Typical Error for 2x1000 events: 11°

Tom McKetterick (2010/11 Bristol MSc student)



MC study of binned B→DK with D→ππππ

Bin events in terms of the phase difference between D→ππππ and Dbar→ππππ



- 2×5k events
- input: $\gamma=70^{\circ}$, $\delta=0^{\circ}$, $r_B=0.1$
- Fit (floating γ only): $\gamma=77^{\circ} \pm 5^{\circ}$
- Consistent with unbinned precision (does not include uncertainty due to - yet non-existent - CLEO-c input)

Searches for CPV by comparing binned Dalitz plots

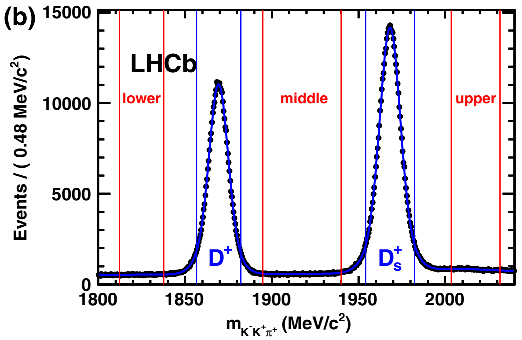
PhysRevD.84.112008

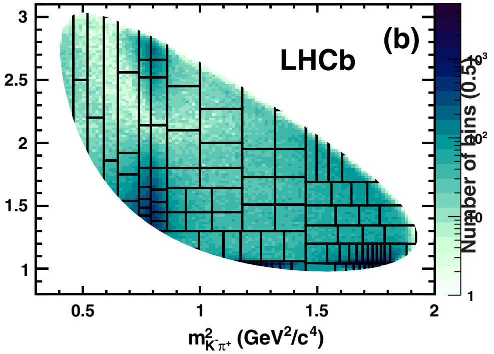
- Compare yields in CP-conjugate bins

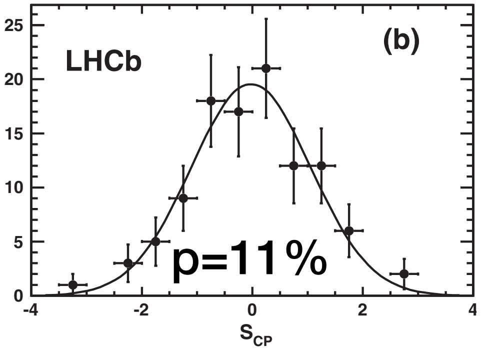
$$S_{CP} = \frac{N_i - \alpha \bar{N}_i}{\sqrt{N_i + \alpha^2 \bar{N}_i}}$$

$$\alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$

330k $D^+ \rightarrow K^- K^+ \pi^+$ in 35/pb





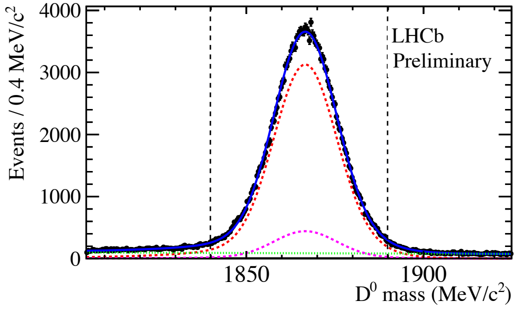


- Calculate p-value for no-CPV hypothesis based on

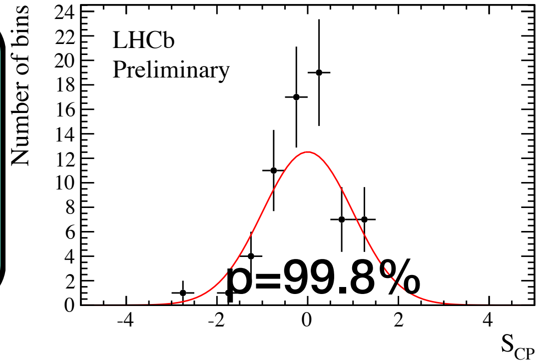
$$\chi^2 = \sum_i \left(S_{CP}^i\right)^2$$

- Model independent. Many production and detection effects cancel.

~180k $D^{*+} \rightarrow D^o \pi$, $D^o \rightarrow \pi\pi\pi\pi$ in 1/fb

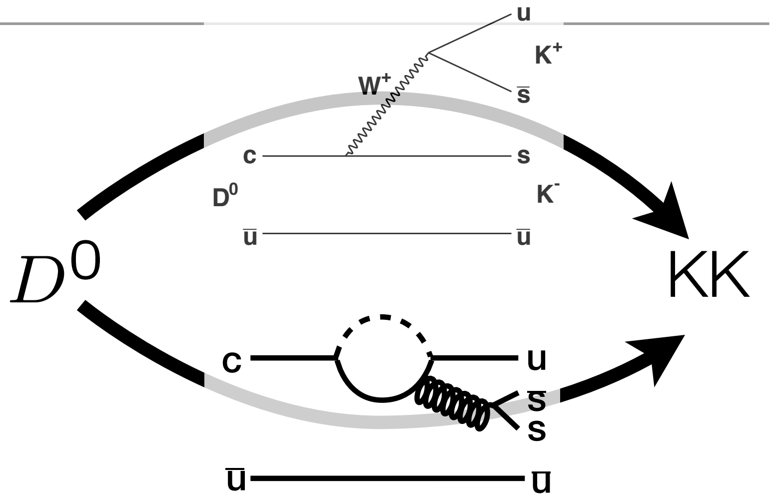


5-dim. "Dalitz" plot, binned.



LHCb-CONF-2012-019

CPV in $D^* \rightarrow D\pi$, $D \rightarrow \pi\pi\pi\pi$

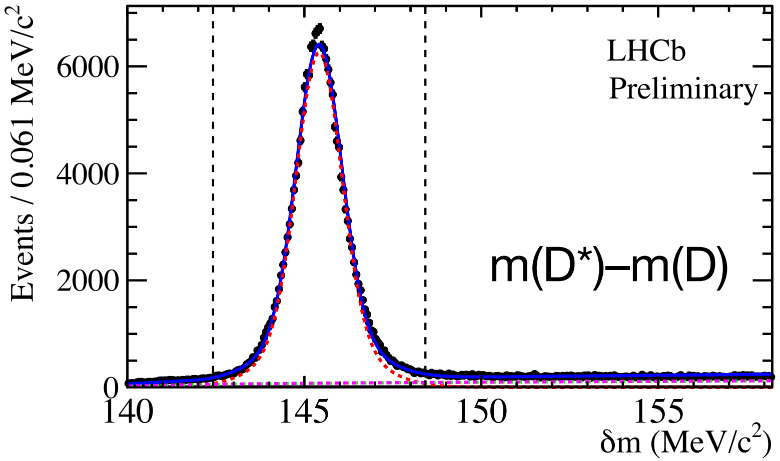


- CPV is an interference effect - need interfering decay paths.

- Singly Cabibbo Suppressed charm decays offer tree and penguin contributions of comparable magnitude.

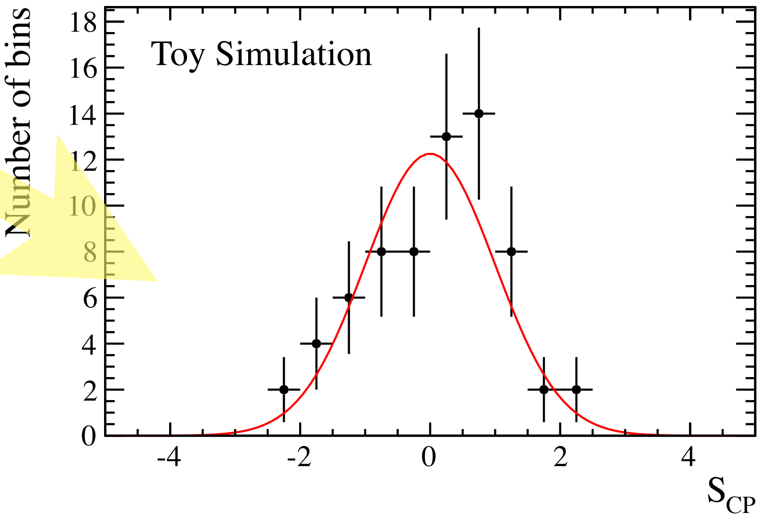
- Remarkably clean signal - for a 5-pion final state in a hadronic environment!

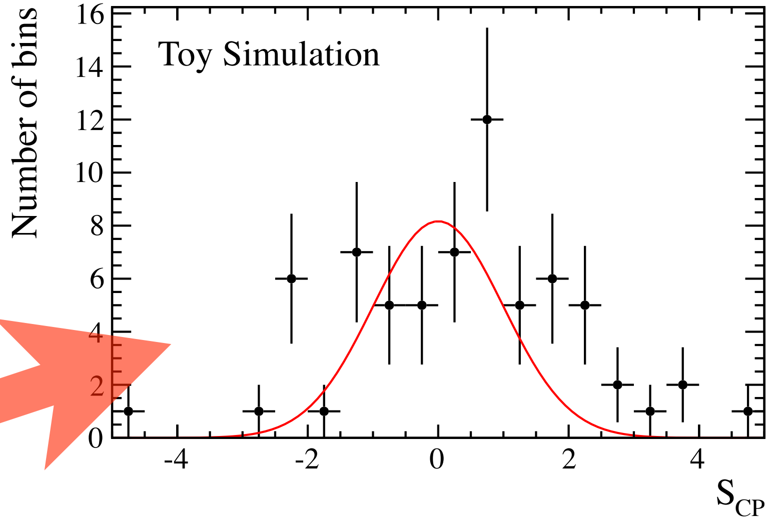
- Both, an interesting test of CPV and an excellent first step for measuring γ with $B^\pm \rightarrow D(\pi\pi\pi\pi)K^\pm$ as we need to investigate essentially the same systematics.



Simulation study - would we see CPV if it was there?

CPV	Adaptive bins	p-values (%)
No CPV	15	49.6
	29	31.8
	66	45.8
5° in $\rho^0\rho^0$ phase	15	30.0
	29	27.8
	66	9.96
10° in $\rho^0\rho^0$ phase	15	1.2e-06
	29	3.05e-08
	66	1.74e-16
5° in $a_1(1260)^+\pi^-$ phase	15	0.40
	29	0.26
	66	0.24
10° in $a_1(1260)^+\pi^-$ phase	15	5.05e-06
	29	2.38e-08
	66	7.34e-13
5% in $\rho^0\rho^0$ magnitude	15	0.57
	29	6.9
	66	12.1
10% in $\rho^0\rho^0$ magnitude	15	2.9e-11
	29	1.1e-09
	66	1.2e-12

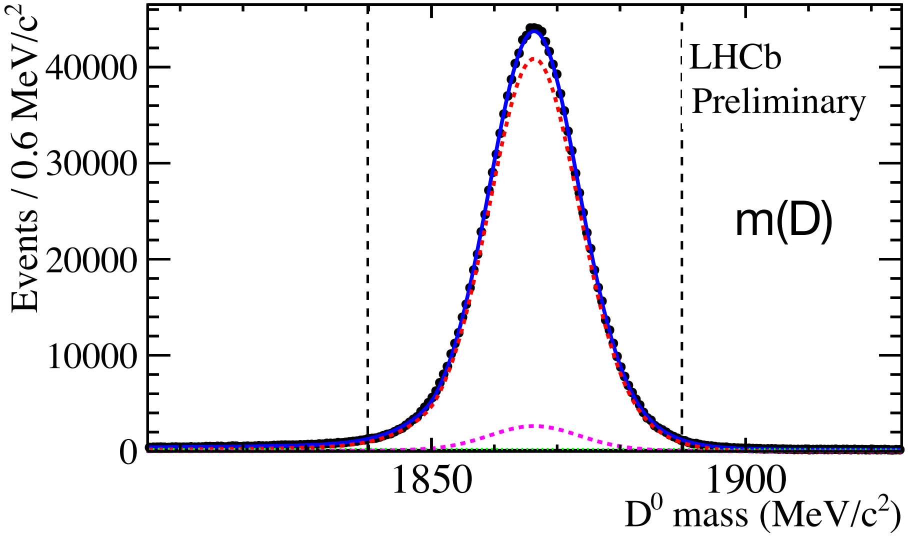


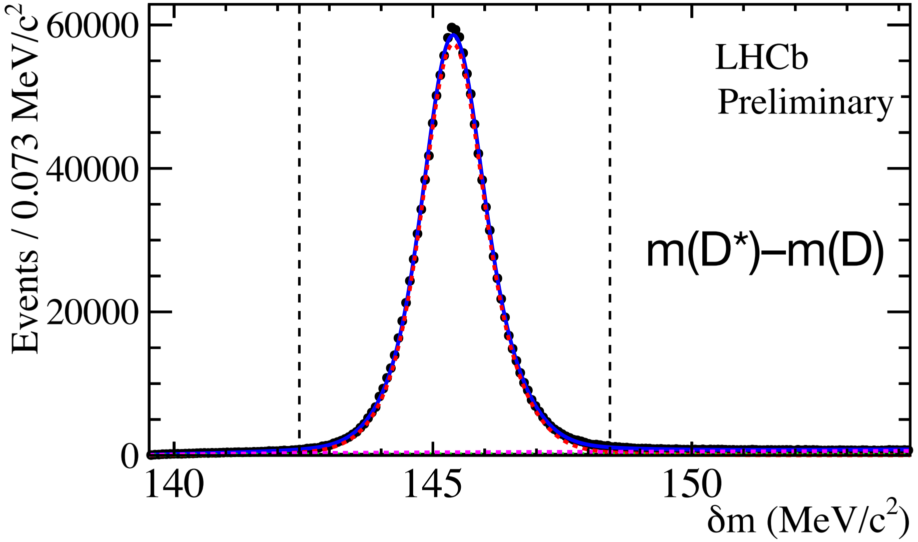


D->Kπππ control channel

- Use the more abundant, CP-favoured D→Kπππ as control channel (completely dominated by tree diagram, no interfering paths, expect no CPV)

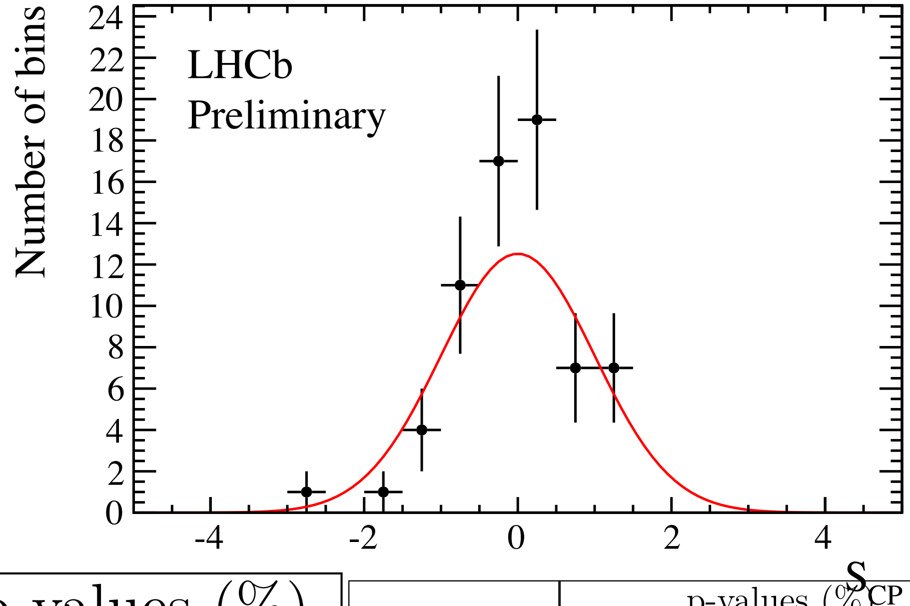
	p-values %		
Bins	Magnet down	Magnet up	Combined polarities
7	6.67	58.8	5.18
23	16.5	71.1	32.2
49	45.3	37.3	20.0
91	30.3	35.4	20.0
150	15.3	61.4	30.3





CPV in D→ππππ result

- We get a high p-value, so no evidence for CP violation.
- Apart from finding yet another disappointing piece of evidence in support of the Standard Model, we also demonstrated that we understand CPV-relevant detector effects in 5-D phase space very well.
- Next step: Same with KKππ and move towards γ.



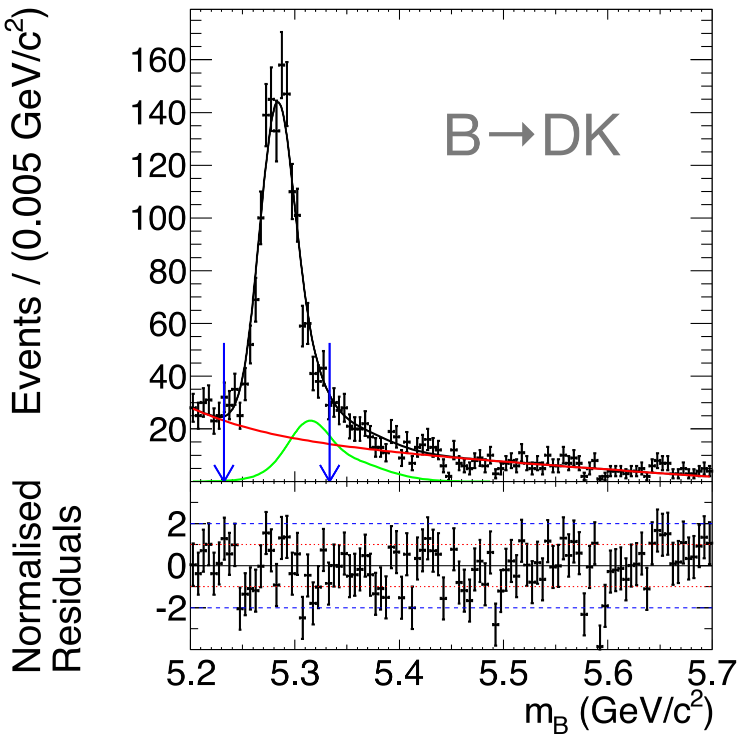
Bins	p-values (%)
15	97.1
29	95.6
66	99.8

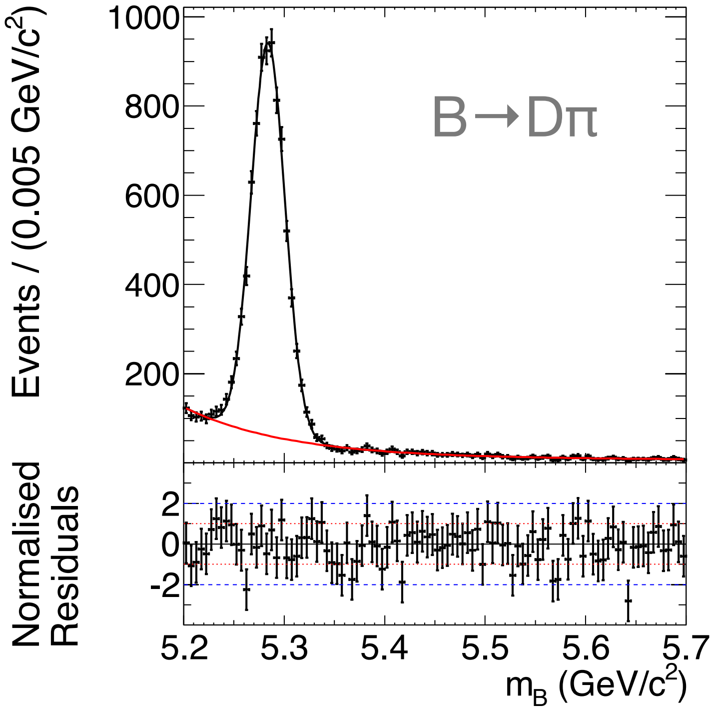
	p-values (%)	
data subset	Magnet down	Magnet up
1	9.15	11.0
2	15.3	81.1
3	91.4	75.9
4	76.7	86.1
5	1.59	18.3
6	35.6	50.8
7	5.77	99.8
8	40.6	26.0
9	76.8	71.1
10	17.8	66.9

Towards γ with $B^{\pm} \rightarrow D(KK\pi\pi)K^{\pm}$

Signal

Control Channel

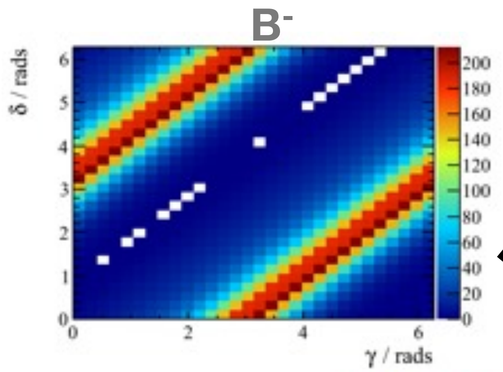




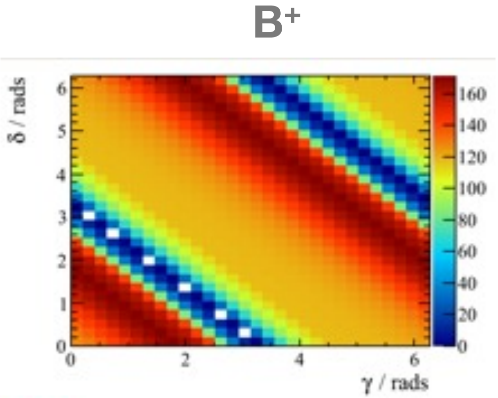
Towards γ with $B^{\pm} \to D(KK\pi\pi)K^{\pm}$: Toy MC studies

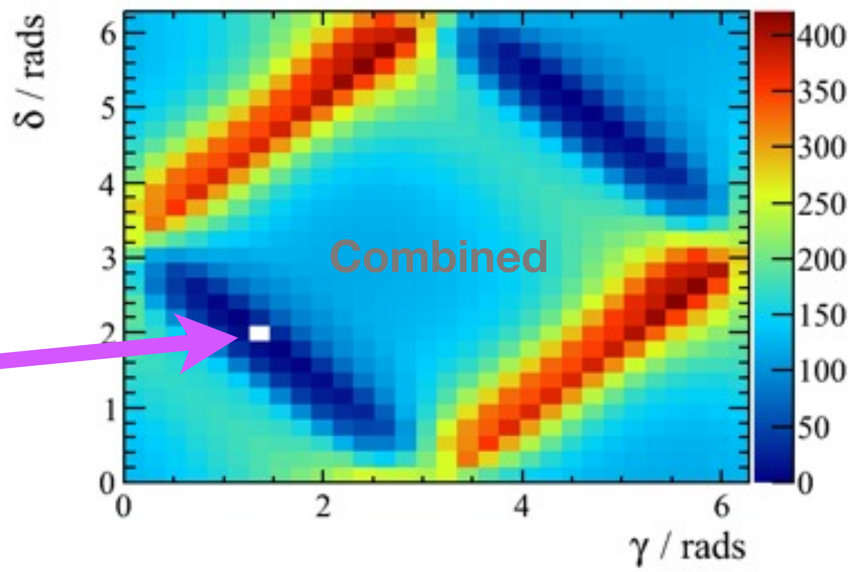
- MC studies indicate that our method to cancel efficiency effects using $B^{\pm} \to D(KK\pi\pi)K^{\pm}$ works in principle.

- Likelihood scan across δ and γ



Can not resolve γ and δ with only B^+ or B^-





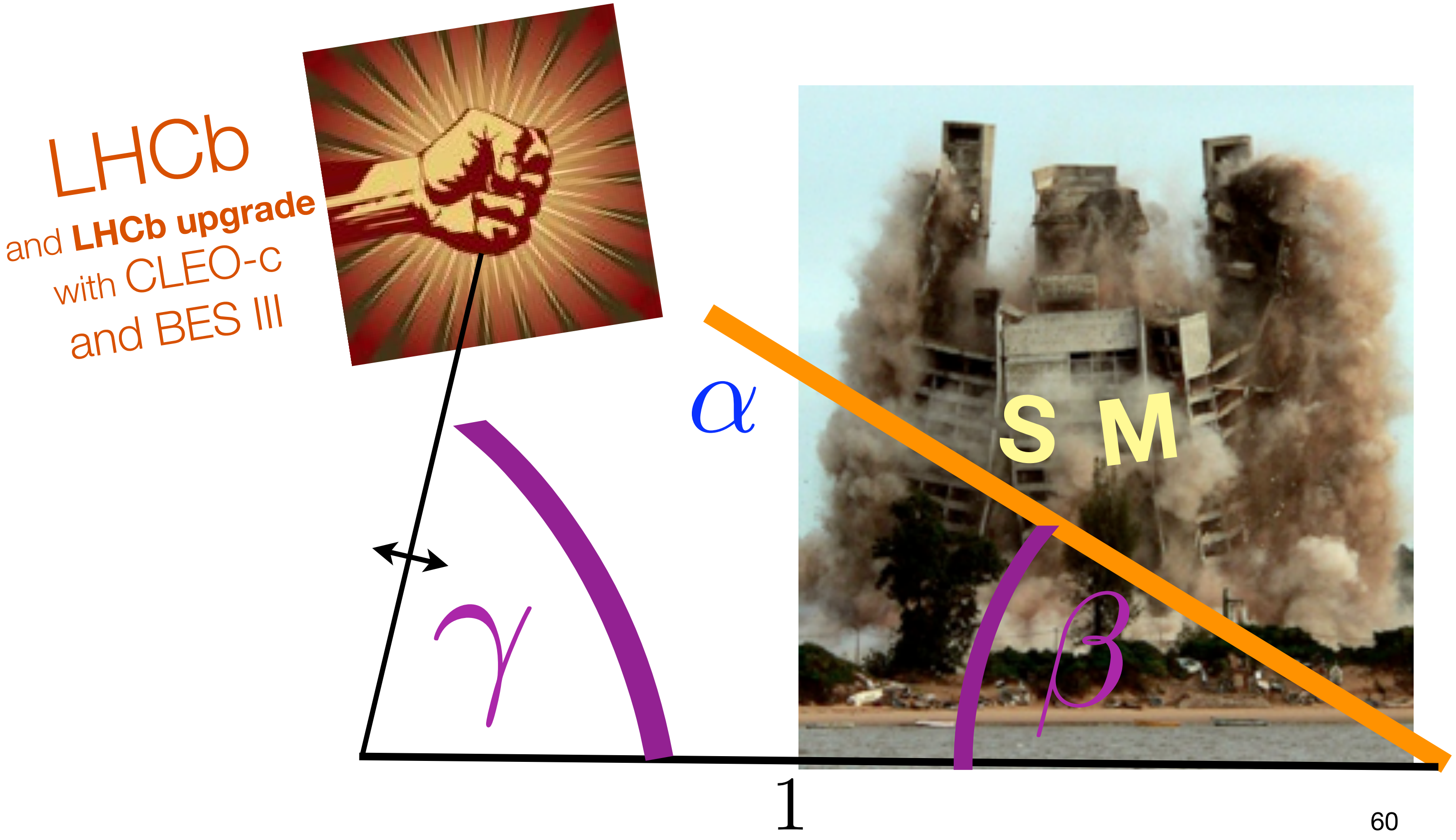
Solution

- Expect a uncertainty of ~20° from this mode - expect better from ππππ (more events), but need amplitude model, first.

