Theory concluding talk

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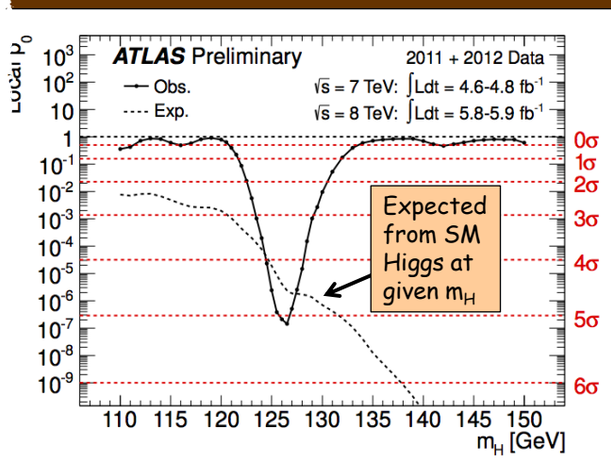
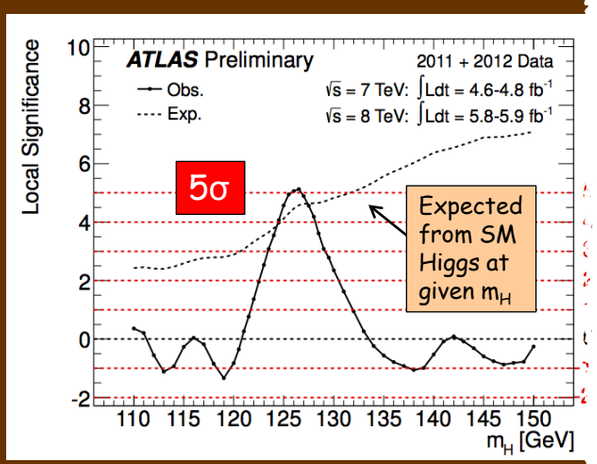
Casa de Zafra, Granada