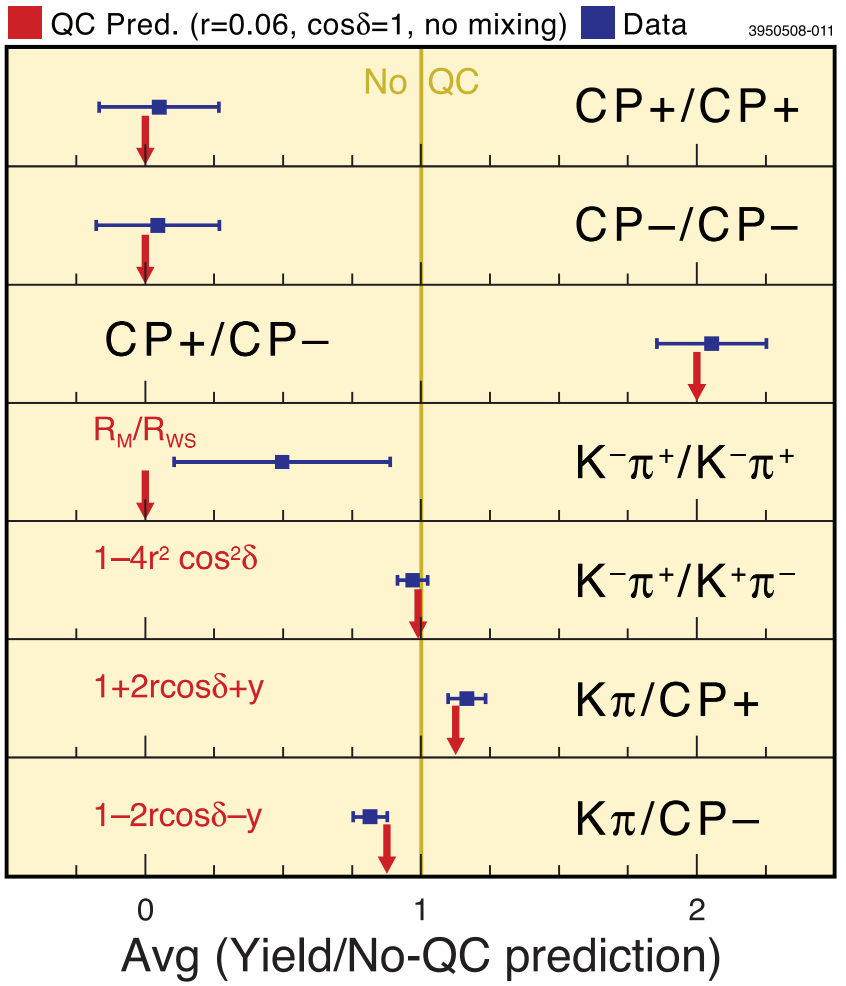
Summary

- High precision flavour physics sees beyond the energy frontier. The high NP mass scales towards which LHC's recent results (LHCb's precision results, the absence of direct production signals, ~126GeV Higgs) point make these measurements even more important. γ is key to the New Physics sensitivity of the flavour sector.
- LHCb now has the world's best γ measurement. Crucial for precision γ measurements are amplitude analyses (so far 3-body, soon also 4-body) and input from charm threshold (CLEO-c, BES III)
- Same input also applies to experimentally closely related, but theoretically very different precision measurements of CP violation in charm, with their own, unique sensitivity to NP, e.g. in FCNCs of up-type quarks.
- The LHCb upgrade provides the opportunity towards sub-1° precision on γ and precision in charm reaching down to the SM values.

Summary


LHCb
and **LHCb upgrade**
with CLEO-c
and BES III
α
S M
γ
β
1

Exploiting Quantum Correlations at CLEO-c



PRL 100, 221801 (2008), PRD 78, 012001 (2008)

- CP-tagged rates

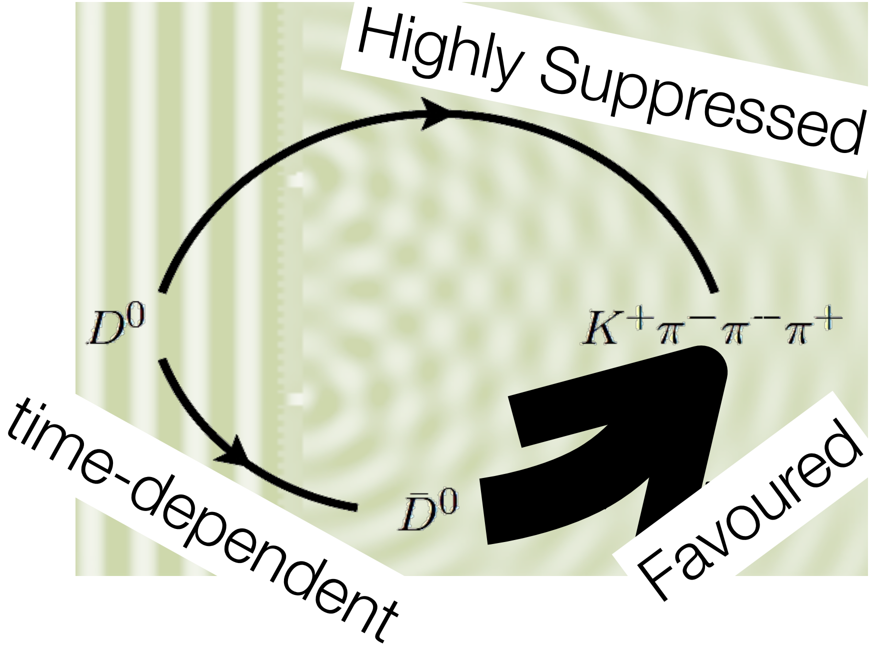
$$\propto (1 \pm 2\, r_D^{K\pi} \cos \delta_D^{K\pi} \pm y)$$

- Combined analysis in many modes sensitive to $\delta_D^{K\pi}$ w/o ambiguity.
- Crucial input to charm mixing measurements, as well as helping measure γ
- Result: $\delta^{K\pi} = \left(18\,^{+11}_{-17}\right)^0$

(including input from charm mixing - excluding that (and thus allowing the result to be used as independent input to mixing measurements) gives: $\left|\delta^{K\pi}\right| = \left(10\,^{+28}_{-53}\,^{+13}_{-0}\right)^0$

Phys.Rev. D86 (2012) 112001

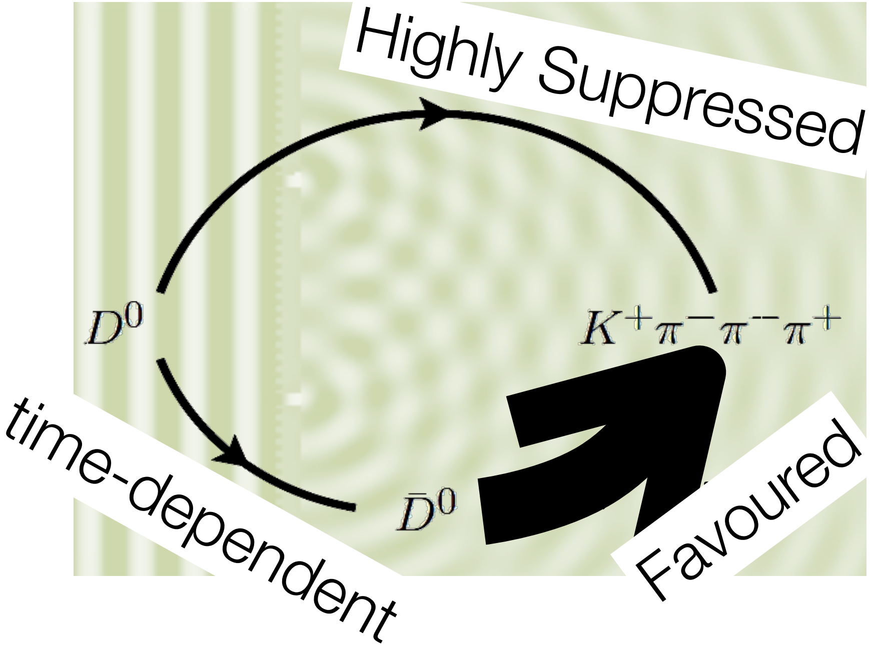
Charm Mixing



The interference term in this time-dependent decay rate tells us a lot about D→Kπππ that we need for γ

From Sam’s talk at the LHCb s/w and analysis week Jan 2013

Charm Mixing



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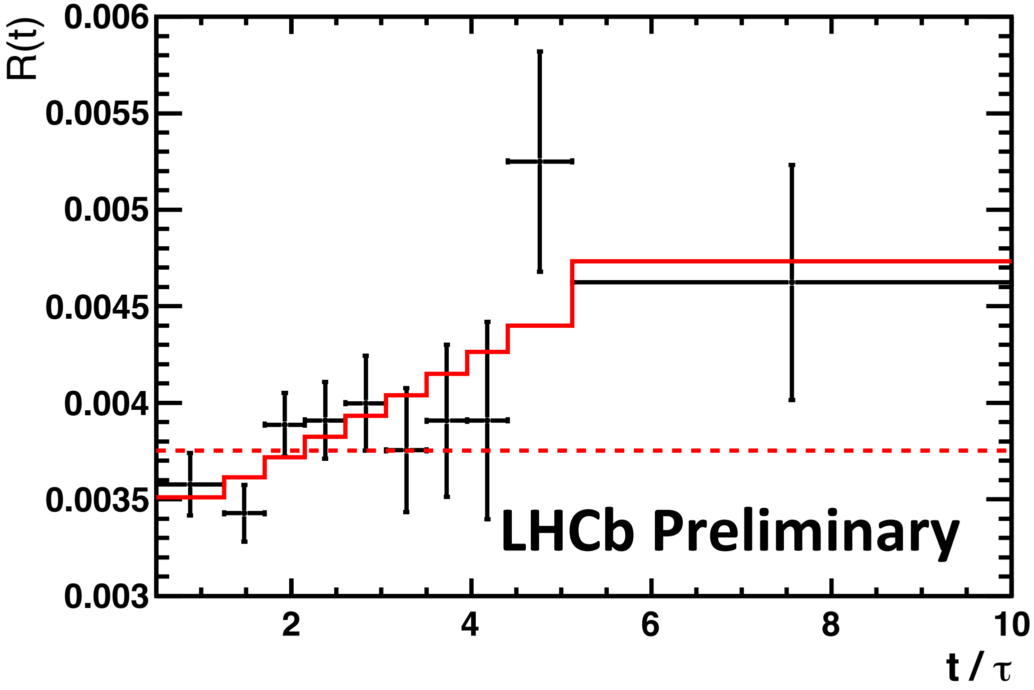


From Sam’s talk at the LHCb s/w and analysis week Jan 2013

It’s mixing, but not about mixing.

- K3π is not really the best way to constrain mixing. Not as precise as Kπ, and we depend on additional, not precisely known parameters:

$$r(t) \approx \boxed{r^2_{K3\pi}} + \boxed{r_{K3\pi}}\boxed{R_{K3\pi}}\left(y\cos\boxed{\delta_{K3\pi}} - x\sin\boxed{\delta_{K3\pi}}\right) t + \frac{x^2+y^2}{4}(\Gamma t)^2$$

- Turn this into our advantage - use others’ precise mixing measurement as input and *measure* those additional parameter that also affect the γ measurement:

$$\Gamma\left[B^- \to (K^+\pi^-\pi^+\pi^-)_D K^-\right] \propto r_B^2 + \boxed{(r_D^{K3\pi})^2} + \boxed{2R_{K3\pi}}\, r_B \boxed{r_D^{K3\pi}} \cos(\delta_b + \boxed{\delta_{K3\pi}} - \gamma)$$

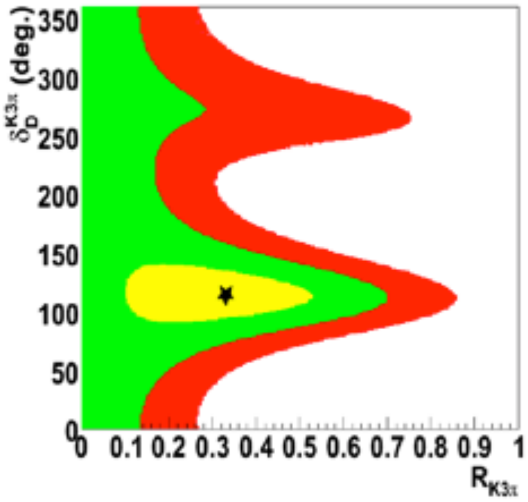
- So we measure
  - $r^2_{K3\pi}$, the ratio of DCS to CF decay rates (w/o mixing)
  - We put a 2-D constraint on the coherence factor $R_{K3\pi}$ and the average strong phase difference $\delta_{K3\pi}$.

Status (All results from 2011 data only)

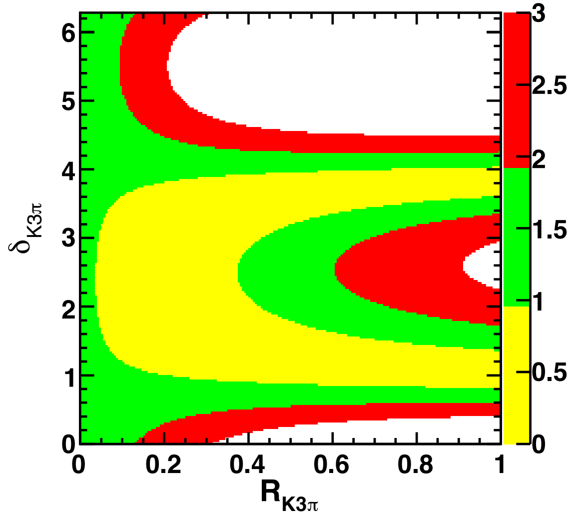
- Tom Hampson's thesis (nearly finalised): $r^2_{K3\pi} = (0.341 \pm 0.018)\%$
  from this follows: $BR(D0 \rightarrow K^+\pi^-\pi^+\pi^-)$ via DCS $= (2.75 \pm 0.16) \times 10^{-4}$
  Compare to PDG (from time-integrated measurements) $BR = (2.69^{+0.2}_{-0.19}) \times 10^{-4}$

- Constraint on coherence factor and strong phase

Cleo-c

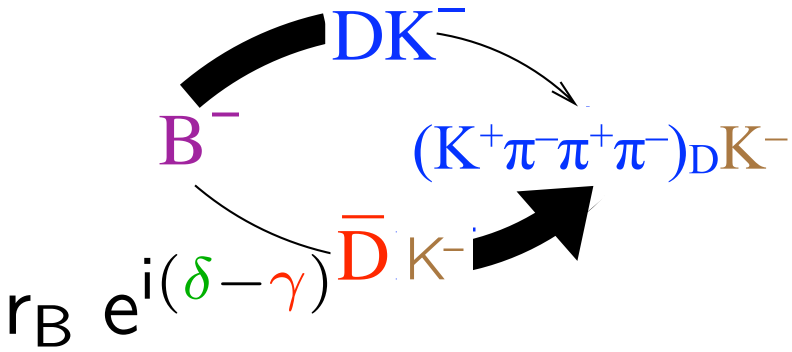


LHCb Preliminary



- To do: Main task: include efficiency effects on the coherence factor analysis (in progress, Sam already has a remarkably good 5-D parameterisation).

Coherence Factor Analysis of:



Atwood, Soni: Phys.Rev. D68 (2003) 033003

- Treat K3π like two-body decay with single effective strong phase δ_D.

- New parameter: Coherence factor R < 1.

$$\Gamma\left(B^- \to \left(K^+3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

- CLEO-c's coherent ψ(3770)→DD events allow measurement of R, δ_D.

Phys.Rev.D80:031105,2009

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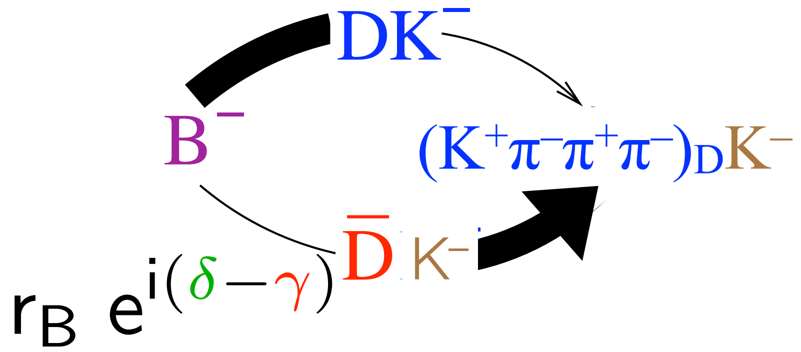

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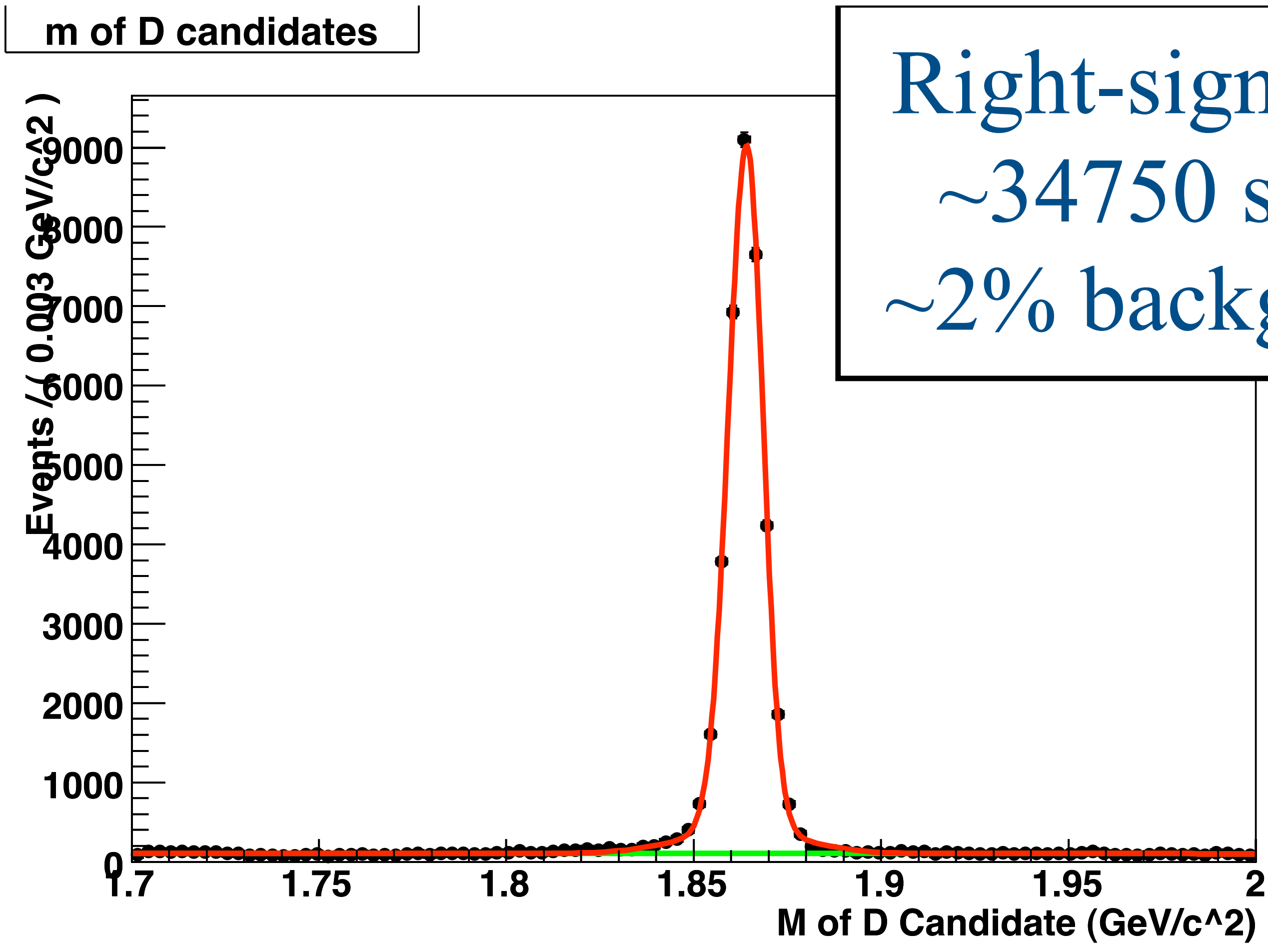
- CLEO-c's coherent ψ(3770)→DD events allow measurement of R, δ_D - important input for LHCb

Double Tag Rate	**Sensitive To**
$K^\pm\pi^\mp\pi^+\pi^-$ vs. $K^\pm\pi^\mp\pi^+\pi^-$	$(R_{K3\pi})^2$
$K^\pm\pi^\mp\pi^+\pi^-$ vs. CP	$R_{K3\pi}\cos(\delta^{K3\pi})$
$K^\pm\pi^\mp\pi^+\pi^-$ vs. $K^\pm\pi^\mp$	$R_{K3\pi}\cos(\delta^{K\pi} - \delta^{K3\pi})$

Phys.Rev.D80:031105,2009

D→K3π events at CLEO

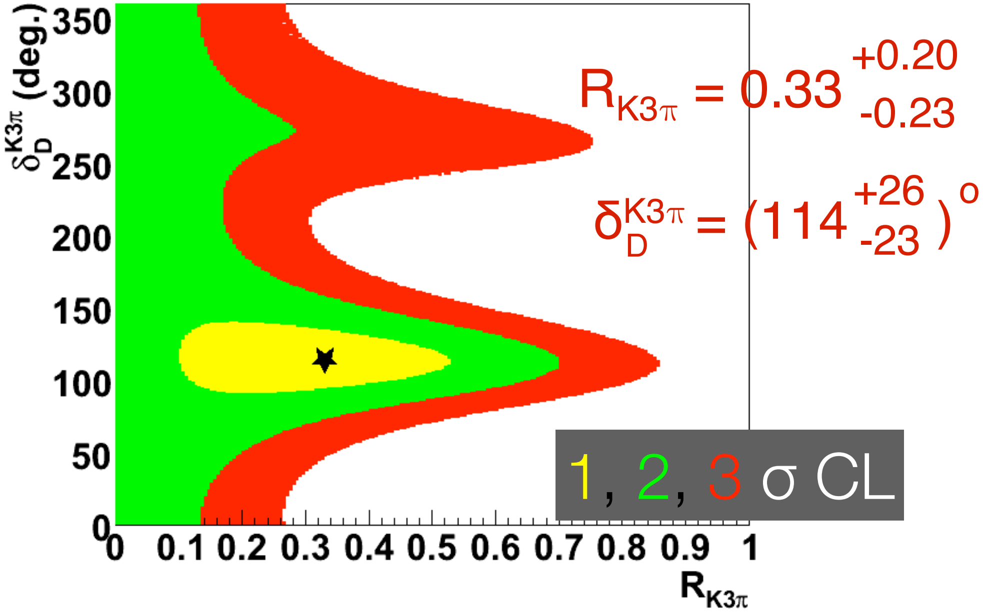


Right-sign Kπππ
~34750 signal
~2% background

Phys.Rev.D80:031105,2009

Kπππ coherence factor

- Low value preferred. This channel on its own would not be very sensitive to γ.
- For a combined analysis of B±→DK± modes, this provides powerful constraints.



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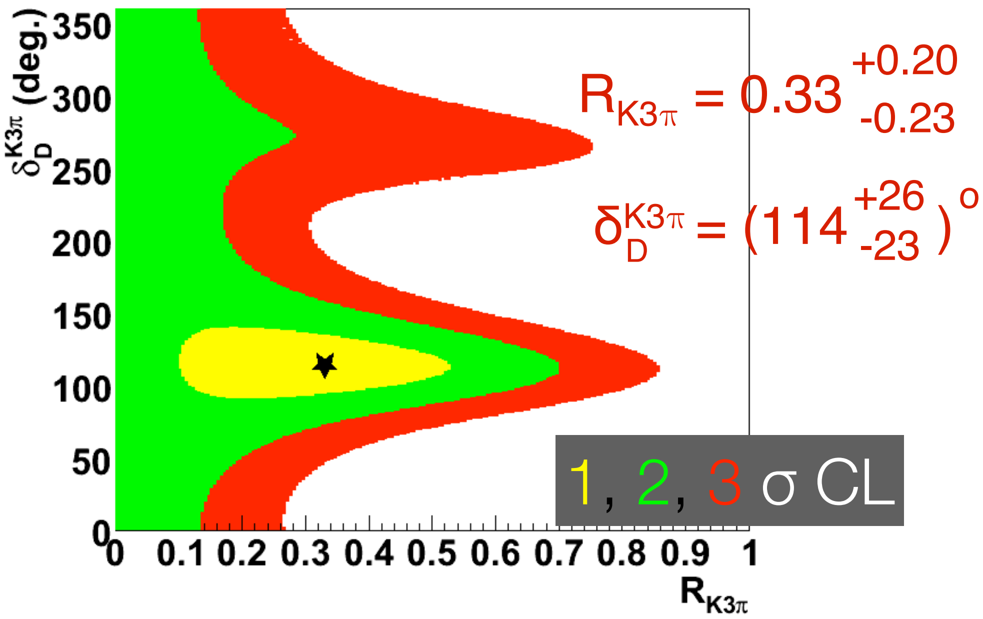

$R_{K3\pi} = 0.33^{+0.20}_{-0.23}$

$\delta_D^{K3\pi} = (114^{+26}_{-23})^{o}$

1, 2, 3 σ CL

$$\Gamma\left(\mathrm{B}^- \to \left(\mathrm{K}^+3\pi\right)_\mathrm{D}\mathrm{K}^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

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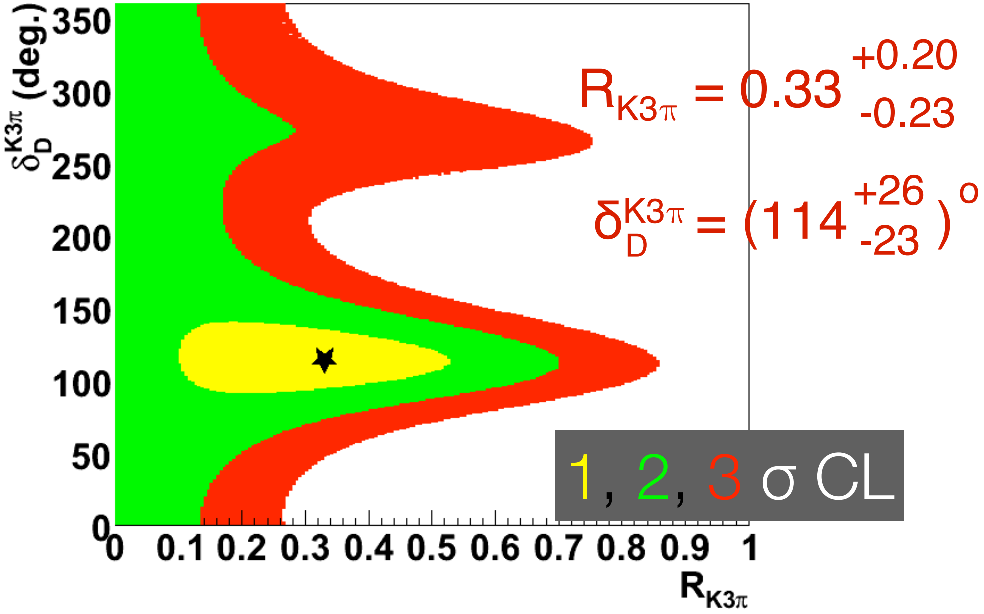

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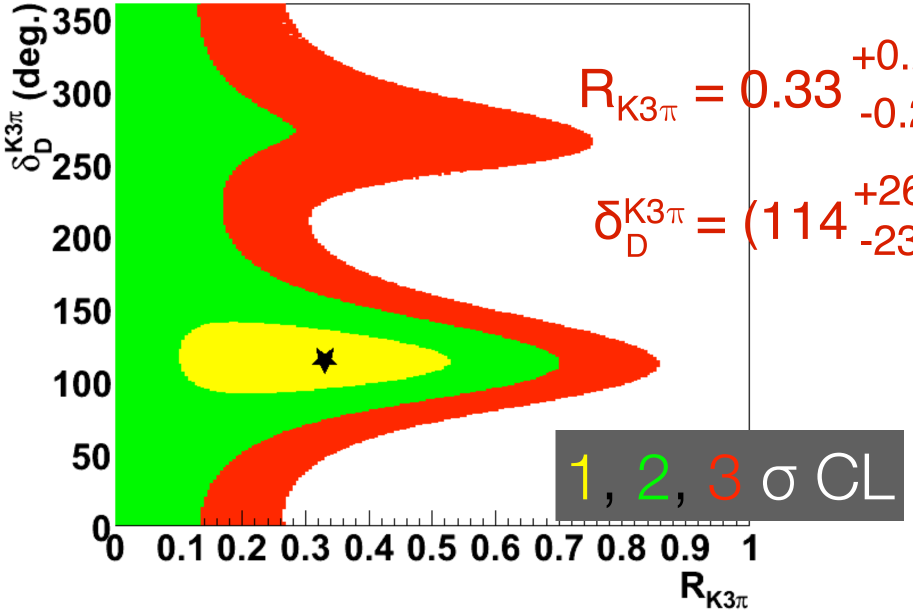

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badly known

Phys.Rev.D80:031105,2009

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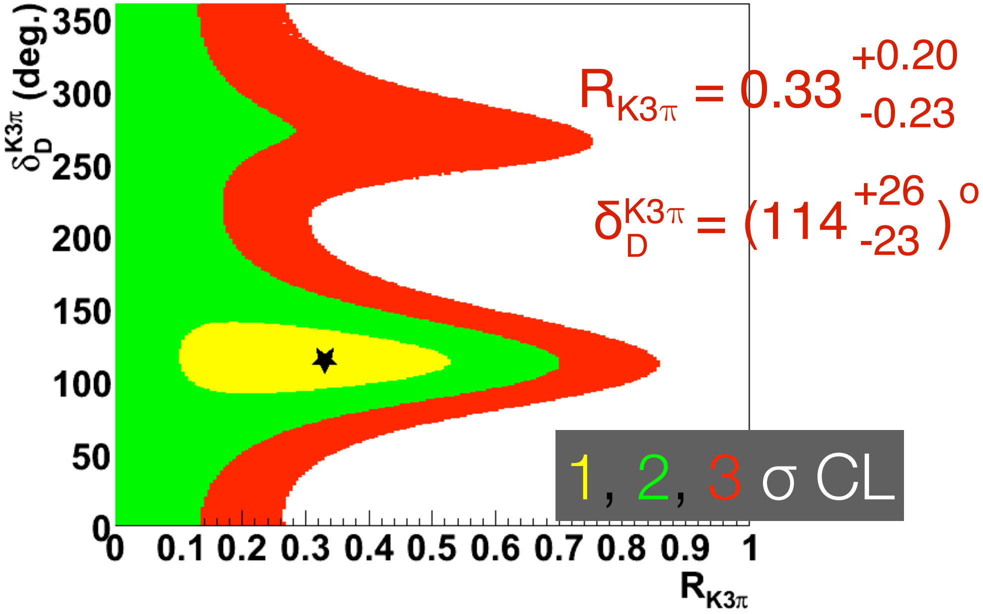

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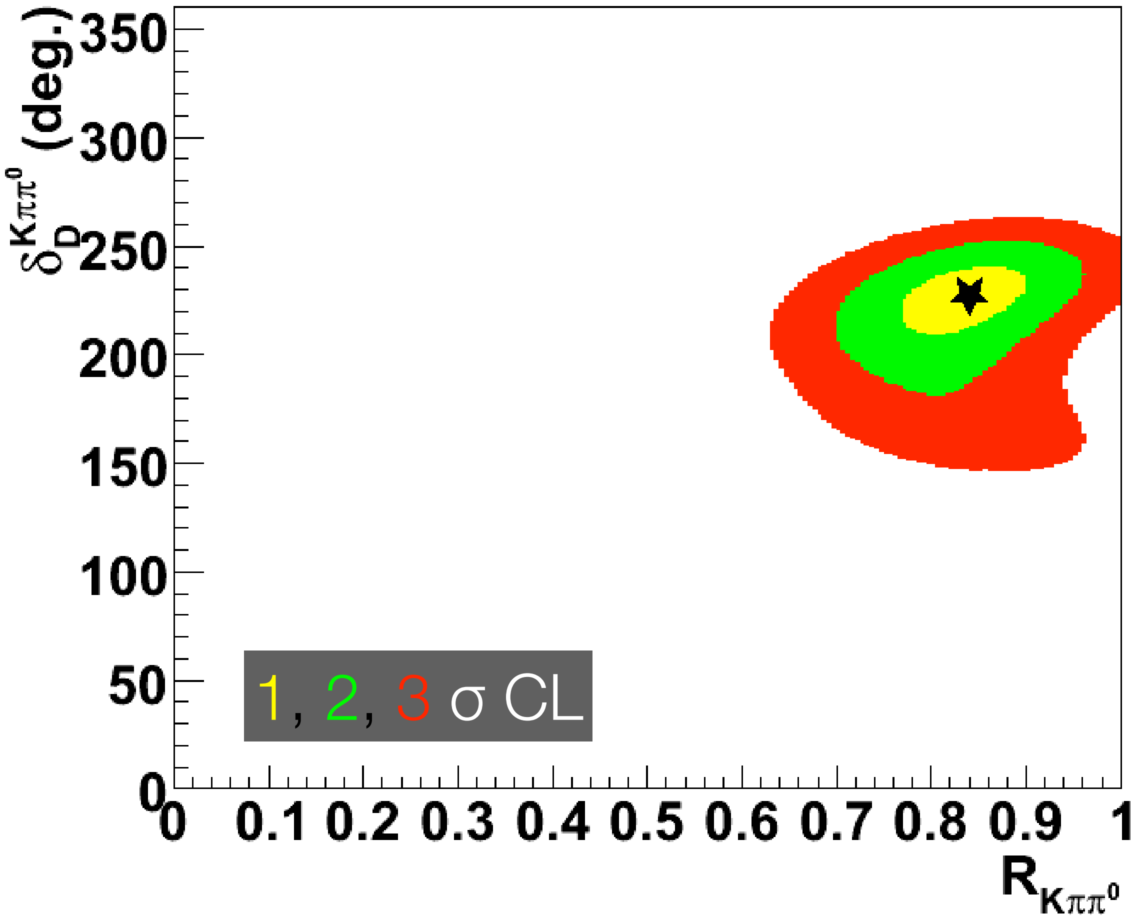
badly known

- At LHCb, using B±→D(hh)K±, B±→D(Kπππ)K±, for 2/fb (average year): This input improves σ(γ) from 9.5° to 7.9°. (typical values used - exact size of improvement depends on input parameters and can be larger as well as smaller).

Phys.Rev.D80:031105,2009

Kππ° Coherence Factor



$R_{K\pi\pi^0} = 0.84 \pm 0.07$

$\delta^{K\pi\pi^0} = (227^{+14}_{-17})^{\circ}$

Very coherent!

Expect significant further improvement (not evaluated at LHCb, yet)

Phys.Rev.D80:031105,2009

LHCb's γ combination

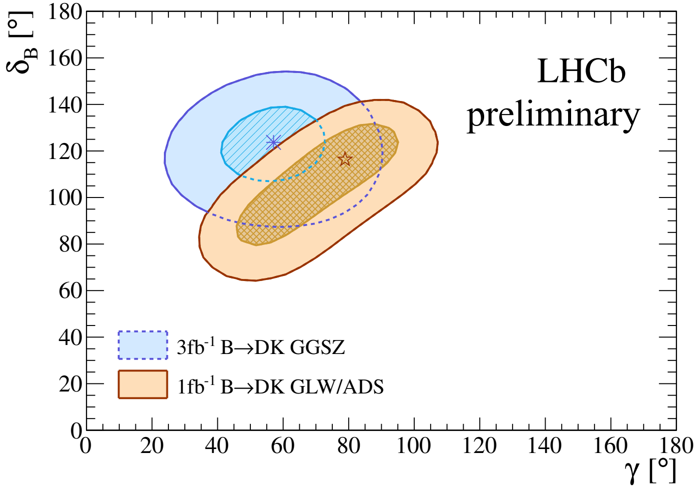
technique & 2011 results: arXiv:1305.2050 (2013)
2012 data: LHCb-CONF_2013-006) (in preparation)

- LHCb combines inputs from
  $B^\pm \to (hh')_D K^\pm$ (2011)
  $B^\pm \to (K_S\pi\pi)_D K^\pm$ (2012)
  $B^\pm \to (K_S KK)_D K^\pm$ (2012)
  $B^\pm \to (K\pi\pi\pi)_D K^\pm$ (2011)
- Result:

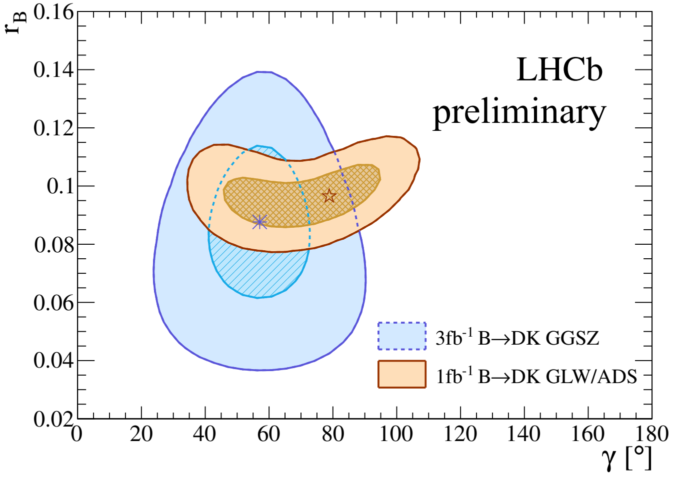
$$\gamma = (67.2 \pm 12)^o$$

- More channels and more data to be added, soon.

δ_B vs γ



r_B vs γ



	best fit	68% CL	95% CL
δ_B	114.3°	$[101.7, 126.6]^\circ$	$[89.1, 136.5]^\circ$
r_B	0.0924	[0.0847, 0.1004]	[0.0766, 0.1077]
γ	67.2°	$[55.7, 79.6]^\circ$	$[44.6, 90.0]^\circ$

Searches for CPV by comparing binned Dalitz plots

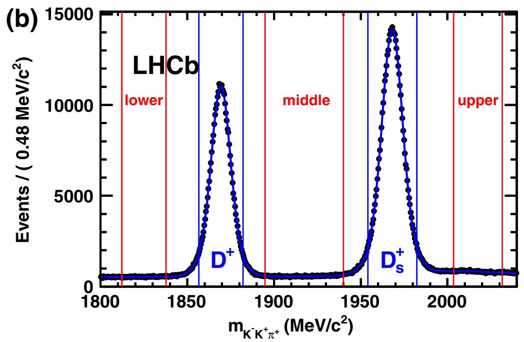
PhysRevD.84.112008

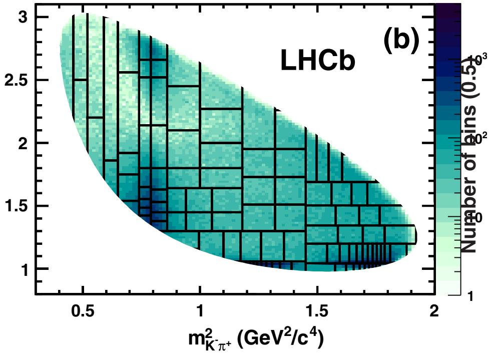
- Compare yields in CP-conjugate bins

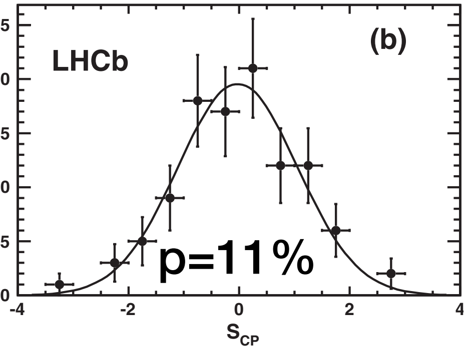
$$S_{CP} = \frac{N_i - \alpha \bar{N}_i}{\sqrt{N_i + \alpha^2 \bar{N}_i}}$$

$$\alpha = \frac{N_{\text{total}}}{\bar{N}_{\text{total}}}$$

330k $D^+ \to K^- K^+ \pi^+$ in 35/pb





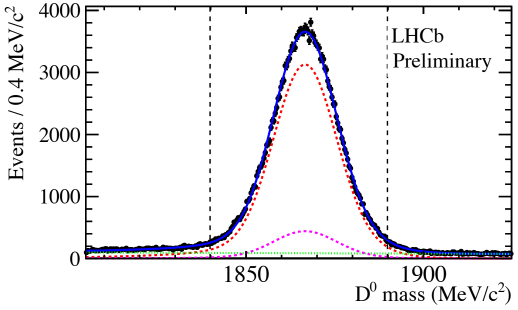


- Calculate p-value for no-CPV hypothesis based on

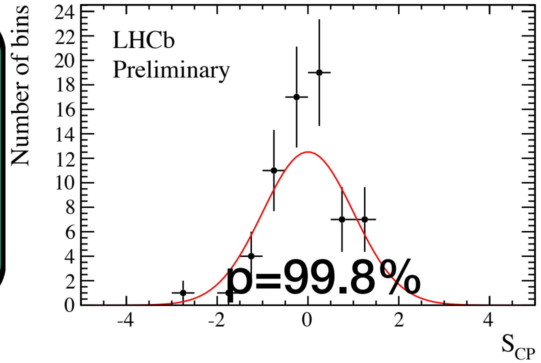
$$\chi^2 = \sum_i (S^i_{CP})^2$$

- Model independent. Many production and detection effects cancel.

~180k $D^{*+} \to D^o \pi$, $D^o \to \pi\pi\pi\pi$ in 1/fb



5-dim. “Dalitz” plot, binned.

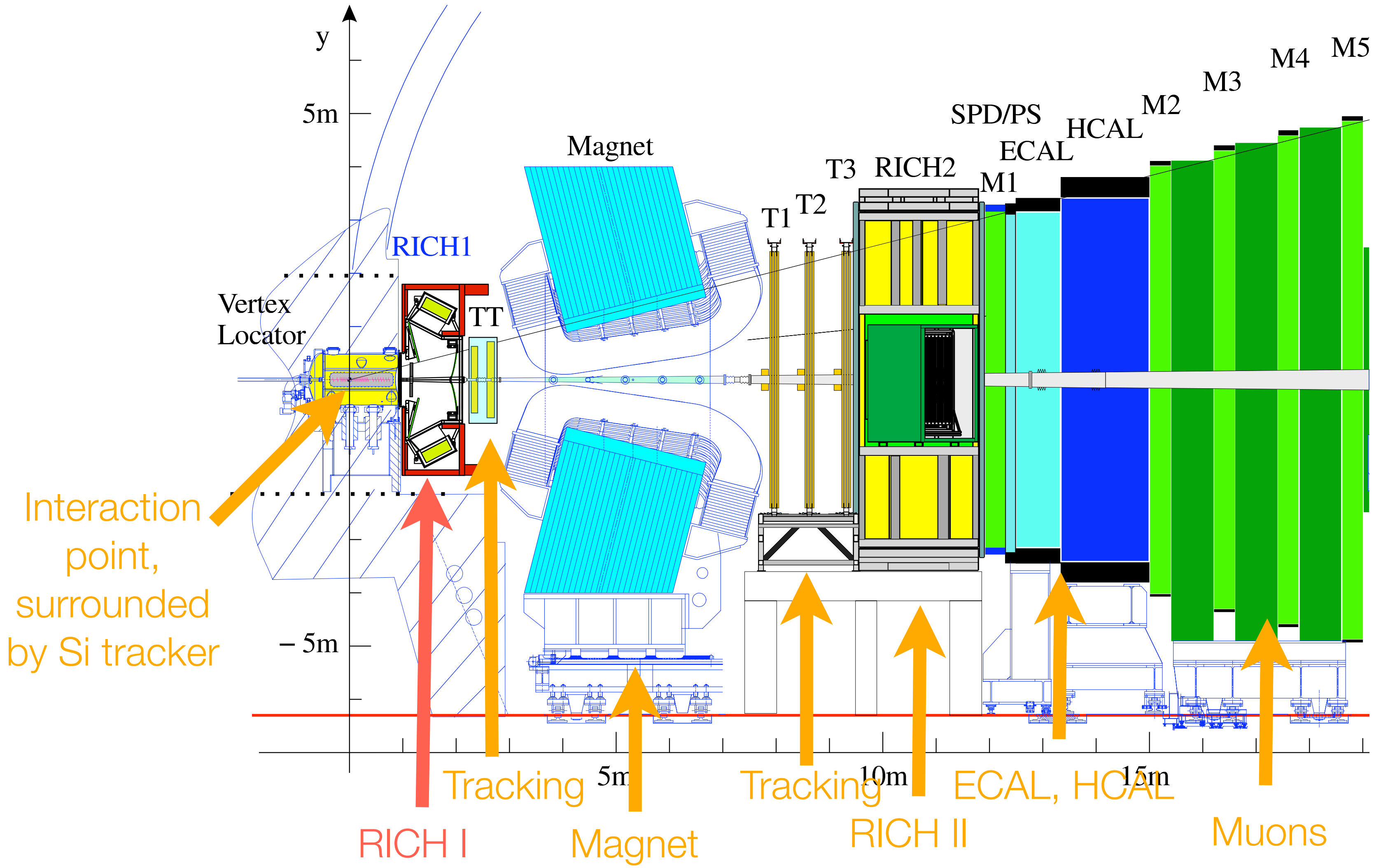


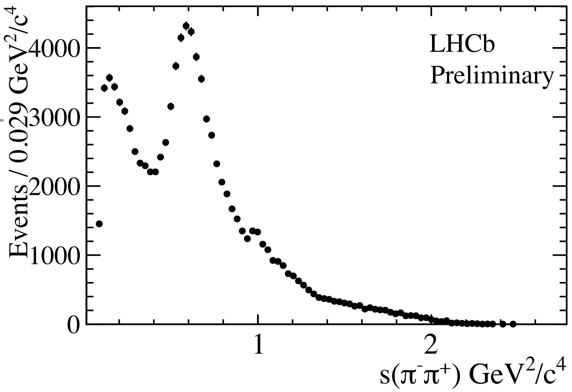
LHCb-CONF-2012-019

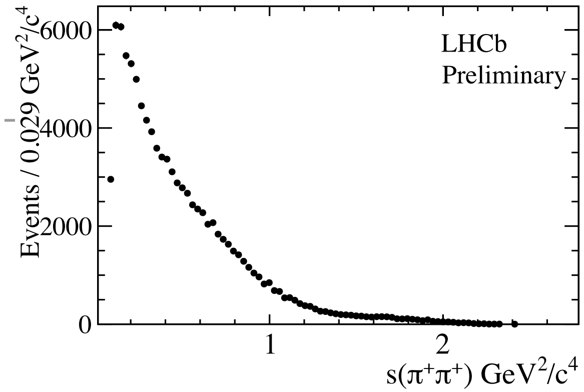
The LHCb collaboration

- 15 countries
- 52 institutes
- 660 members
- ...small and beautiful, by LHC standards.
- Comprehensive flavour physics programme, highly sensitive to NP...
- ... includes, amongst many important measurements, a precision measurement of γ (aim: few degrees)

LHCb


y
5m
– 5m
5m
10m
15m
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
Interaction point, surrounded by Si tracker
RICH I
Tracking
Magnet
Tracking
RICH II
ECAL, HCAL
Muons


LHCb
Preliminary
Events / 0.029 GeV^2/c^4
0
1000
2000
3000
4000
1
2
s(π$^-$π$^+$) GeV^2/c^4


LHCb
Preliminary
Events / 0.029 GeV^2/c^4
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6000
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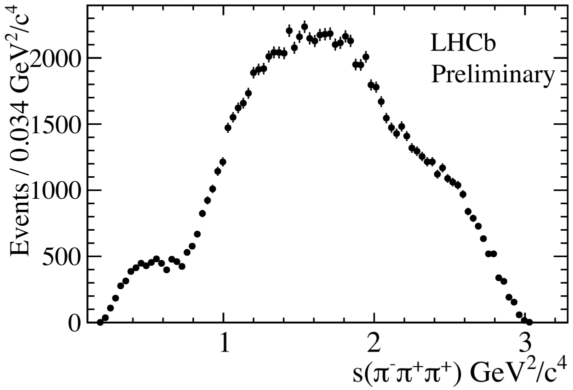
2
s(π$^+$π$^+$) GeV^2/c^4


LHCb
Preliminary
Events / 0.034 GeV^2/c^4
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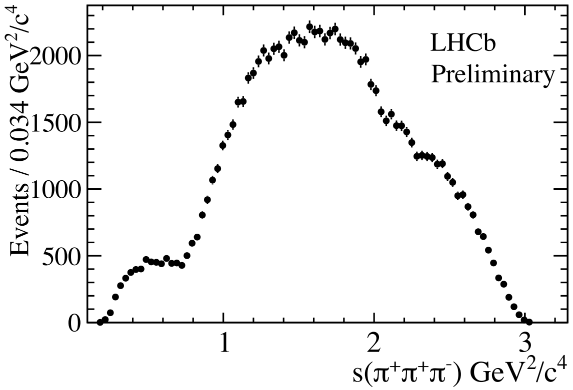
3
s(π$^-$π$^+$π$^+$) GeV^2/c^4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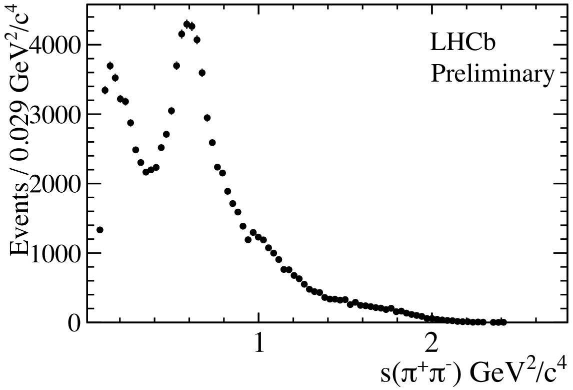
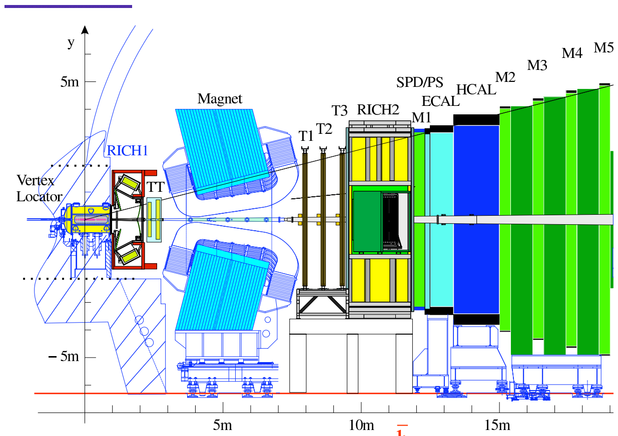
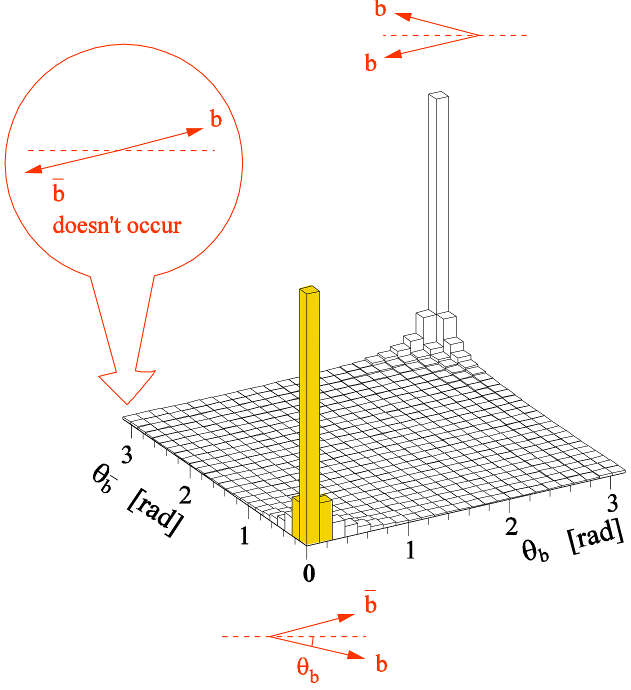

LHCb
Preliminary
Events / 0.029 GeV^2/c^4
0
1000
2000
3000
4000
1
2
s(π$^+$π$^-$) GeV^2/c^4

LHCb’s special skills

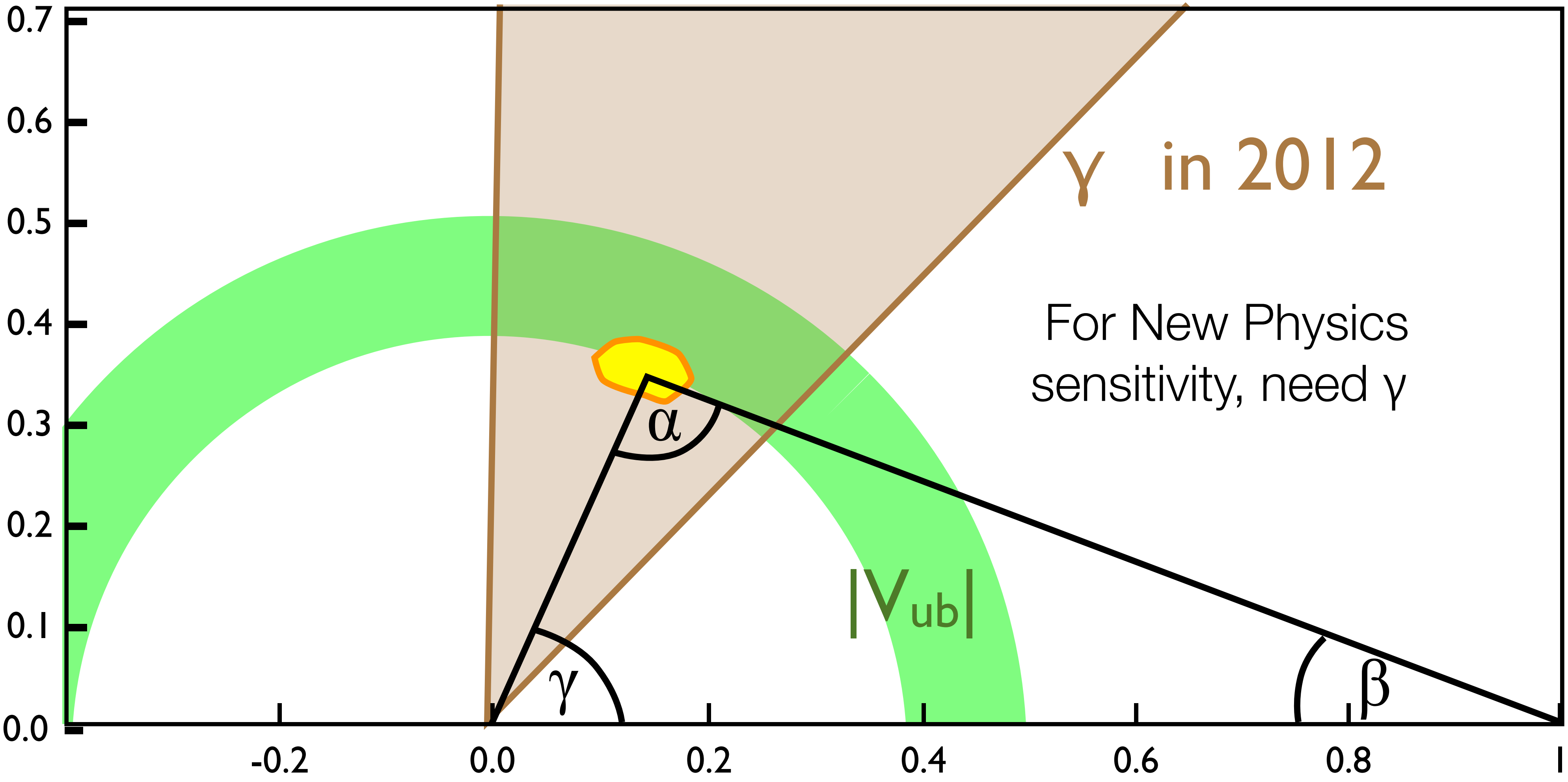
- The location: 100,000 b-bbar pairs per second at the LHCb interaction point ⇒ vast quantities of all b-hadron species (B_d, B_s, ...)
- The geometry: optimised to capture as many B mesons as possible.
- The VELO - a vertex detector INSIDE the beampipe, for excellent impact parameter and decay lengths resolution
- A Ring Imaging Cherenkov detector (RICH) that provides particle identification.





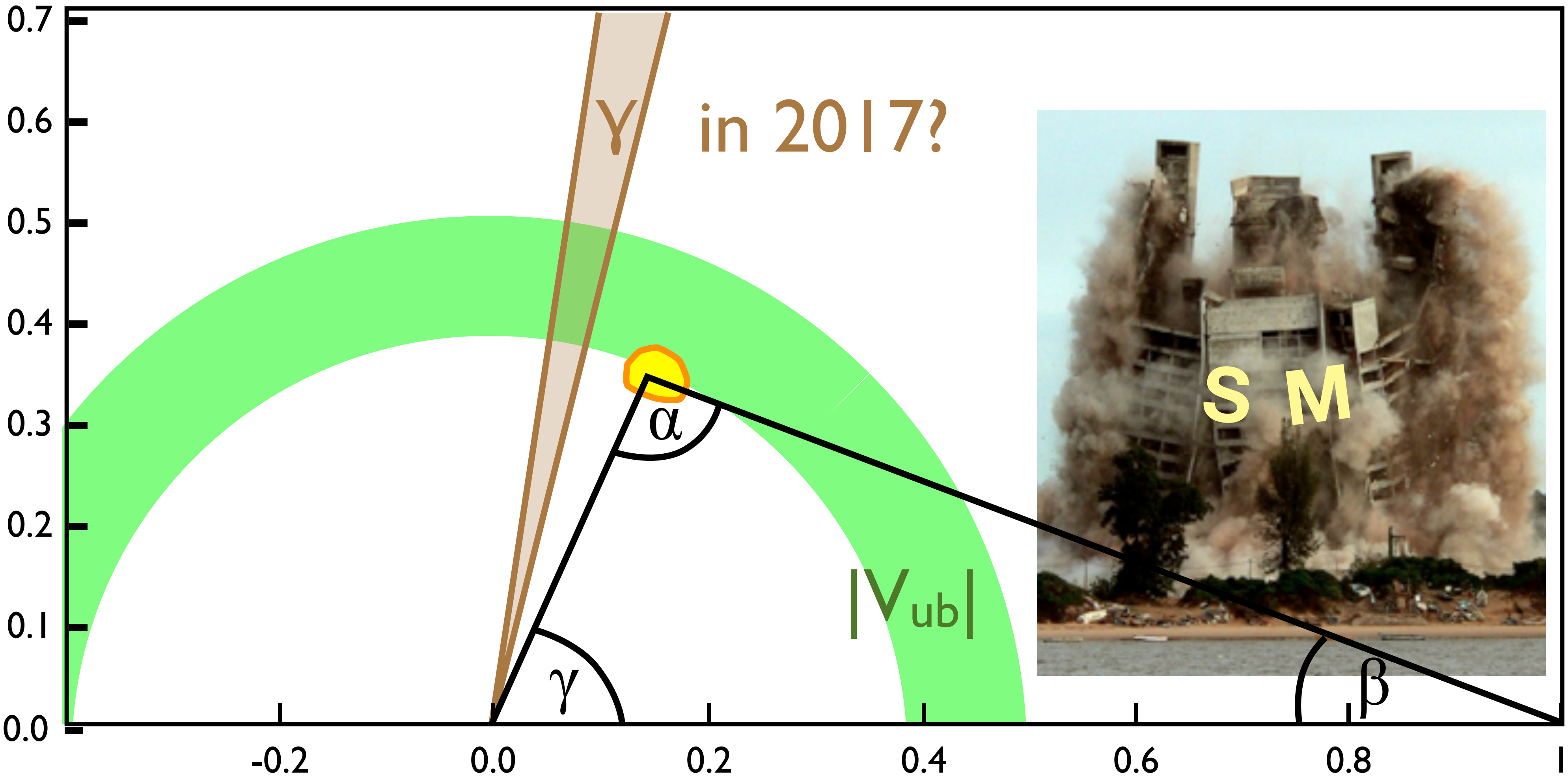
The “Unitarity Triangle” represents key parameters of the Standard Model description of CP violation.

If the Standard Model is correct, we should get consistent constraints on the apex of the triangle. Shaded areas identify constraints from different sources (95% CL). (Yellow: “loops”, others “trees”.)



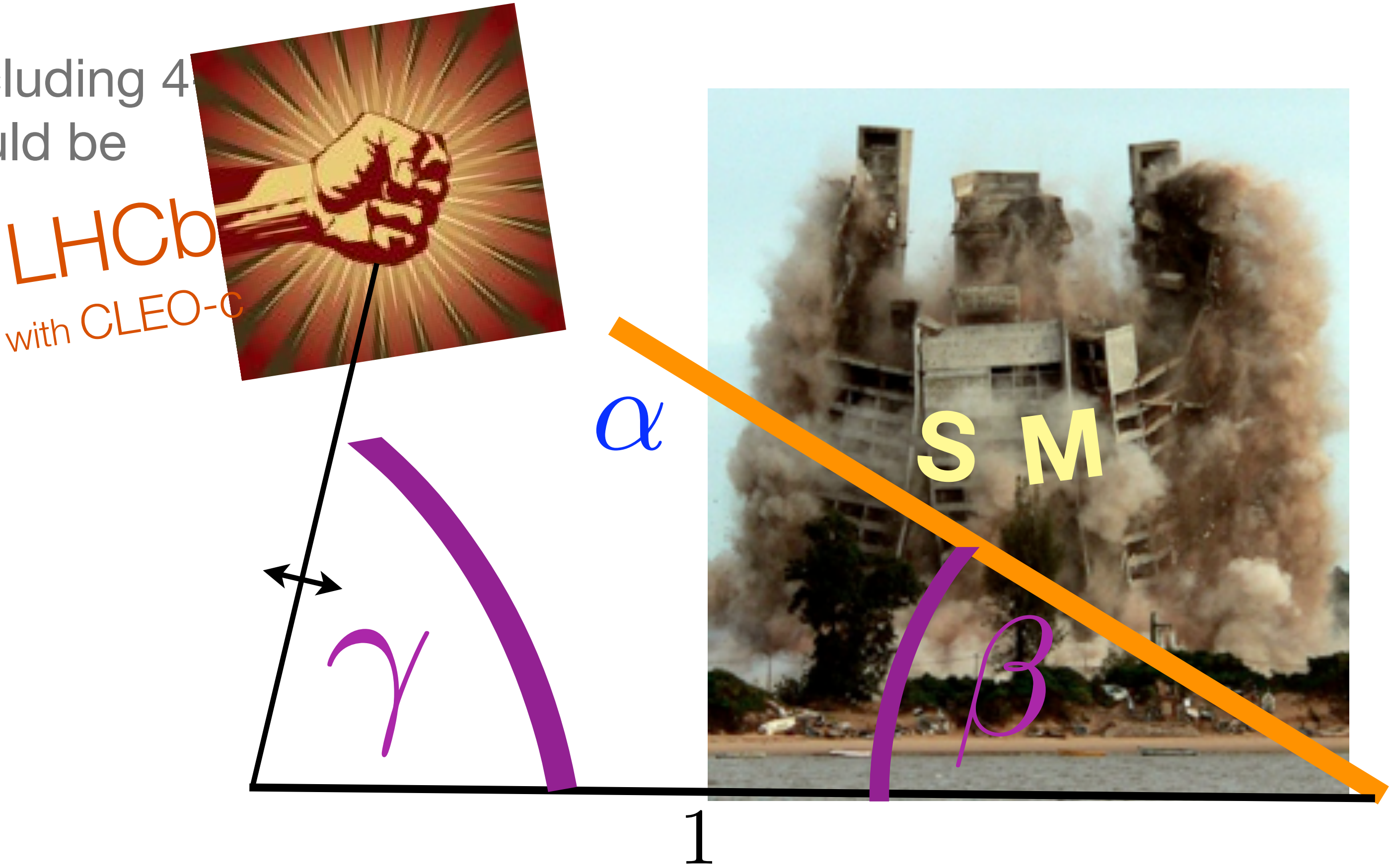
The proposed research will dramatically improve the precision on γ

... which could lead to a long sought-after inconsistency, indicating the breakdown of the Standard model.



Measuring γ.

- LHCb has already the most precise gamma measurements
- With more channels, including 4-body channels, we should be able to reach ~10°.
- ...



Summary

- What high energy does for the “high-pt” physics, is high statistics for flavour physics. Both increase the mass-range of New Physics we can access, but provide complementary information about that physics.
- The LHC delivers both: Unprecedented energy and unprecedented statistics. LHCb is the experiment optimised for flavour physics at the LHC.
- LHC and LHCb performing well, LHCb physics programme can cope comparably well with reduced energy and luminosity (only relatively small cost in heavy flavour yields - partially recovered with to loser trigger threshold - might even benefit charm physics).
- 1/fb is enough to give the Standard Model a few serious blows from flavour physics - either that, or we will start ruling out some of its most highly-regarded alternatives.

Flavour Summary of ESPP Symposium, Krakow

Flavour agenda at ESPP

Physics at High Energy Frontier and Flavour Physics

Convener: Y. Kuno, R. Forty (Scientific Secretary)

11:00 **HEF Experiment Results** *35'*

30' + 5' discussion

Speaker: Guenther Dissertori (ETH Zuerich)

Material: **Slides**

no flavour content

11:35 **Flavour and Symmetries; Experiment Results** *35'*

30' + 5' discussion

Speaker: Frederic Teubert (CERN)

Material: **Slides**

high flavour content

12:10 **Charged Lepton Flavor and Symmetry Physics Implications** *25'*

20' + 5' discussion

Speaker: Gino Isidori (Istituto Nazionale Fisica Nucleare)

Material: **Slides**

high flavour content

(both, cLFV and quark flavour)

12:35 - 14:00 Lunch

Convener: K. Desch, M. Diemoz, A. Lister (Scientific Secretary)

14:00 **Implications on Possible New Physics from Direct and Indirect Measurements** *35'*

Speaker: Christophe Grojean (CERN)

Material: **Slides**

no flavour content

14:35 **Next Step Facilities** *40'*

Speaker: Terry Wyatt (University of Manchester)

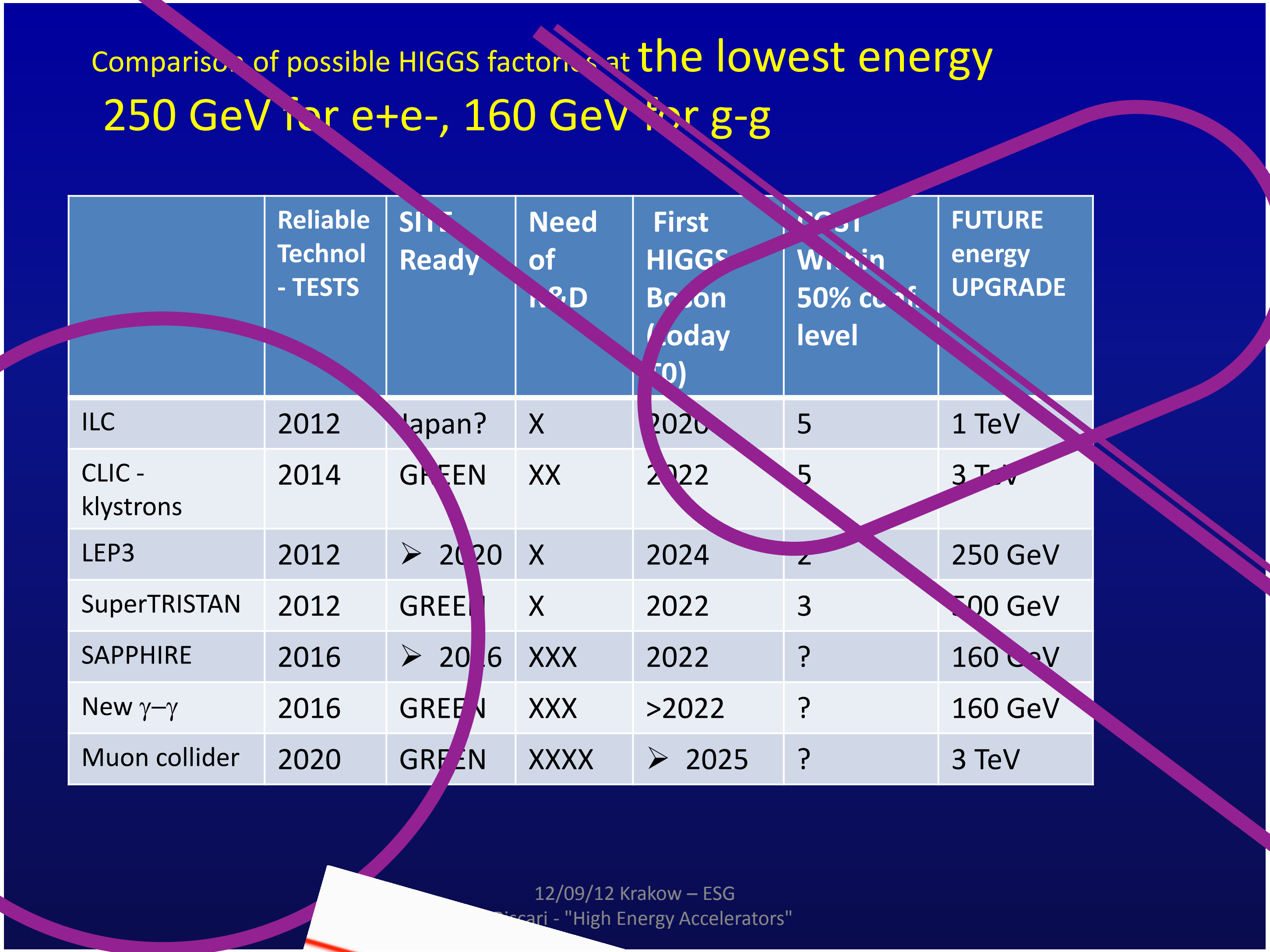
Material: **Slides**

low flavour content (ran out of time)

15:15 **Discussion** *1h15'*

small (but positive) flavour content

Discussions were dominated by: what does the Higgs (like) discovery mean for the next collider?



Comparison of possible HIGGS factories at **the lowest energy**

250 GeV for e+e-, 160 GeV for g-g

	Reliable Technol - TESTS	SITE Ready	Need of R&D	First HIGGS Boson (today T0)	COST Within 50% conf. level	FUTURE energy UPGRADE
ILC	2012	Japan?	X	2020	5	1 TeV
CLIC - klystrons	2014	GREEN	XX	2022	5	3 TeV
LEP3	2012	➢ 2020	X	2024	2	250 GeV
SuperTRISTAN	2012	GREEN	X	2022	3	500 GeV
SAPPHIRE	2016	➢ 2016	XXX	2022	?	160 GeV
New γ–γ	2016	GREEN	XXX	>2022	?	160 GeV
Muon collider	2020	GREEN	XXXX	➢ 2025	?	3 TeV

12/09/12 Krakow – ESG
iscari - "High Energy Accelerators"

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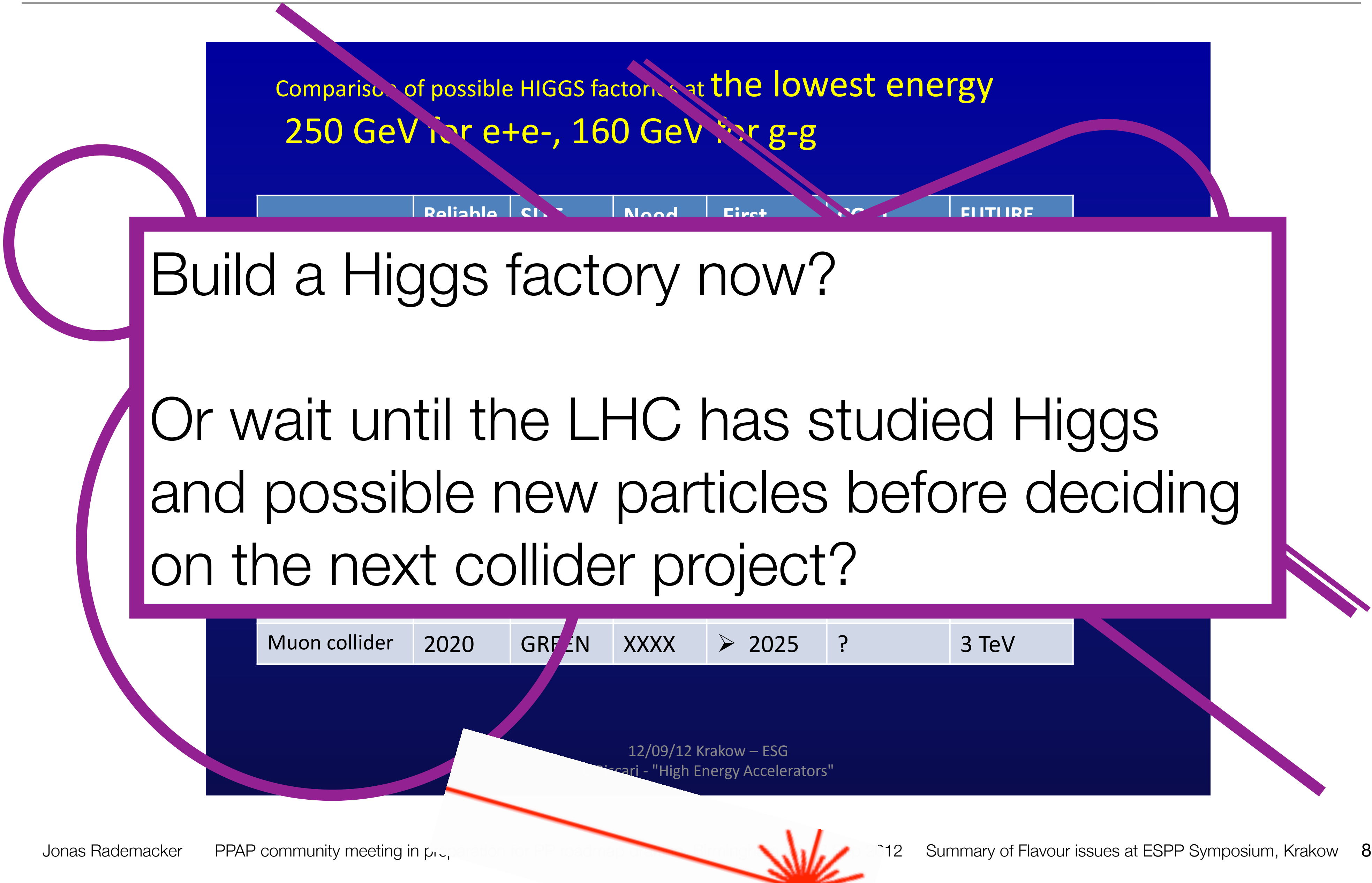


Compariso of possible HIGGS factori at the lowest energy

250 GeV f r e+e-, 160 GeV f r g-g

	Reliable	SI	Need	First	CO	FUTURE
Muon collider	2020	GR EN	XXXX	➢ 2025	?	3 TeV

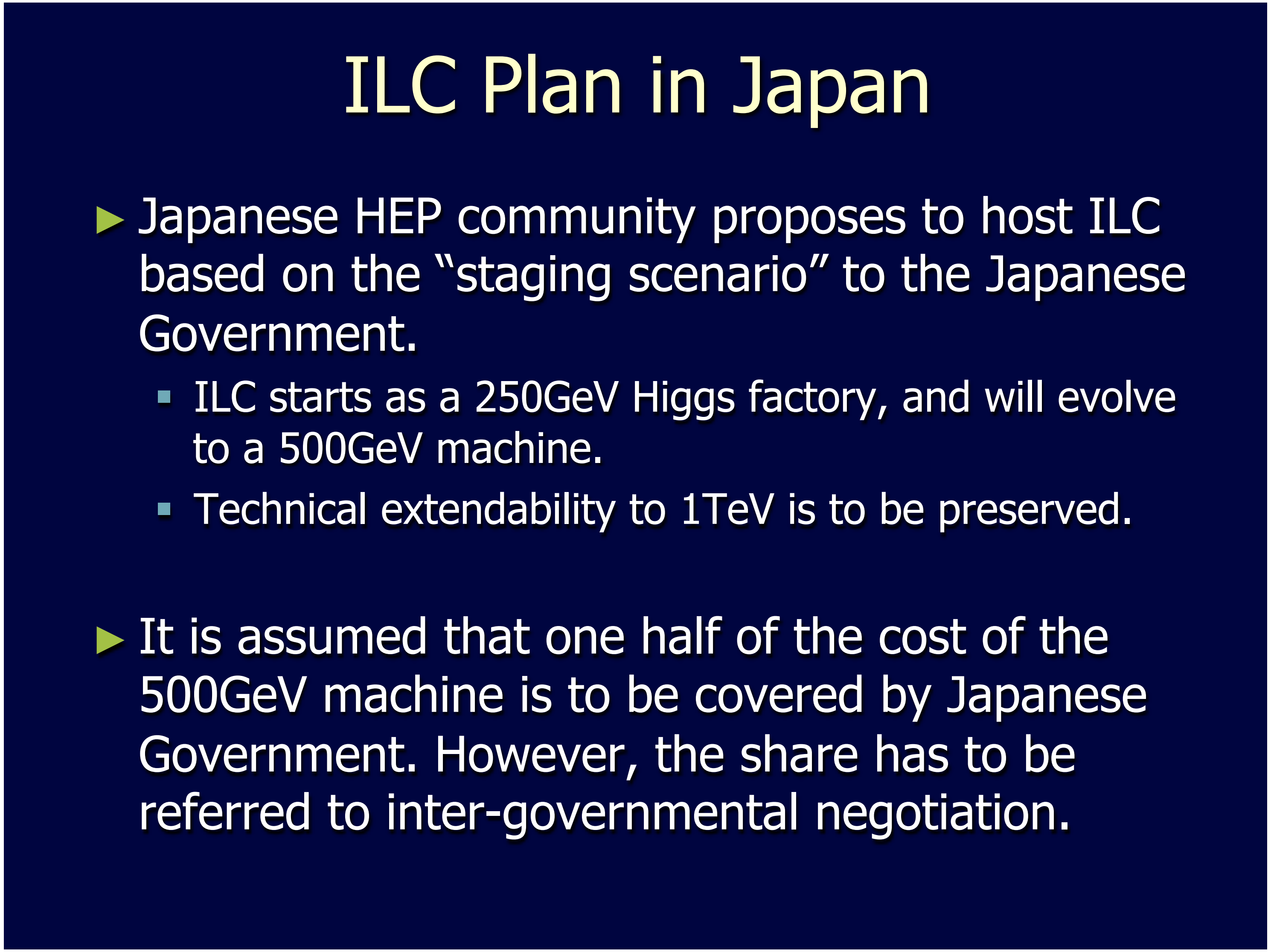
12/09/12 Krakow – ESG

iscari - "High Energy Accelerators"

Build a Higgs factory now?

Or wait until the LHC has studied Higgs and possible new particles before deciding on the next collider project?

One suggestion made some waves:

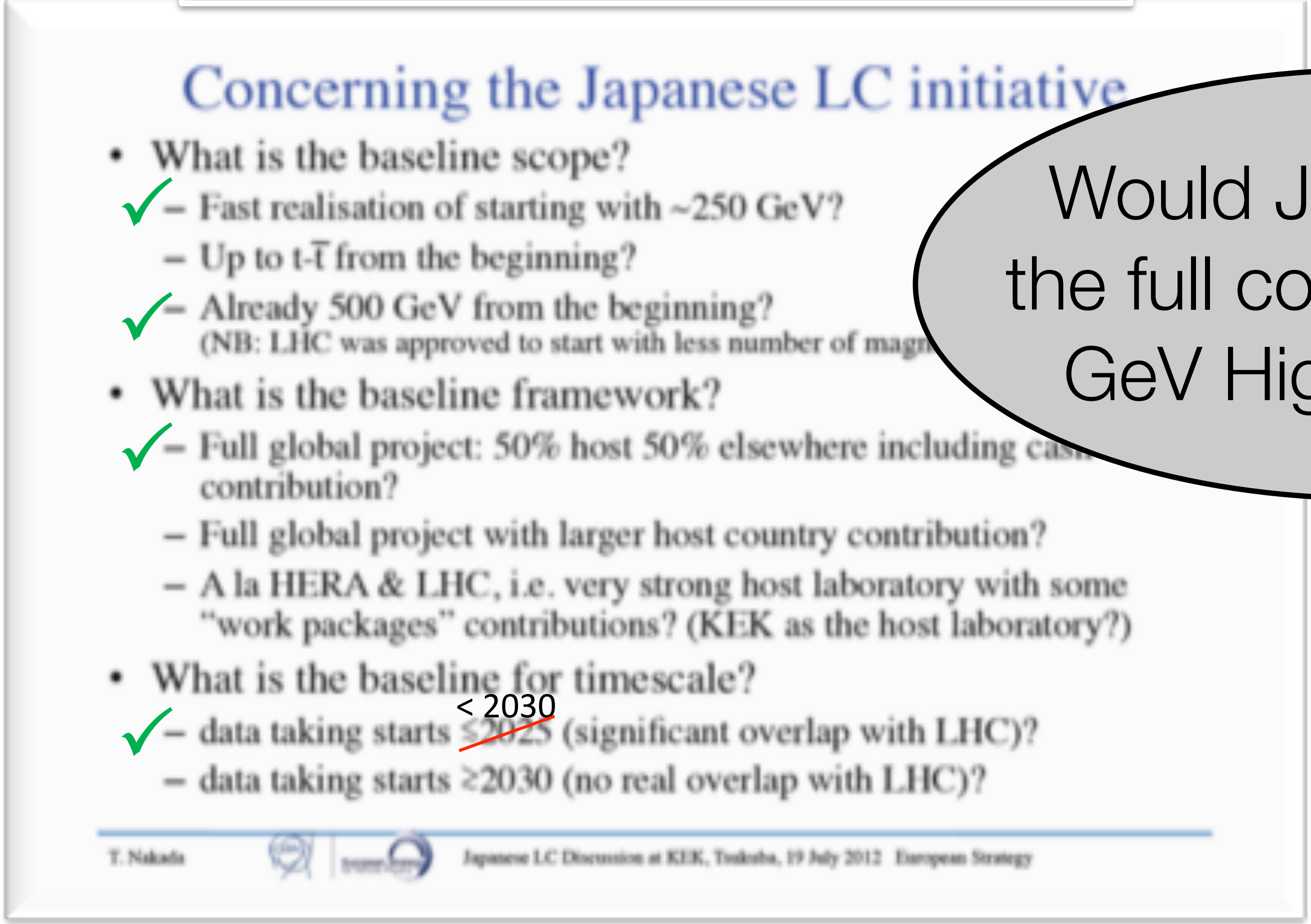


ILC Plan in Japan

- Japanese HEP community proposes to host ILC based on the "staging scenario" to the Japanese Government.
  - ILC starts as a 250GeV Higgs factory, and will evolve to a 500GeV machine.
  - Technical extendability to 1TeV is to be preserved.
- It is assumed that one half of the cost of the 500GeV machine is to be covered by Japanese Government. However, the share has to be referred to inter-governmental negotiation.

Higgs factory / ILC

Answers to Tatsuya's questions

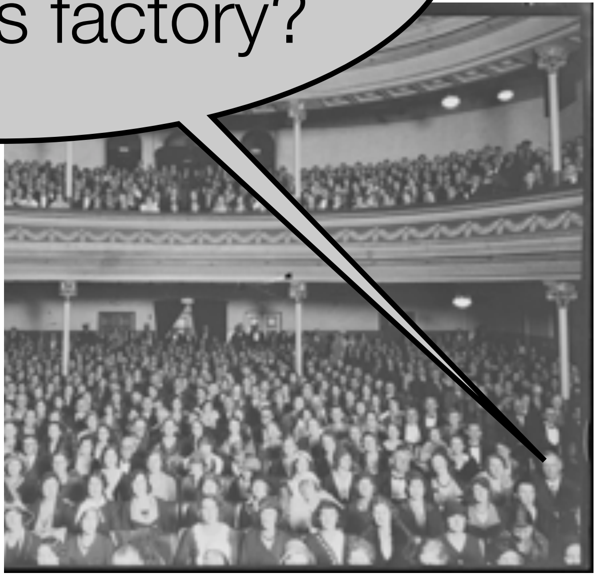


Concerning the Japanese LC initiative

- What is the baseline scope?
  - ✓ – Fast realisation of starting with ~250 GeV?
  - – Up to t-$\bar{t}$ from the beginning?
  - ✓ – Already 500 GeV from the beginning?
    (NB: LHC was approved to start with less number of magn
- What is the baseline framework?
  - ✓ – Full global project: 50% host 50% elsewhere including cas
    contribution?
  - – Full global project with larger host country contribution?
  - – A la HERA & LHC, i.e. very strong host laboratory with some "work packages" contributions? (KEK as the host laboratory?)
- What is the baseline for timescale?
  - ✓ – data taking starts ~~≤2025~~ < 2030 (significant overlap with LHC)?
  - – data taking starts ≥2030 (no real overlap with LHC)?

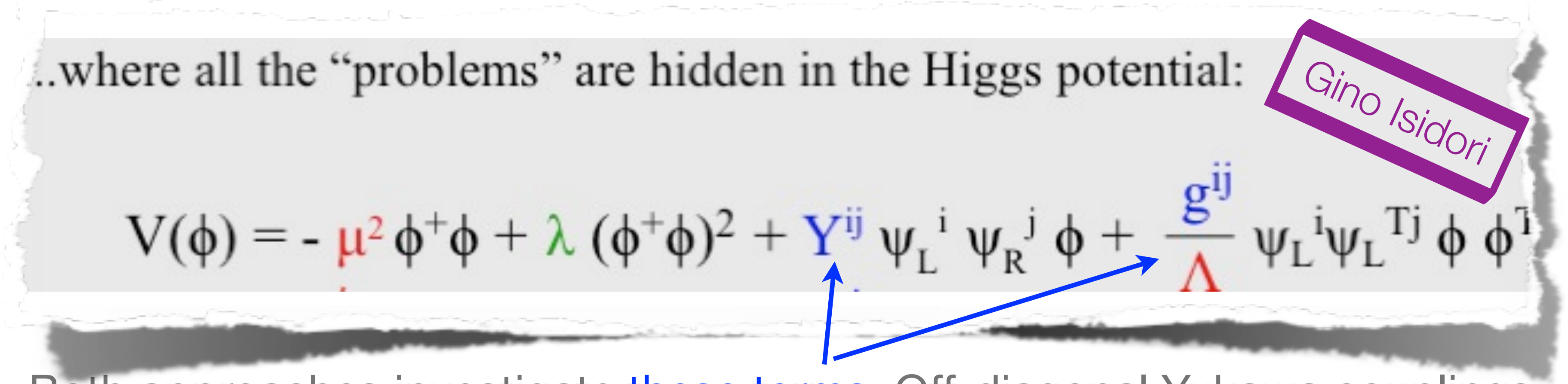
T. Nakada Japanese LC Discussion at KEK, Tsukuba, 19 July 2012 European Strategy

Would Japan put up the full cost for the 250 GeV Higgs factory?



What has Higgs factory got to do with flavour?

- As flavour physicists, we should be delighted to get some help with, and a lot of enthusiasm for, the precise investigation of Higgs Yukawa couplings.



..where all the “problems” are hidden in the Higgs potential:

$$V(\phi) = -\mu^2\phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\psi_L{}^i\psi_R{}^j\phi + \frac{g^{ij}}{\Lambda}\psi_L{}^i\psi_L{}^{Tj}\phi\,\phi^T$$

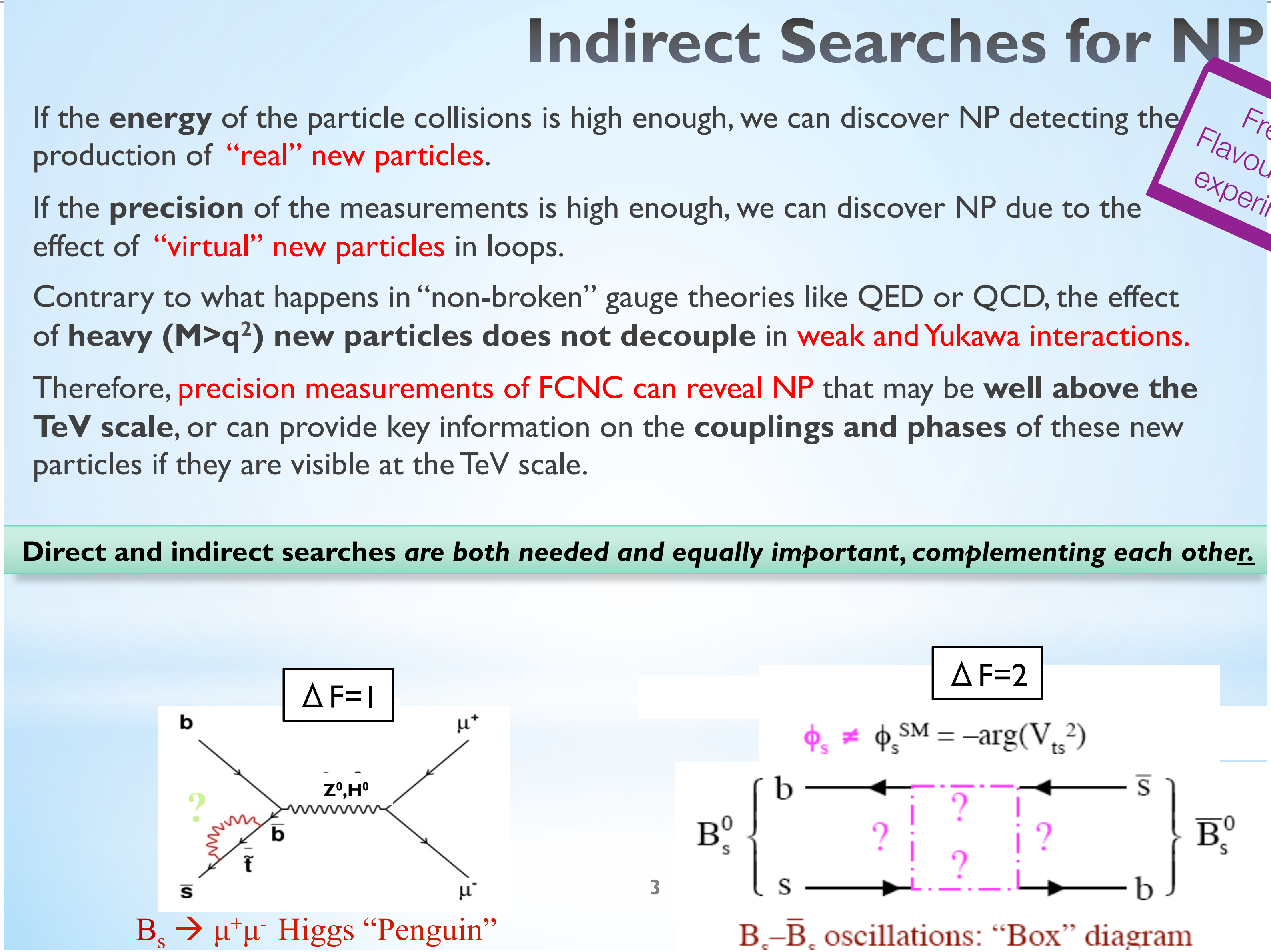
Gino Isidori

- Both approaches investigate these terms. Off-diagonal Yukawa couplings are responsible for flavour changes. Higgs factory measures the rest.

- Full set of measurements clearly essential for our understanding of the SM and, even more importantly, highly sensitive to physics beyond the SM - the common main target. Both approaches share the need for very high precision to maximise BSM sensitivity.

Complementarity between precision flavour and direct searches

Frederic Teubert:
Flavour & symmetries,
experimental results



Indirect Searches for NP

If the **energy** of the particle collisions is high enough, we can discover NP detecting the production of "real" new particles.

If the **precision** of the measurements is high enough, we can discover NP due to the effect of "virtual" new particles in loops.

Contrary to what happens in "non-broken" gauge theories like QED or QCD, the effect of **heavy (M>q^2) new particles does not decouple** in weak and Yukawa interactions.

Therefore, precision measurements of FCNC can reveal NP that may be **well above the TeV scale**, or can provide key information on the **couplings and phases** of these new particles if they are visible at the TeV scale.

Direct and indirect searches *are both needed and equally important, complementing each other.*

$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2)$

$B_s \rightarrow \mu^+\mu^-$ Higgs "Penguin"

B_s–$\bar{B}_s$ oscillations: "Box" diagram

New Physics

The non-observation of NP in direct searches, as well as the mass of the Higgs, suggest an unexpectedly high mass scale...

New Physics

The non-observation of NP in direct searches, as well as the mass of the Higgs, suggest an unexpectedly high mass scale...

Luis Alvarez-Gaume: Theory

It deserves a nice mausoleum...

Naturalness vs Flavour Problem

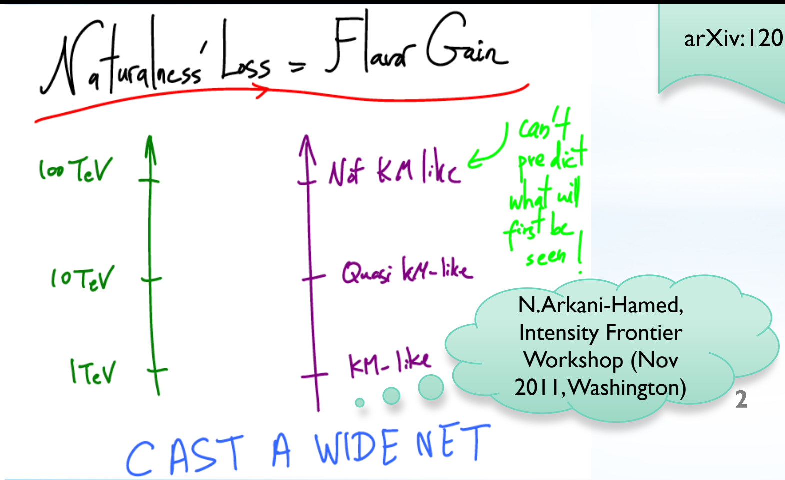
Frederic Teubert:
Flavour & symmetries,
experimental results

Status of Searches for NP

So far, no significant signs for NP from direct searches at LHC while a Higgs-like boson has been found with a mass of ~125 GeV/c^2.

Before LHC, expectations were that *"naturally"* the masses of the new particles would have to be light in order to reduce the *"fine tuning"* of the EW energy scale. However, the absence of NP effects observed in flavour physics implies some level of *"fine tuning"* in the flavour sector → **NP FLAVOUR PROBLEM** → Minimal Flavour Violation (MFV).

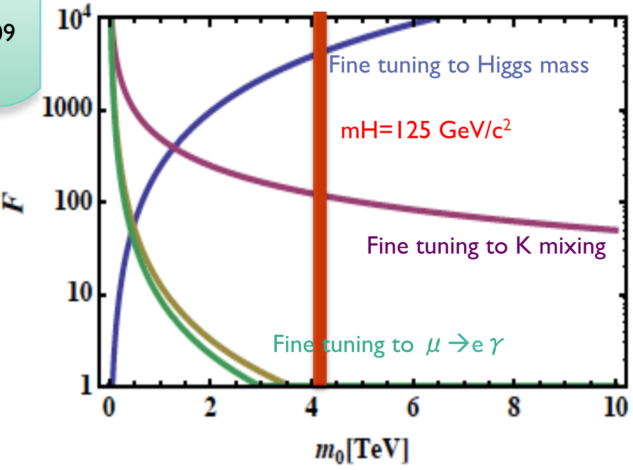
As we push the energy scale of NP higher (within MSSM the measured value of the Higgs mass pushes the scale up), the NP FLAVOUR PROBLEM is reduced, hypothesis like MFV look less likely → **chances to see NP in flavour physics have, in fact, increased!**



N.Arkani-Hamed, Intensity Frontier Workshop (Nov 2011, Washington)

2

arXiv:1205.709



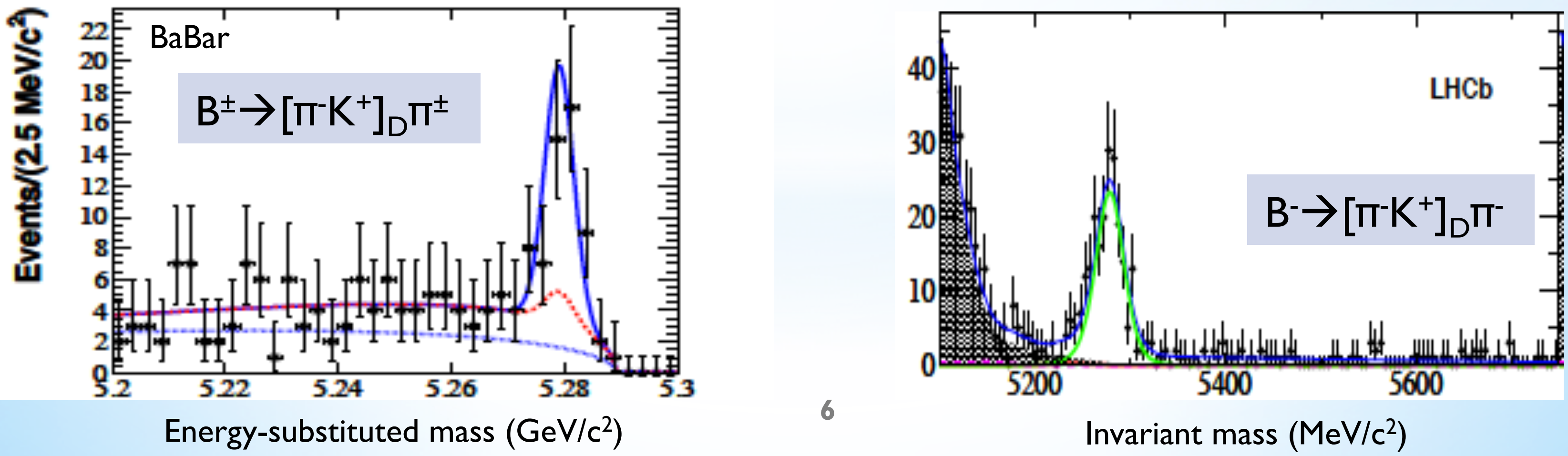
Recent experimental results (F. Teubert)

- Recent heavy flavour results dominated by LHCb. Data samples not only large, but also impressively clean, despite challenging environment.

Frederic Teubert: Flavour & symmetries, experimental results

Rule of thumb:*

1/fb at 7TeV at LHCb is equivalent to (1-5)/ab at the B-factories before tagging.



arXiv:1006.4241

arXiv:1203.3662

Energy-substituted mass (GeV/c^2)

Invariant mass (MeV/c^2)

*) Will get twice the heavy flavour x-section at 14 TeV, so this is effectively ca 10% of projected LHCb data (before upgrade)

- However, for channels with neutral/invisible particles in the final state the clean B-factory environment is an advantage.

Flavour Results

Frederic Teubert discusses an impressive set of recent flavour results, including:

- A large number of LHCb results in $B^{\pm}$, B_d, B_s decays, destroying many dreams of new physics esp in the B_s system (for $B_s \to \mu\mu$, also big contribution from CMS).
- B-factories, having completed data taking, continue to produce important results, incl. $B \to \tau\nu$, which is now within ~1.2σ of CKM fit.
- Charm physics, incl CPV (1st evidence at LHCb, confirmed by CDF). NP or SM?
- Precision Kaon physics, incl. 1st results from NA62 (which is under construction!)
- CLFV limits from B-factories (τ), and dedicated $\mu \to e$ experiments (MEG)
- μ, e g-2 and EDM: hint of NP: $\Delta a_{\mu} = (287 \pm 80) \times 10^{-11}$ (3.6σ) at E821 (Brookhaven), also best limit on $|d_{\mu}| < 1.9 \times 10^{-19}$ e cm

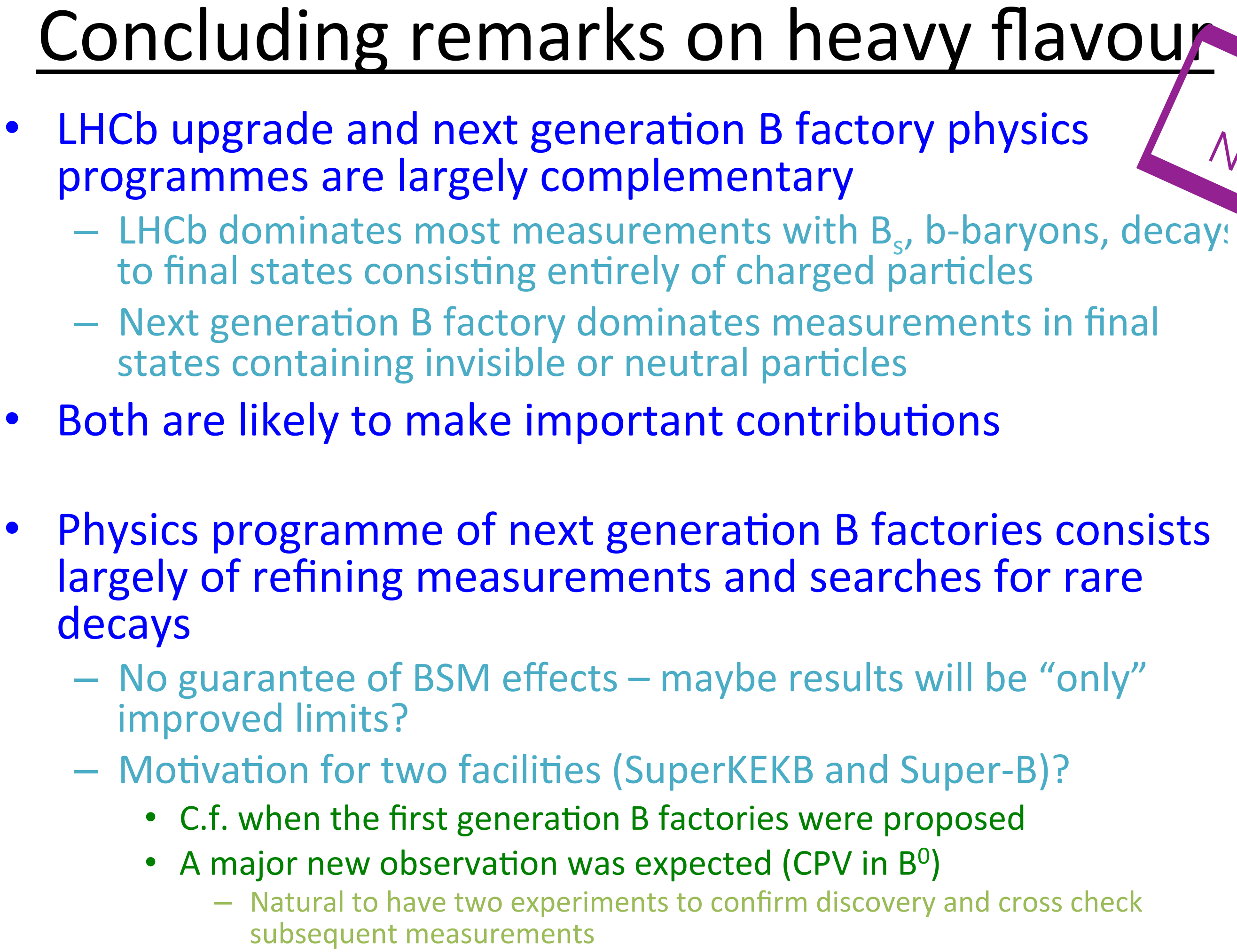
What next?

Flavour Future

- UK/PPAP input to ESPP: Recommendations on flavour (there is more text in the document):
  - The highest priority is to fully exploit the capabilities of the current LHCb detector so as to maximise its scientific output, especially in probing BSM physics. In addition, investment should be made in the LHCb upgrade to enable full exploitation of the LHC flavour physics potential.
  - Precision experiments in the bottom, charm, kaon, tau and muon sectors that bring complementarity and breadth to the global physics programme should be pursued, along with the associated theoretical work to maximise their impact; global coordination of national- or regional-scale programmes would be desirable.

Flavour Future

- Talk on future facilities talk ran out of time before discussing flavour - the extra time given, concentrated on LHCb upgrade and Super Flavour Factories:

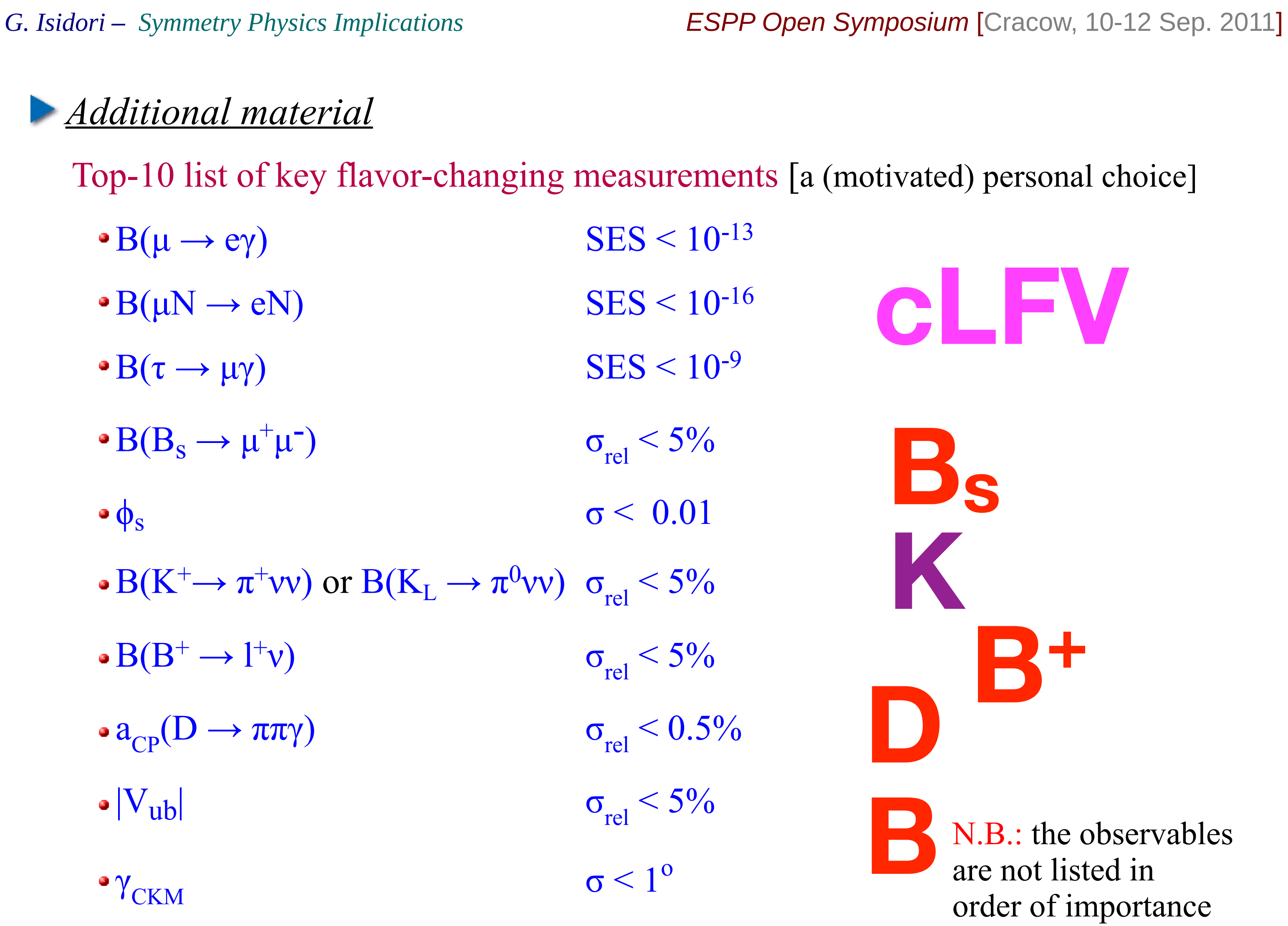


Concluding remarks on heavy flavour

- LHCb upgrade and next generation B factory physics programmes are largely complementary
  - LHCb dominates most measurements with B_s, b-baryons, decay to final states consisting entirely of charged particles
  - Next generation B factory dominates measurements in final states containing invisible or neutral particles
- Both are likely to make important contributions
- Physics programme of next generation B factories consists largely of refining measurements and searches for rare decays
  - No guarantee of BSM effects – maybe results will be "only" improved limits?
  - Motivation for two facilities (SuperKEKB and Super-B)?
    - C.f. when the first generation B factories were proposed
    - A major new observation was expected (CPV in B^0)
      - Natural to have two experiments to confirm discovery and cross check subsequent measurements

Terry Wyatt:
Next Step Facilities

Gino Isidori's top-10 flavour changing measurements



G. Isidori – Symmetry Physics Implications

ESPP Open Symposium [Cracow, 10-12 Sep. 2011]

Additional material

Top-10 list of key flavor-changing measurements [a (motivated) personal choice]

$B(\mu \to e\gamma)$	SES $< 10^{-13}$
$B(\mu N \to eN)$	SES $< 10^{-16}$
$B(\tau \to \mu\gamma)$	SES $< 10^{-9}$
$B(B_s \to \mu^+\mu^-)$	$\sigma_{rel} < 5\%$
ϕ_s	$\sigma < 0.01$
$B(K^+ \to \pi^+\nu\nu)$ or $B(K_L \to \pi^0\nu\nu)$	$\sigma_{rel} < 5\%$
$B(B^+ \to l^+\nu)$	$\sigma_{rel} < 5\%$
$a_{CP}(D \to \pi\pi\gamma)$	$\sigma_{rel} < 0.5\%$
$\lvert V_{ub} \rvert$	$\sigma_{rel} < 5\%$
γ_{CKM}	$\sigma < 1^o$

cLFV

B_s

K

B^+

D

B

N.B.: the observables are not listed in order of importance

Flavour Future

Frederic Teubert:
Flavour & symmetries,
experimental results

Interest in precision flavour measurements is stronger than ever.
In some sense it would have been very “unnatural” to find NP at LHC7 from direct searches with the SM CKM structure.

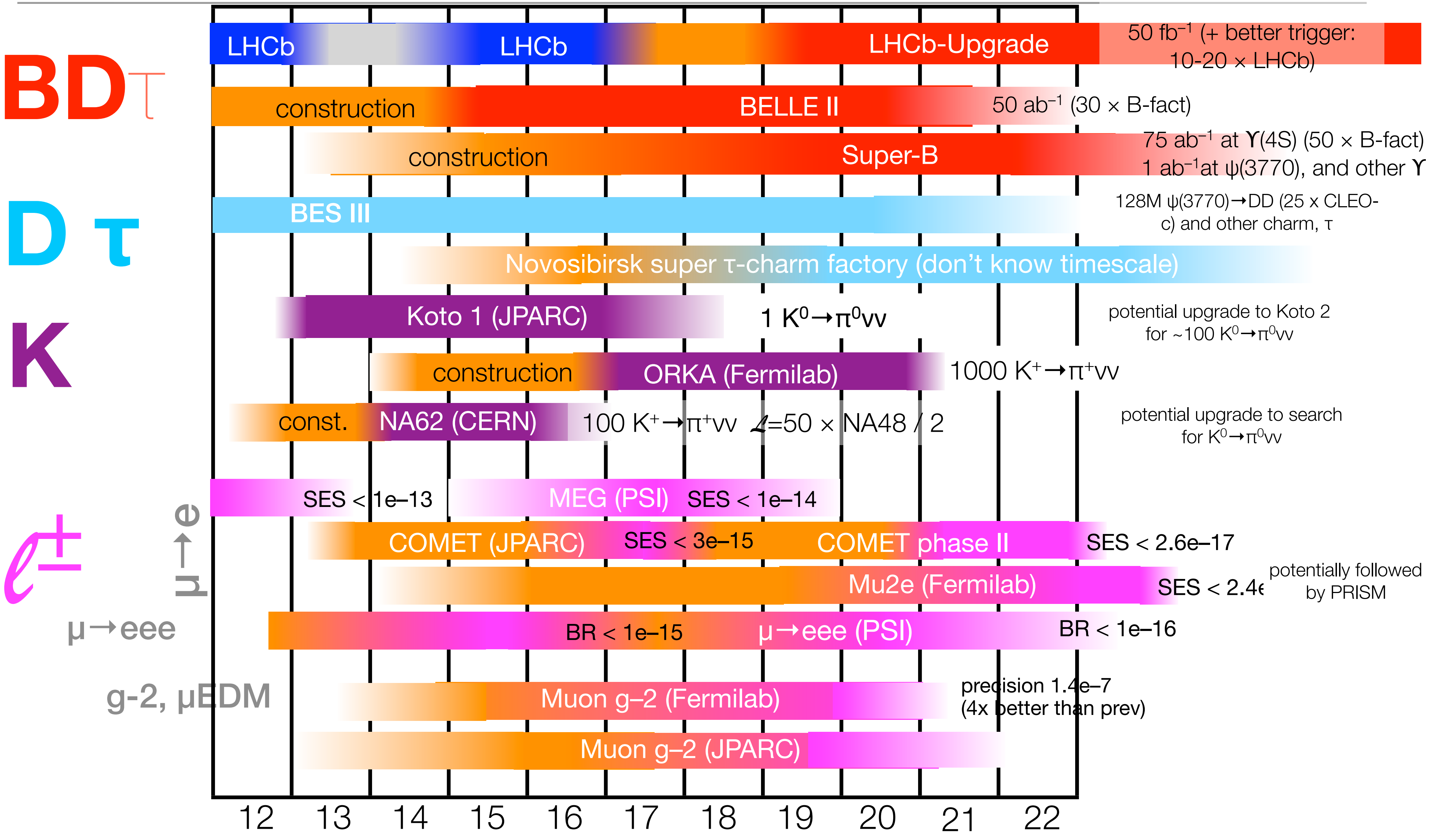
In my opinion, our best chances to find NP in flavour physics are:

- Precise determination of (ρ , η) with tree level processes.
- Precise determination of CP-violating in ΔB=2 processes.
- Improved precision in rare penguins ΔF=1 processes.
- LFV in muon and tau decays.
- EDM

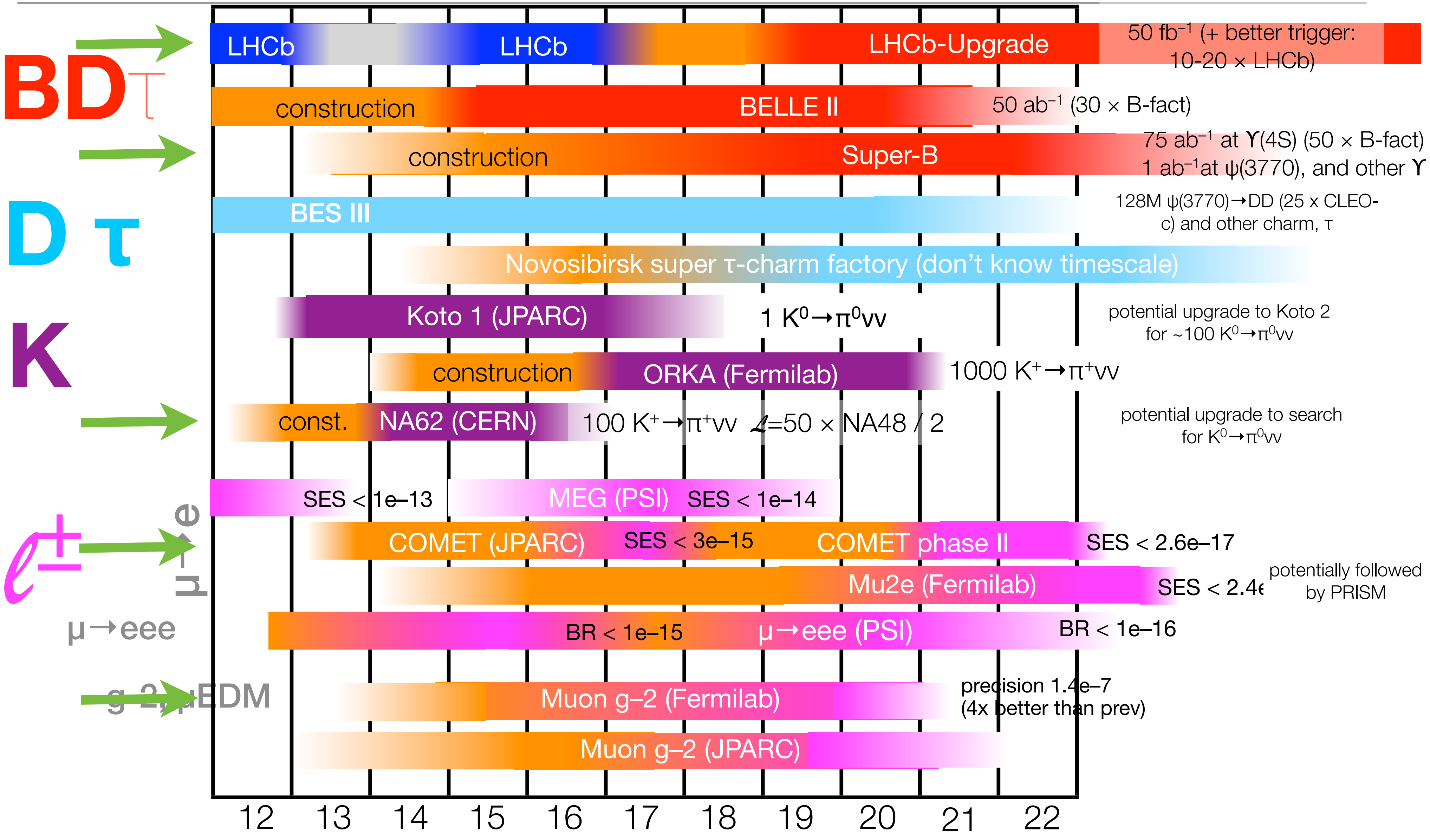
A large part of this program can be performed with upgrades of existing “large” experiments (S-LHCb, Belle-2) while new “smaller” experiments are being proposed for Kaons, LFV and EDM measurements.

There is a priory as many good reasons to find NP by measuring precisely the Higgs couplings as by precision measurements in the flavour sector!

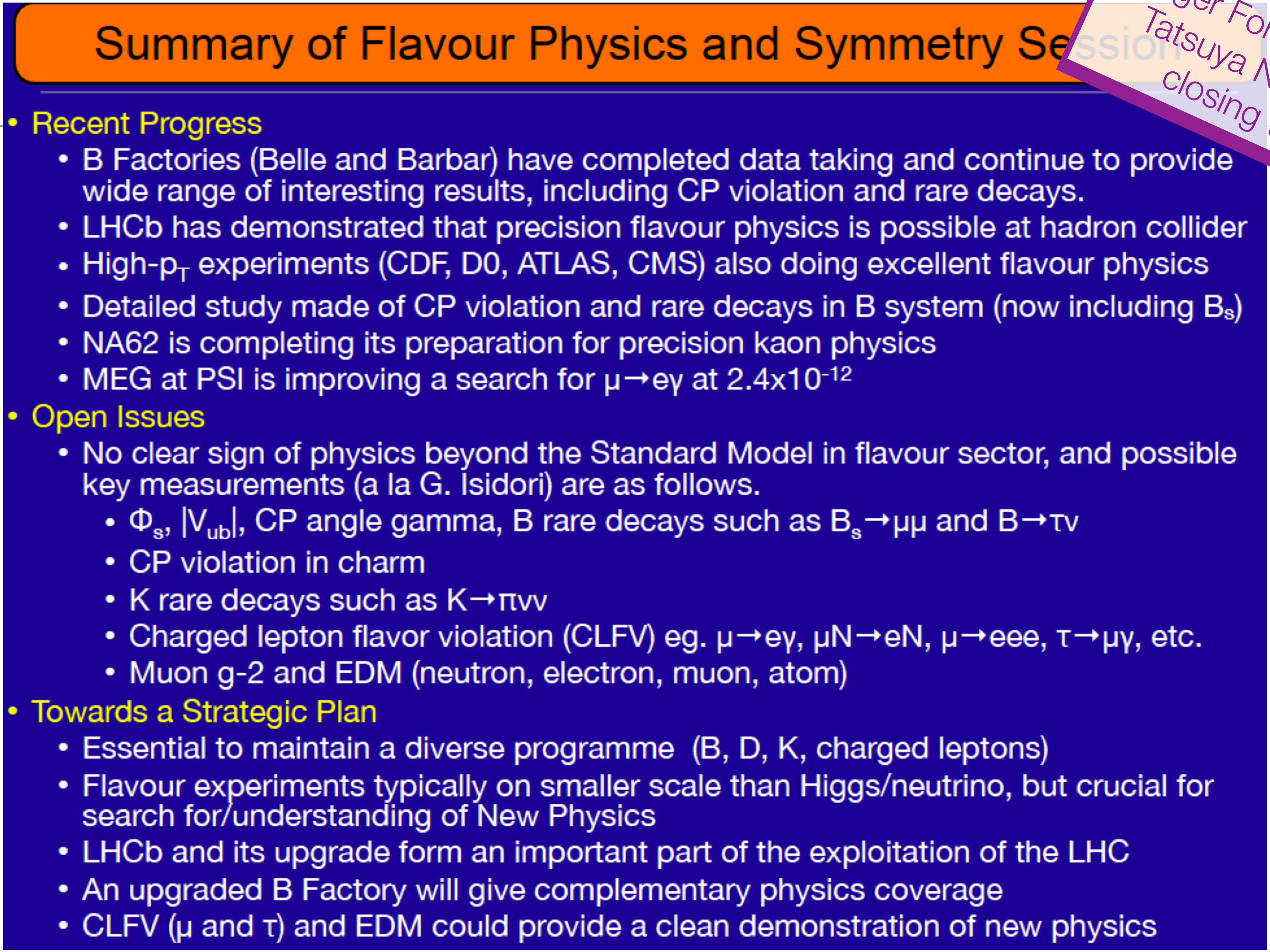
Future Flavour Experiments



Future Flavour Experiments



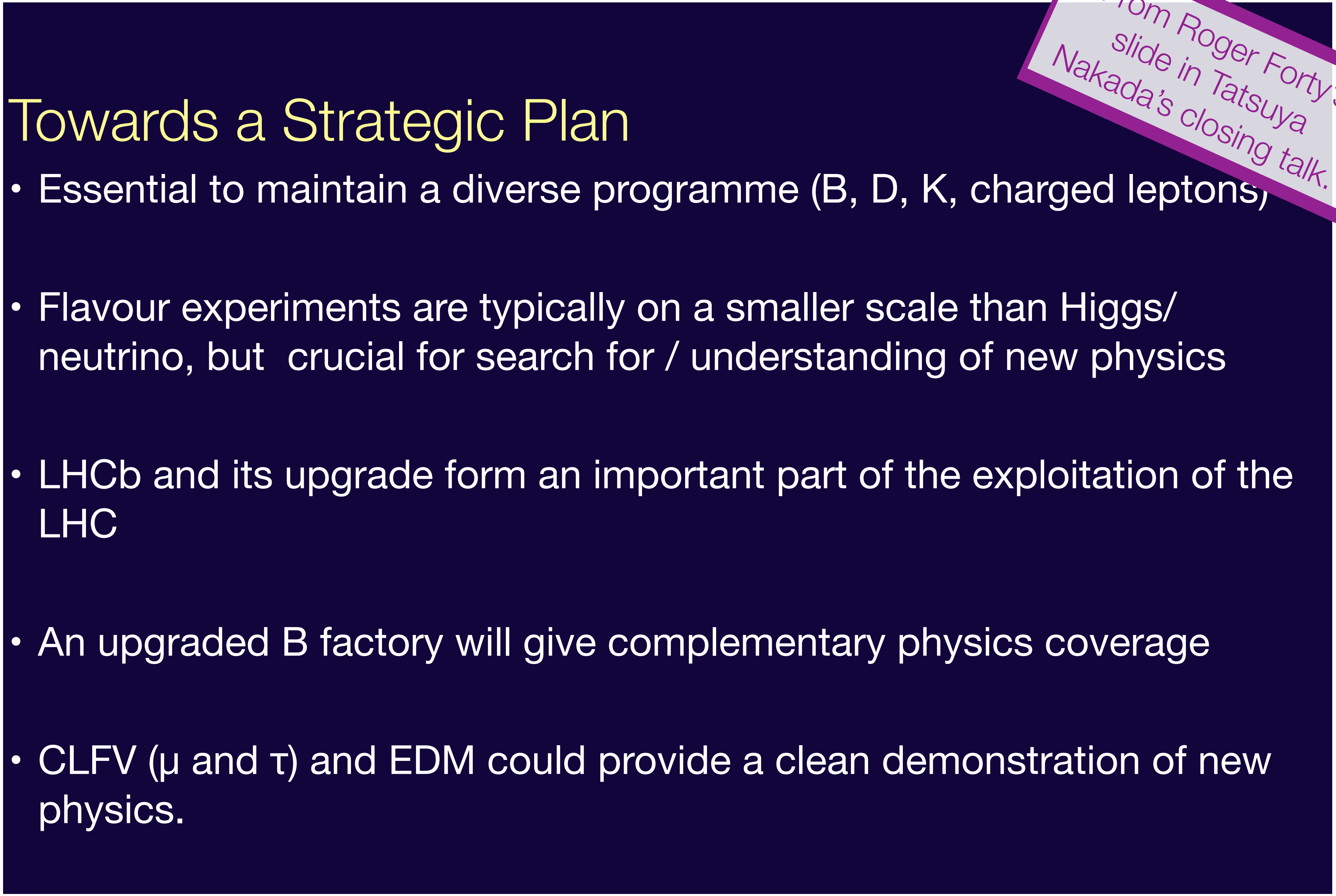
Roger Forty's slide in Tatsuya Nakada's closing talk.



Summary of Flavour Physics and Symmetry Session

- Recent Progress
  - B Factories (Belle and Barbar) have completed data taking and continue to provide wide range of interesting results, including CP violation and rare decays.
  - LHCb has demonstrated that precision flavour physics is possible at hadron collider
  - High-p_T experiments (CDF, D0, ATLAS, CMS) also doing excellent flavour physics
  - Detailed study made of CP violation and rare decays in B system (now including B_s)
  - NA62 is completing its preparation for precision kaon physics
  - MEG at PSI is improving a search for $\mu \to e\gamma$ at 2.4×10^{-12}
- Open Issues
  - No clear sign of physics beyond the Standard Model in flavour sector, and possible key measurements (a la G. Isidori) are as follows.
    - Φ_s, $|V_{ub}|$, CP angle gamma, B rare decays such as $B_s \to \mu\mu$ and $B \to \tau\nu$
    - CP violation in charm
    - K rare decays such as $K \to \pi\nu\nu$
    - Charged lepton flavor violation (CLFV) eg. $\mu \to e\gamma$, $\mu N \to eN$, $\mu \to eee$, $\tau \to \mu\gamma$, etc.
    - Muon g-2 and EDM (neutron, electron, muon, atom)
- Towards a Strategic Plan
  - Essential to maintain a diverse programme (B, D, K, charged leptons)
  - Flavour experiments typically on smaller scale than Higgs/neutrino, but crucial for search for/understanding of New Physics
  - LHCb and its upgrade form an important part of the exploitation of the LHC
  - An upgraded B Factory will give complementary physics coverage
  - CLFV (μ and τ) and EDM could provide a clean demonstration of new physics

From Roger Forty's slide in Tatsuya Nakada's closing talk.



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Flavour Physics

- Flavour physics will let us see beyond the energy frontier, be it through a desert...

Flavour Physics

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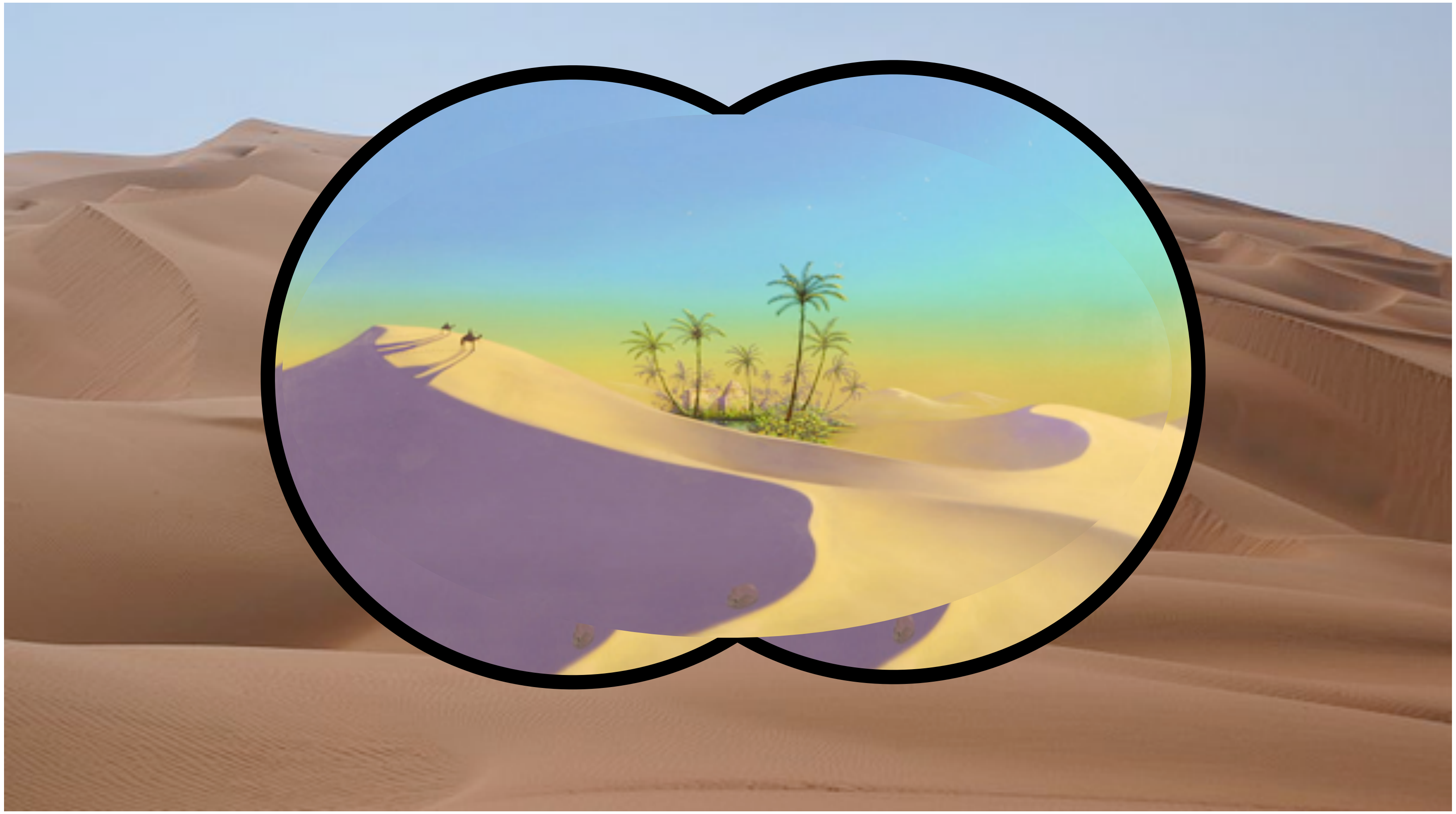
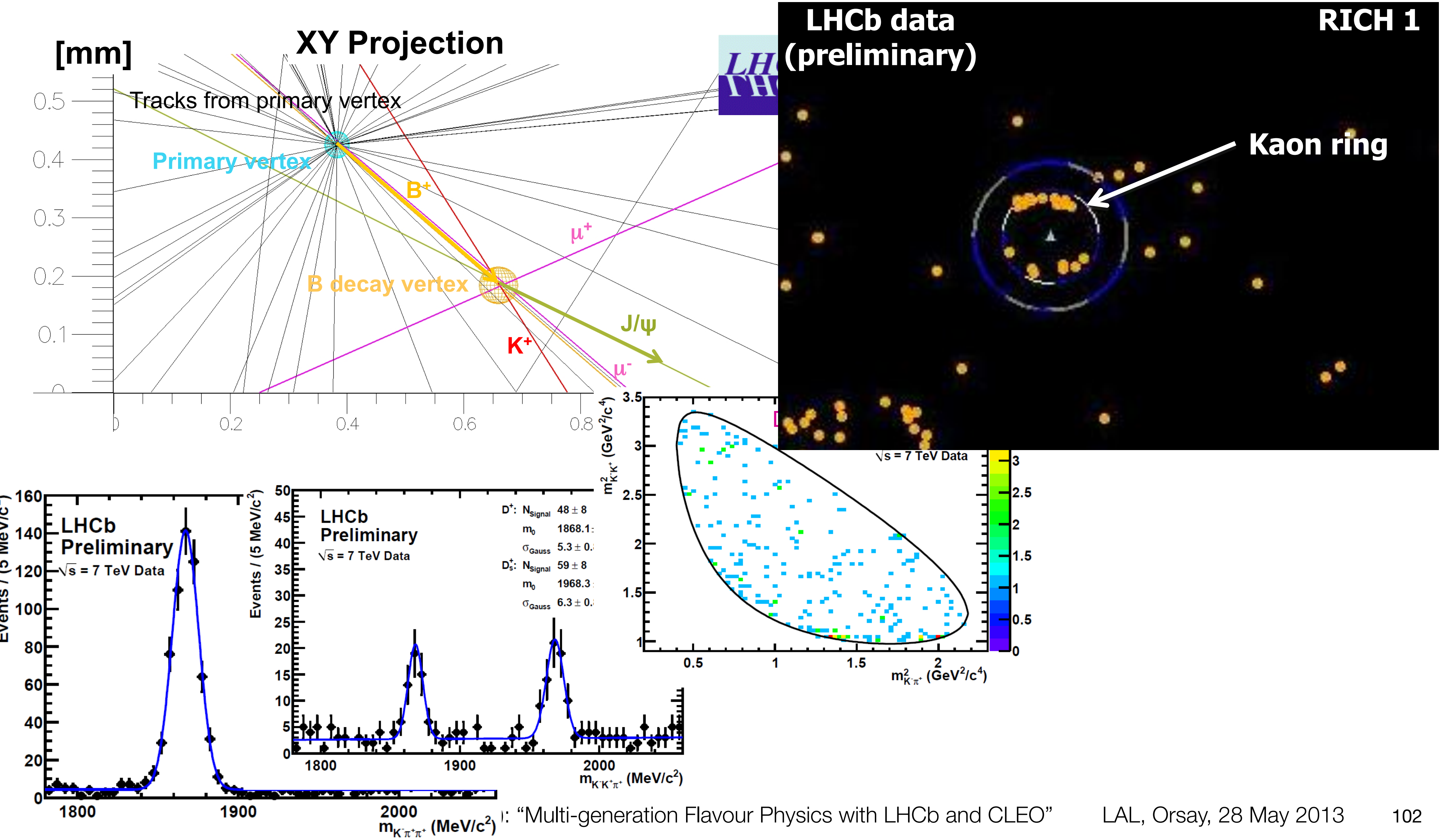


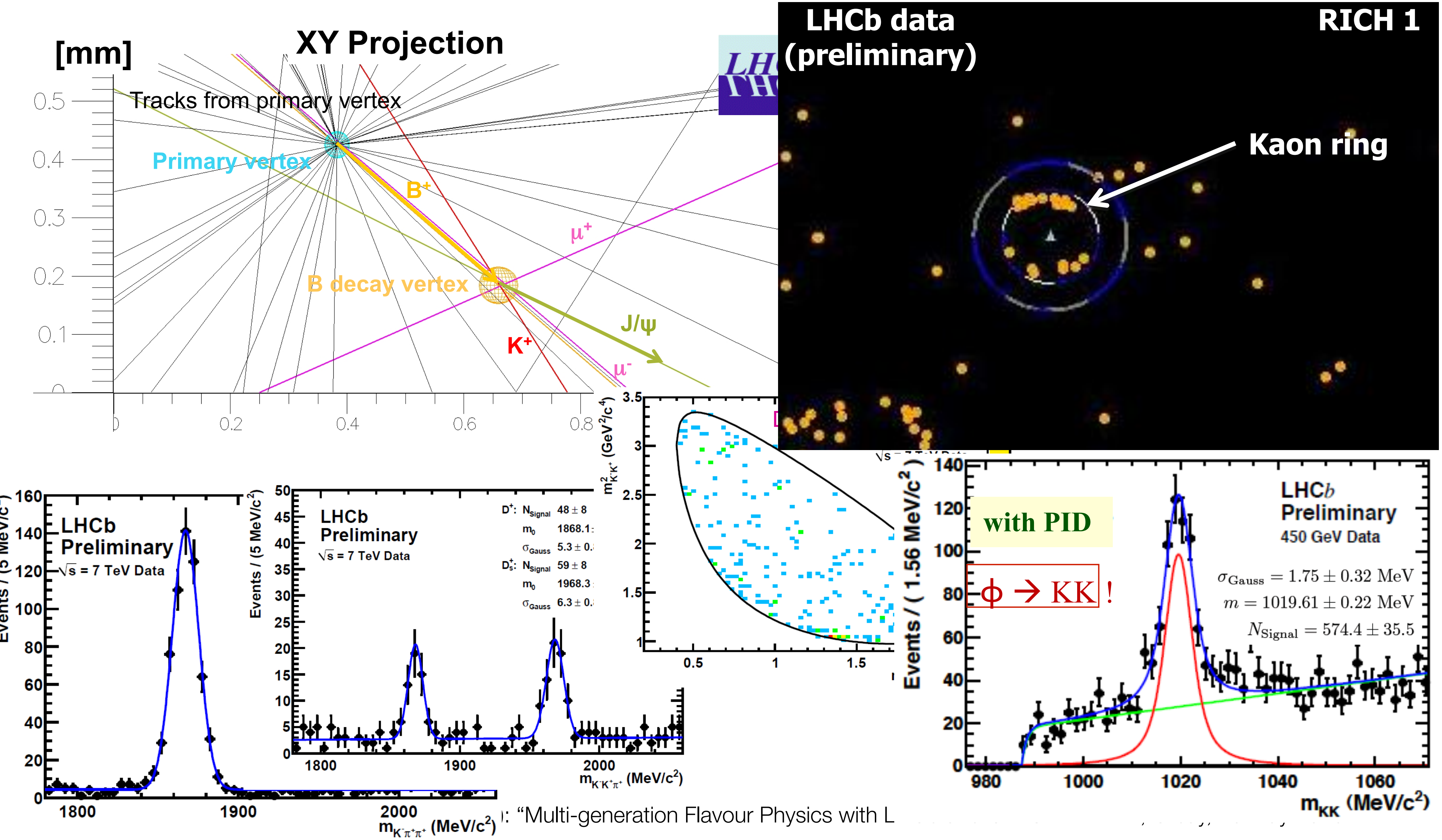
Or to bring clarity into a thicket of new discoveries

Or to bring clarity into a thicket of new discoveries

We have data!


XY Projection
[mm]
Tracks from primary vertex
Primary vertex
B decay vertex
B+
K+
J/ψ
μ+
μ-
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
LHCb data (preliminary)
RICH 1
Kaon ring
LHCb Preliminary
√s = 7 TeV Data
Events / (5 MeV/c2)
m K-π+π+ (MeV/c2)
1800
1900
2000
LHCb Preliminary
√s = 7 TeV Data
D+: N signal 48 ± 8
m0 1868.1
σ Gauss 5.3 ± 0.
Ds+: N signal 59 ± 8
m0 1968.3
σ Gauss 6.3 ± 0.
m K-K+π+ (MeV/c2)
m2 K-K+ (GeV2/c4)
m2 K-π+ (GeV2/c4)
√s = 7 TeV Data

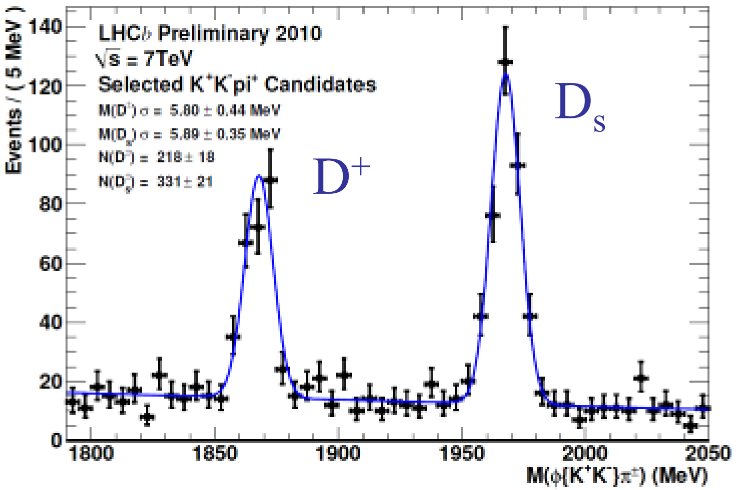
We have data!

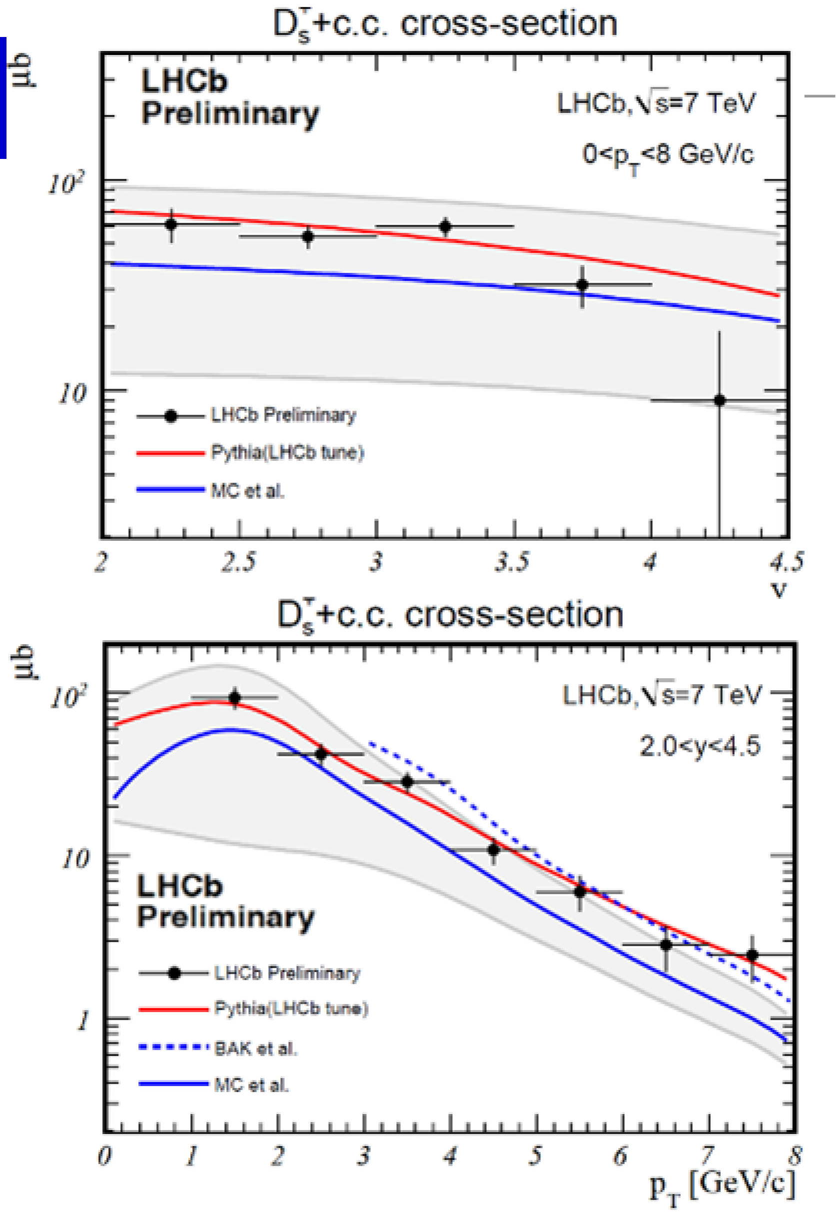

[mm]
XY Projection
Tracks from primary vertex
Primary vertex
B⁺
μ⁺
B decay vertex
J/ψ
K⁺
μ⁻
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
LHCb data
(preliminary)
RICH 1
Kaon ring
LHCb
Preliminary
√s = 7 TeV Data
Events / (5 MeV/c²)
160
140
120
100
80
60
40
20
0
1800
1900
2000
m_{K⁻π⁺π⁺} (MeV/c²)
LHCb
Preliminary
√s = 7 TeV Data
D⁺: N_Signal 48 ± 8
m₀ 1868.1
σ_Gauss 5.3 ± 0.
D_s⁺: N_Signal 59 ± 8
m₀ 1968.3
σ_Gauss 6.3 ± 0.
Events / (5 MeV/c²)
50
45
40
35
30
25
20
15
10
5
0
1800
1900
2000
m_{K⁻K⁺π⁺} (MeV/c²)
m²_{K⁻K⁺} (GeV²/c⁴)
3.5
3
2.5
2
1.5
1
0.5
1
1.5
with PID
φ → KK !
LHCb
Preliminary
450 GeV Data
σ_Gauss = 1.75 ± 0.32 MeV
m = 1019.61 ± 0.22 MeV
N_Signal = 574.4 ± 35.5
Events / (1.56 MeV/c²)
140
120
100
80
60
40
20
0
980
1000
1020
1040
1060
m_KK (MeV/c²)

Dessert

~ 2/nb

D_s



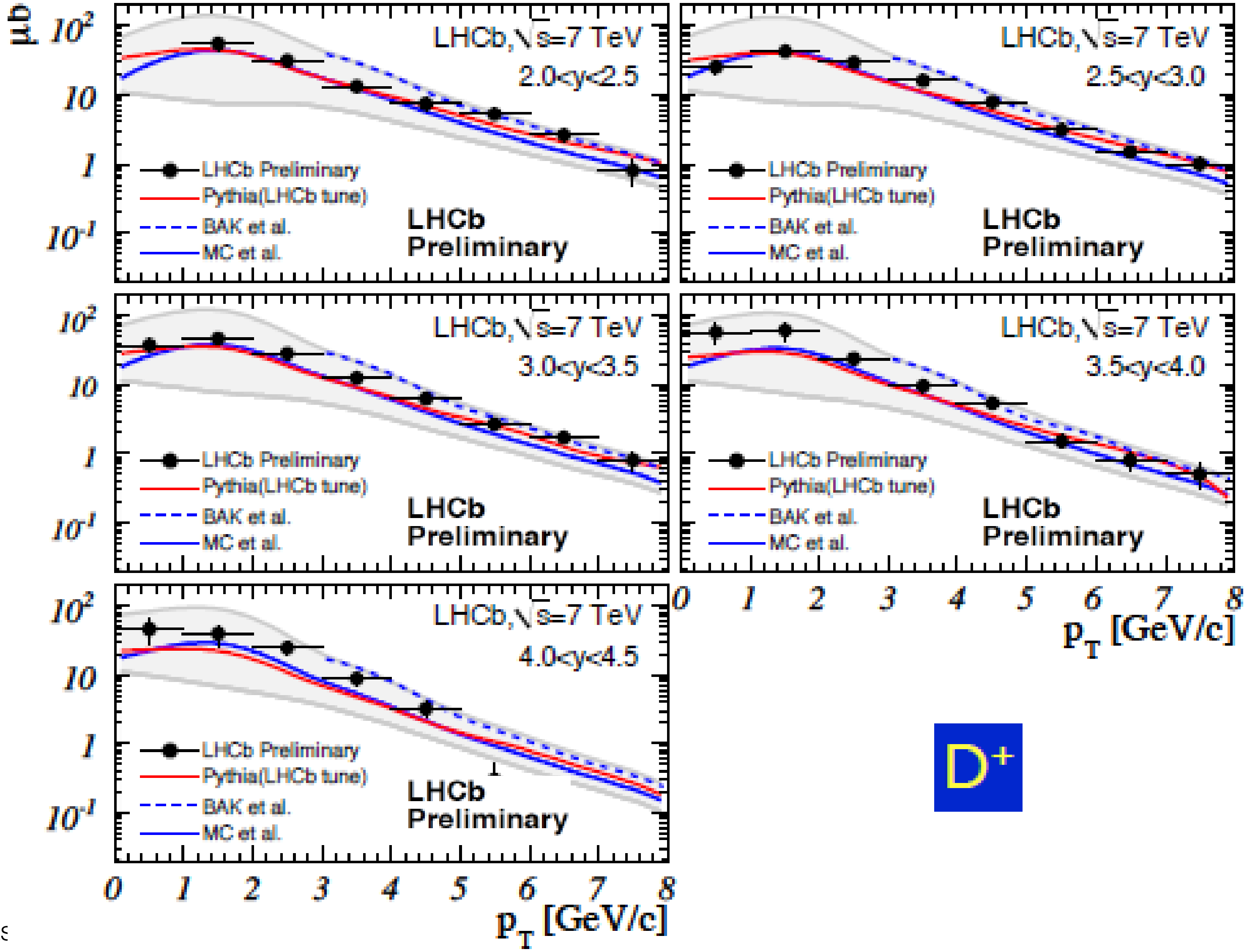


Theory:

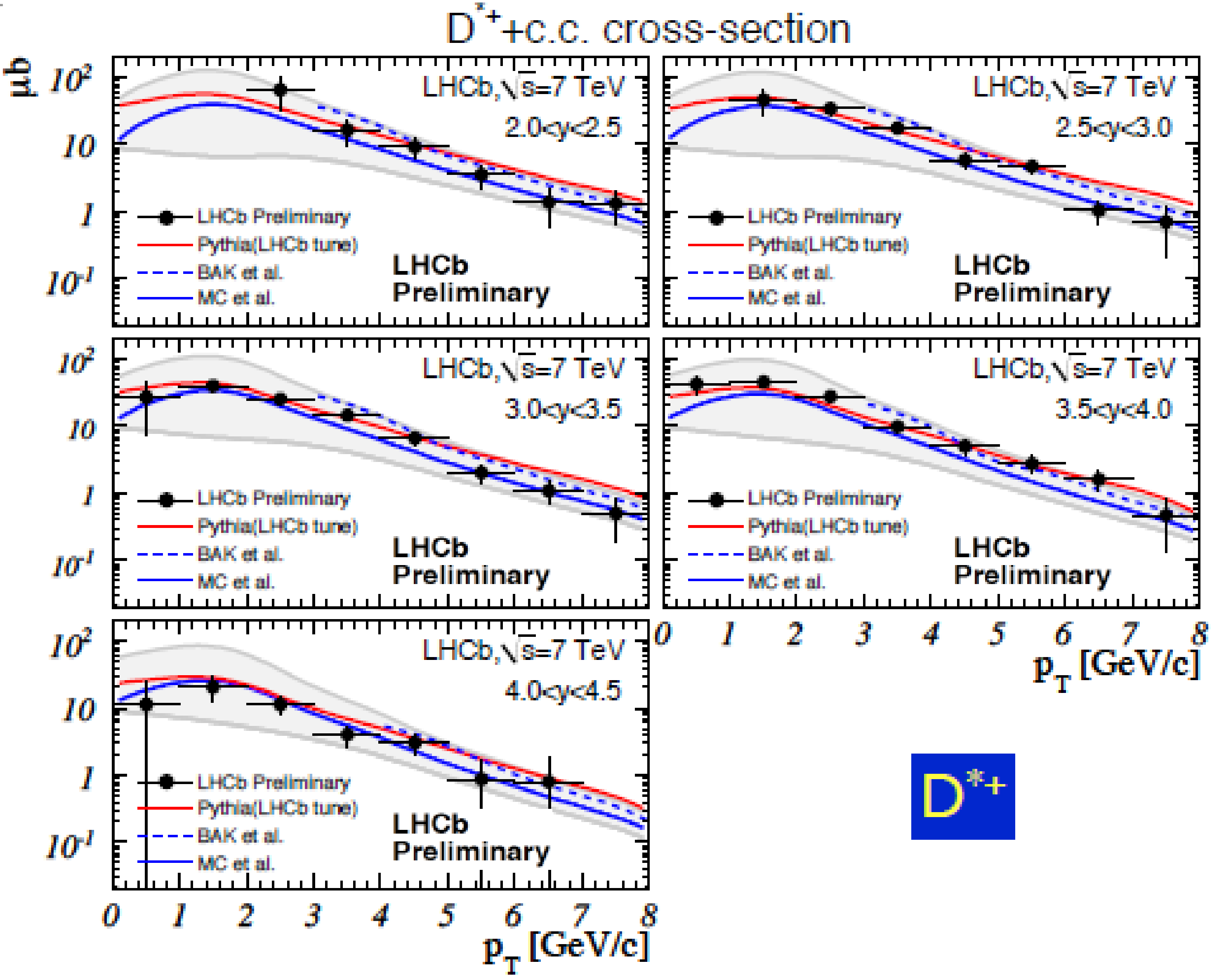
MC - Cacciary M., Frixione, S., Mangano, M., Nason, P. Ridolfi, G.

BAK - B.A.Kniehl, G.Kramer, I.Scheinbein, H.Spiesberger

D^++c.c. cross-section



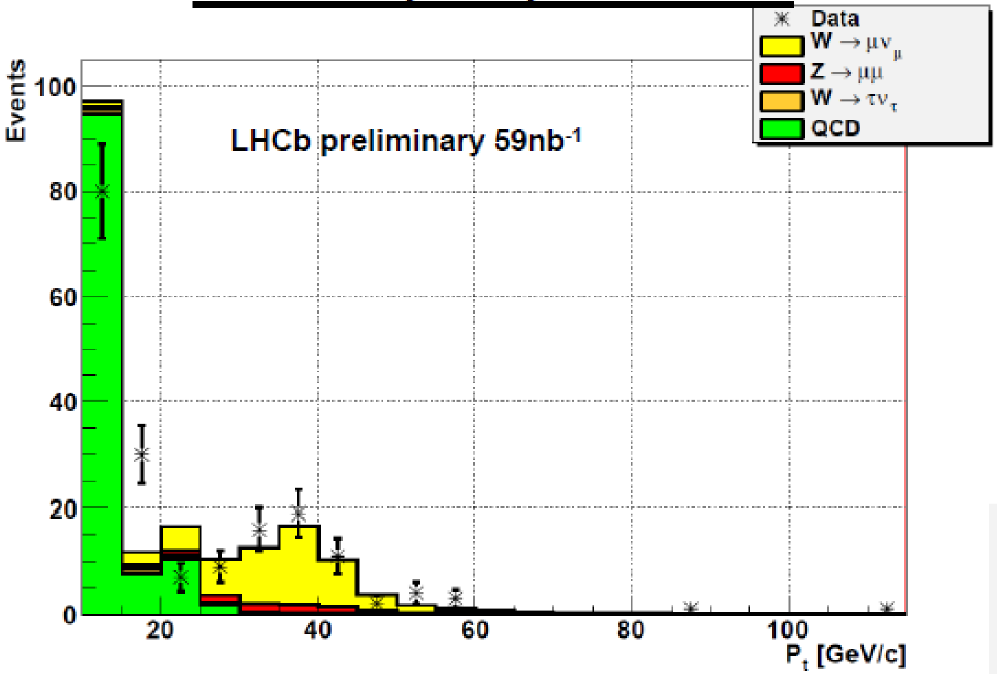
D^+

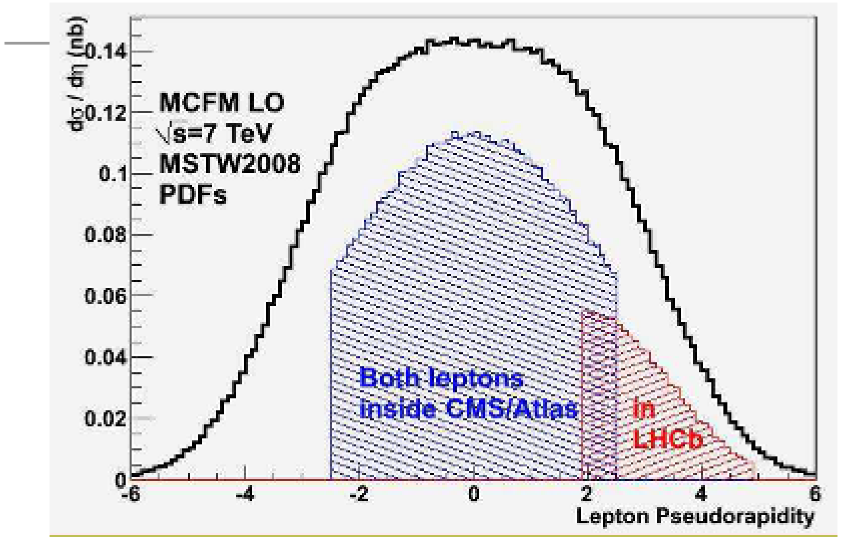

D*+c.c. cross-section
μb
10²
10
1
10⁻¹
LHCb,√s=7 TeV
2.0<y<2.5
2.5<y<3.0
3.0<y<3.5
3.5<y<4.0
4.0<y<4.5
LHCb Preliminary
Pythia(LHCb tune)
BAK et al.
MC et al.
LHCb
Preliminary
0 1 2 3 4 5 6 7 8
pT [GeV/c]

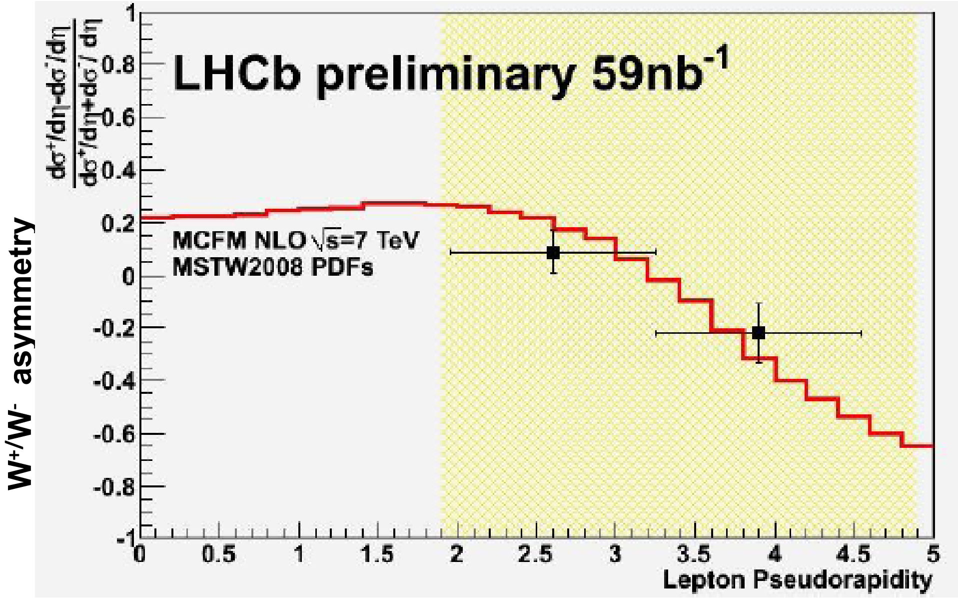
D^{*+}

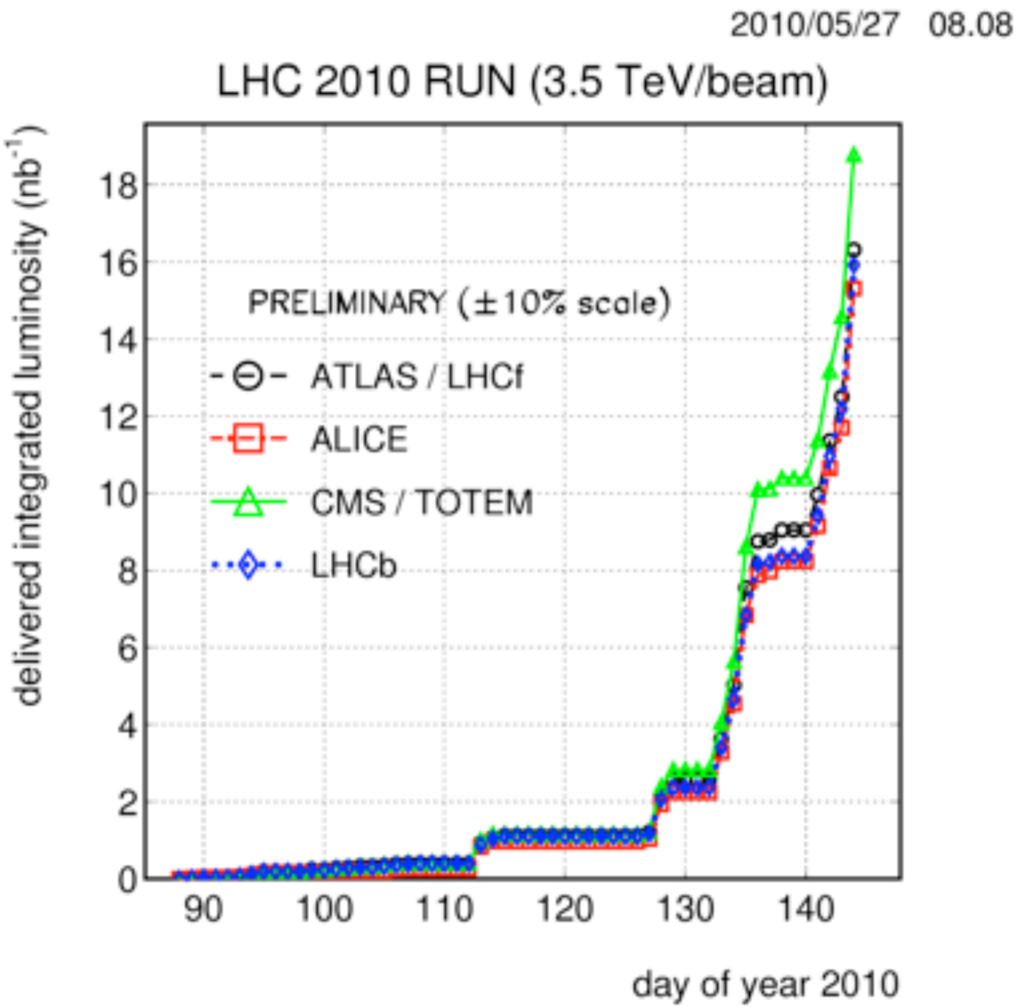
Charge asymmetry in $W^{\pm} \rightarrow \mu^{\pm}\nu$ events

Muon pt spectrum

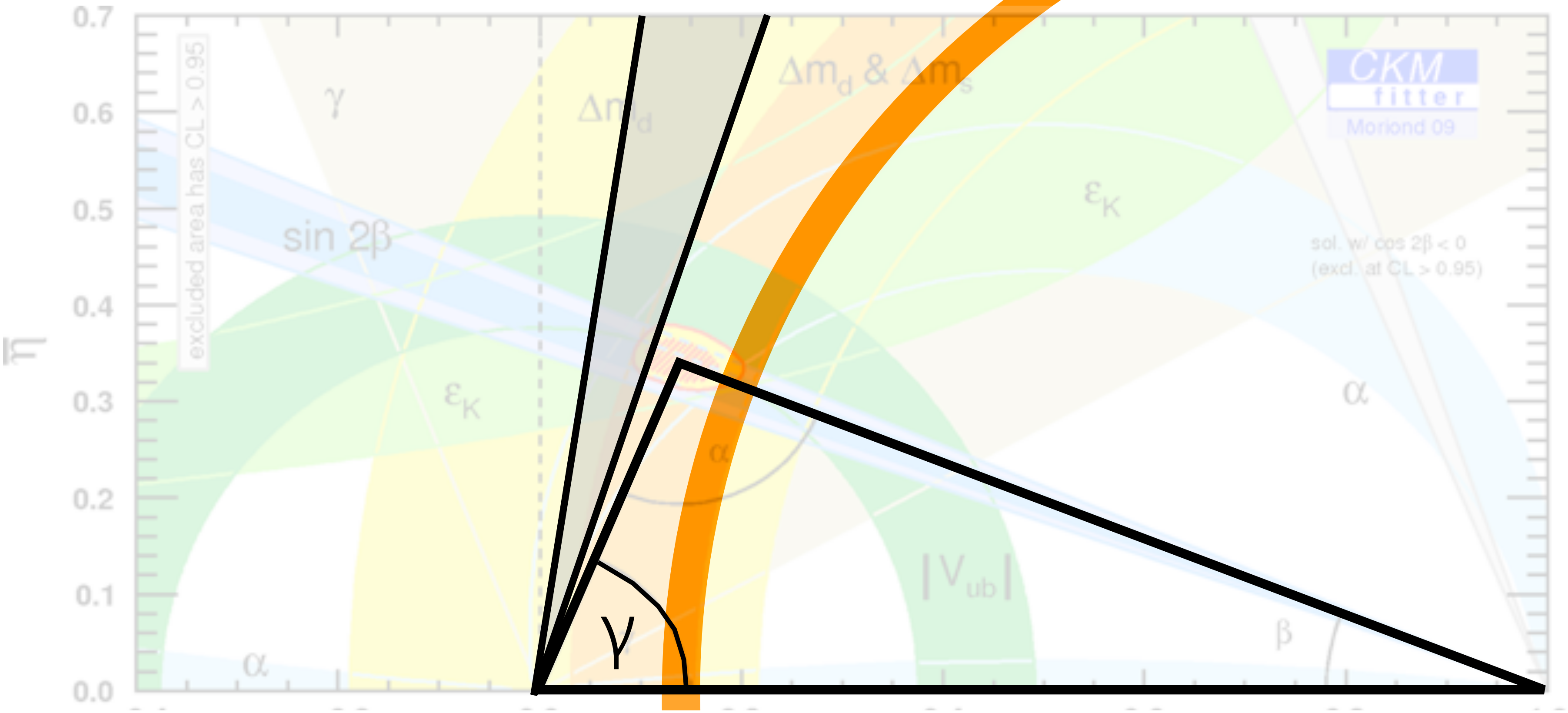






2010/05/27 08.08
LHC 2010 RUN (3.5 TeV/beam)
delivered integrated luminosity (nb^{-1})
PRELIMINARY (±10% scale)
ATLAS / LHCf
ALICE
CMS / TOTEM
LHCb
0
2
4
6
8
10
12
14
16
18
90
100
110
120
130
140
day of year 2010

γ and Δm projections for 2015

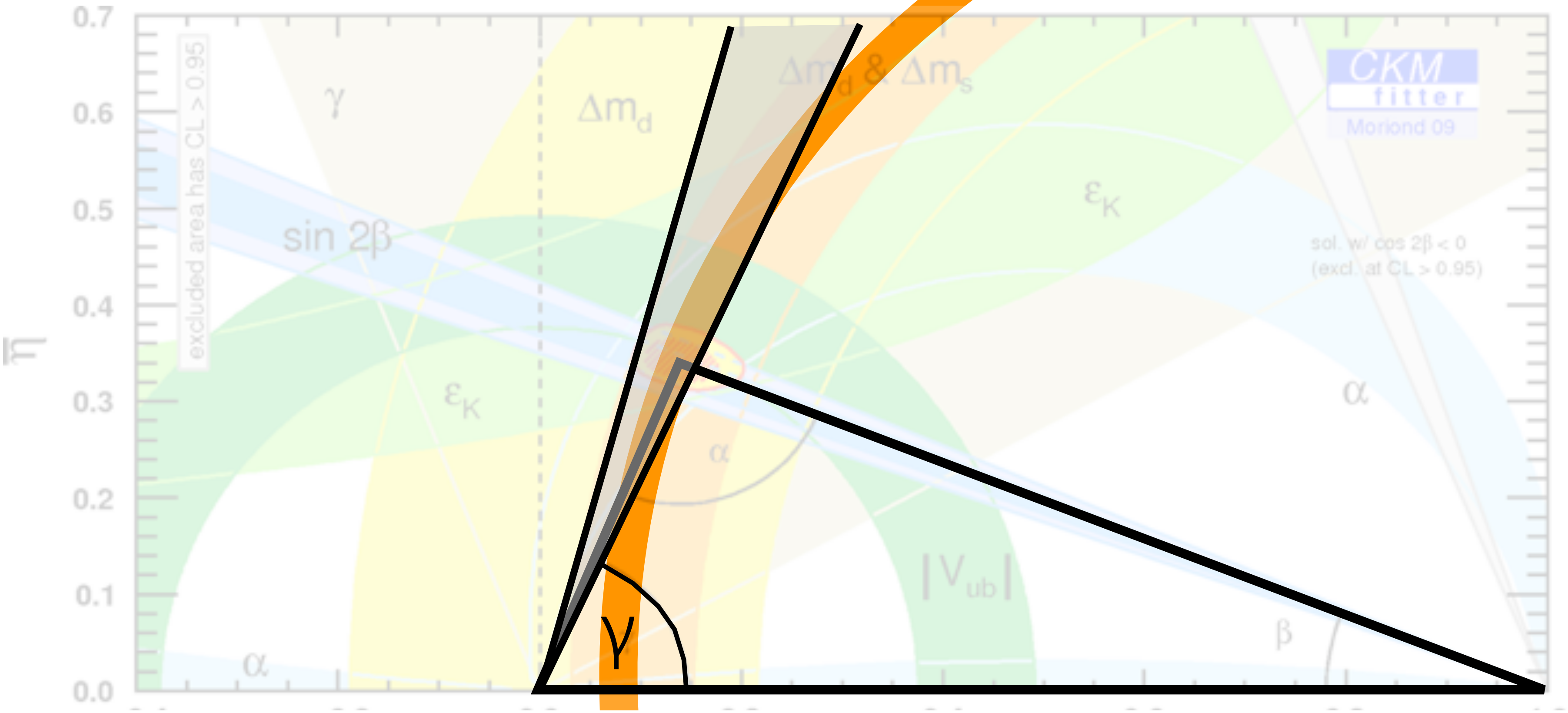


LHCb, 10fb^{-1} (ca 2015): σ_γ(direct, tree) ≈ 2°-3°

σ_γ(from side, loop) ≈ 1°-2°

γ and Δm projections for 2015

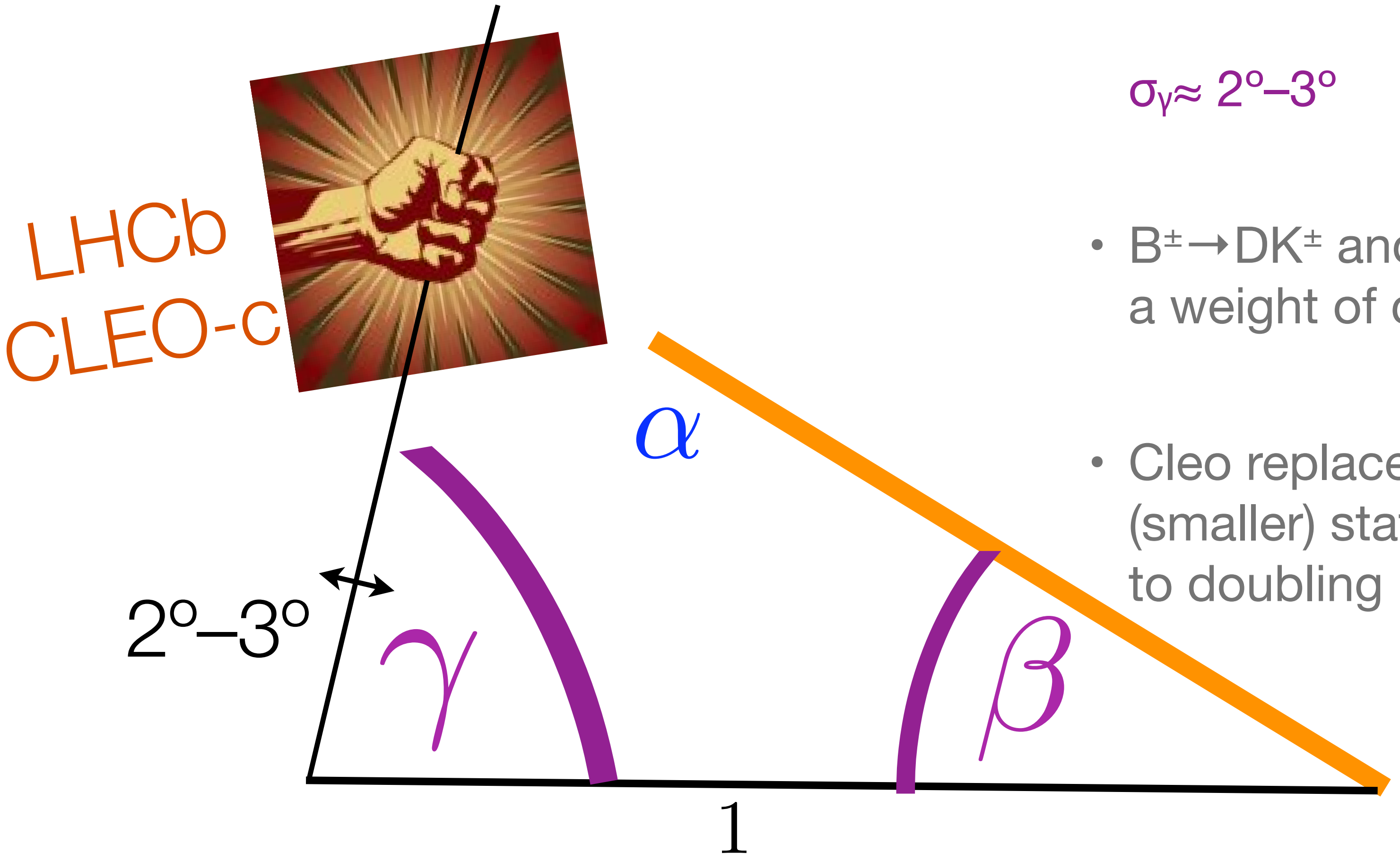
Or, if we are unlucky



LHCb, 10fb^{-1} (ca 2015): σ_γ(direct, tree) ≈ 2°-3°

σ_γ(from side, loop) ≈ 1°-2°

LHCb & CLEO-c & γ



- Combining tree-level γ modes, LHCb expects with 10/fb (5 years):

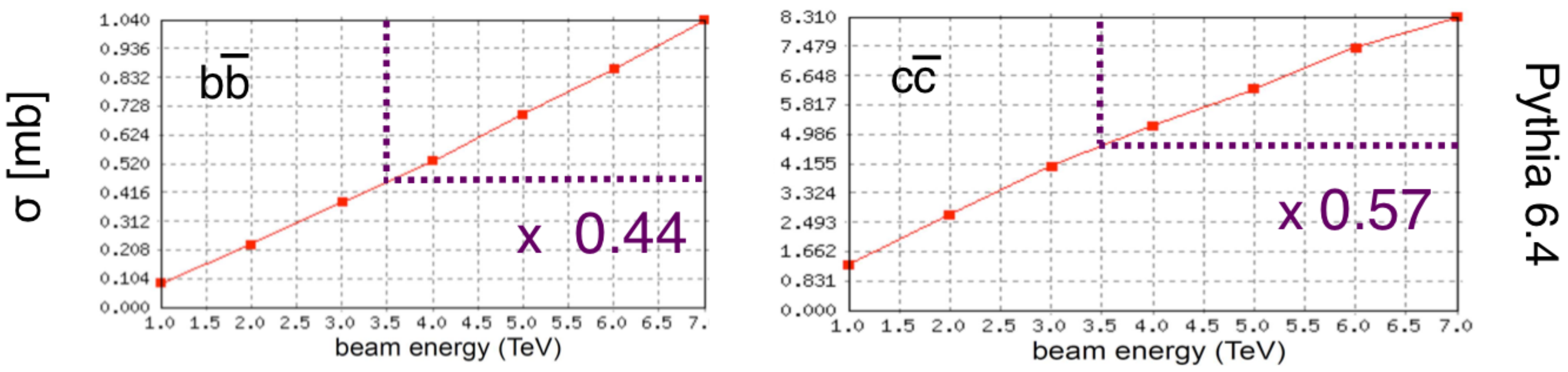
$\sigma_\gamma \approx 2^\circ$–$3^\circ$

- $B^\pm \rightarrow DK^\pm$ and $B^0 \rightarrow DK^{*0}$ modes have a weight of ca 70% in that result.
- Cleo replaces systematic with (smaller) statistical error. Equivalent to doubling LHCb's statistics.

2010-11 Data Taking

Assumed conditions in MC studies pre-2010			
$\sqrt{s}$	σ_{bb}	$\mathcal{L}$	1 year integrated luminosity
14 TeV	500 μb	2×10^{32} cm^{-2}s^{-1}	2 fb^{-1}

Mainwork about LHCb key measurements **(arXiv:0912.4179v2 [hep-ex])**



2010 expected conditions			
$\sqrt{s}$	σ_{bb}	σ_{cc}	$\mathcal{L}$
7 TeV	500 μb	4.7 mb	< 2×10^{31} cm^{-2}s^{-1}

- Some loss in signal yield due to $\sqrt{s}$=7 TeV
- Release of trigger thresholds
- $\varepsilon_{trig}^{charm}$ ~ 40-50%
- Expected **0.1 fb^{-1}** of integrated luminosity

2011 expected conditions			
$\sqrt{s}$	σ_{bb}	σ_{cc}	$\mathcal{L}$
7 TeV	500 μb	4.7 mb	~10^{32} cm^{-2}s^{-1}

- $\mathcal{L}$ close to design value
- $\varepsilon_{trig}^{charm}$ ~ 10%
- ε_{trig}^{B} ~ 75-80%
- $\varepsilon_{trig}^{B\to\mu X}$ > 90%
- Expected **1 fb^{-1}** of integrated luminosity