Higgs Hunting, July 2019

The beginning of a new era

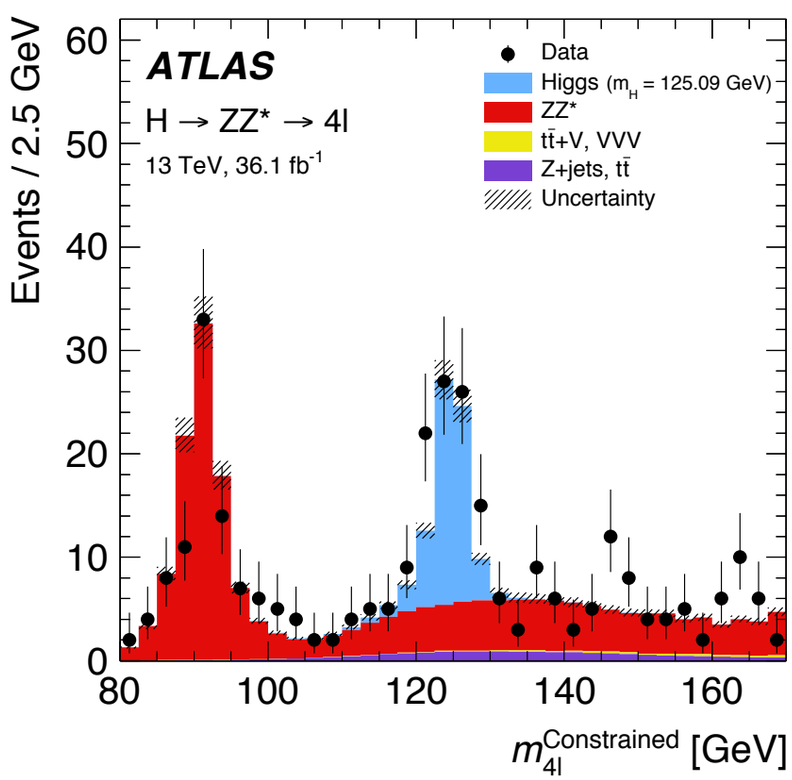
Combined results: the excess

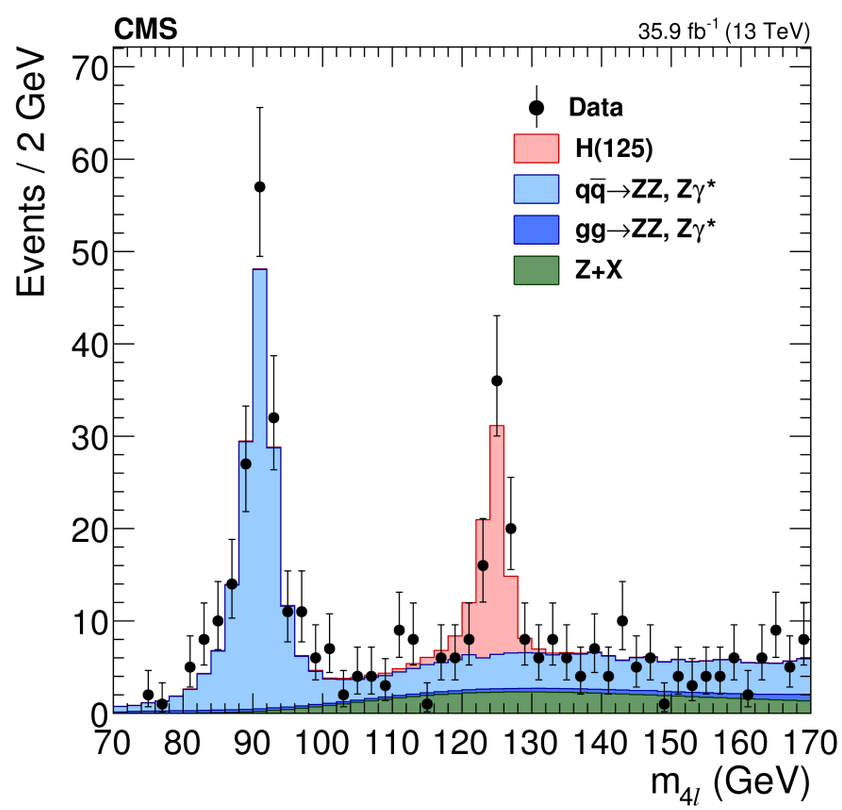




Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

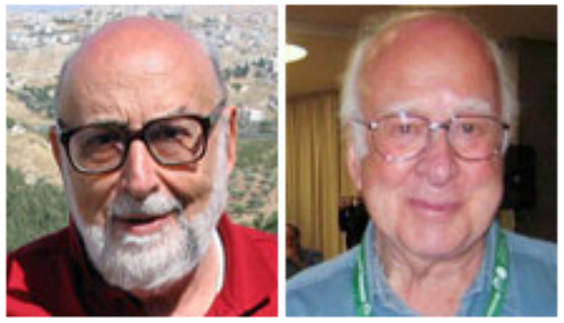
4th July 2012


ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb-1
Data
Higgs (mH = 125.09 GeV)
ZZ*
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
Events / 2.5 GeV
m4l Constrained [GeV]


CMS
35.9 fb-1 (13 TeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
Events / 2 GeV
m4l (GeV)

2013 NOBEL PRIZE IN PHYSICS

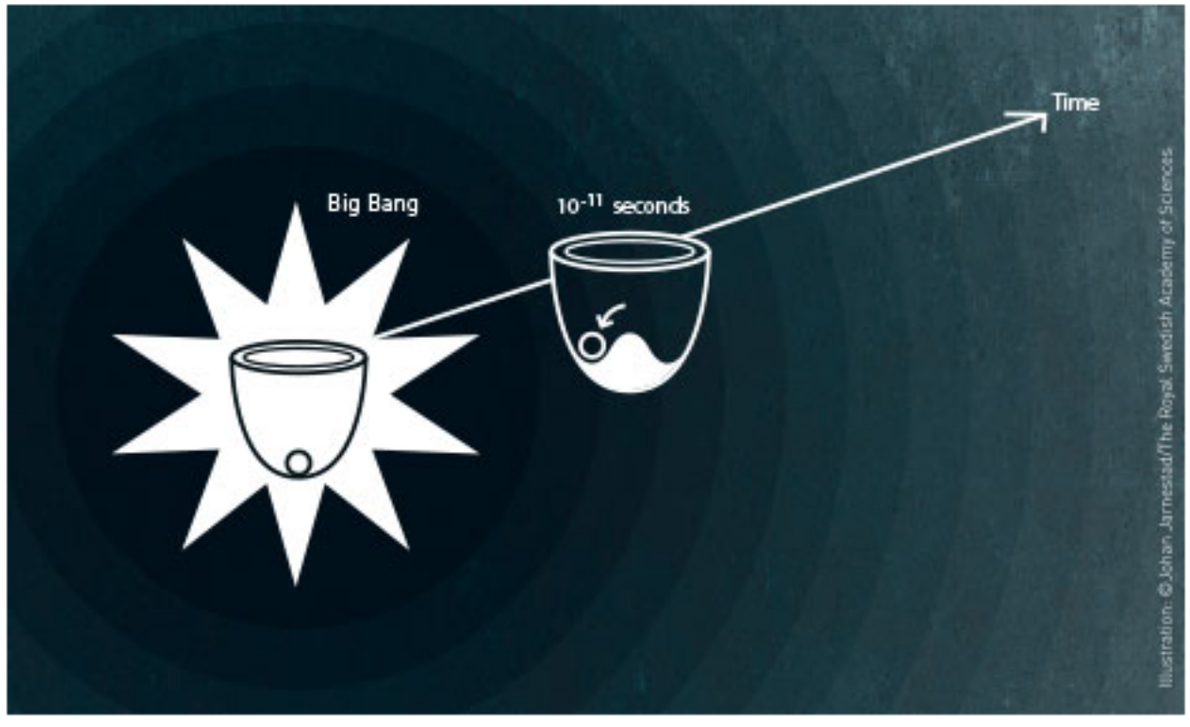
François Englert
Peter W. Higgs



F. Englert and P. Higgs
Photo: Wikimedia Commons

2013 Nobel Prize in Physics

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our*



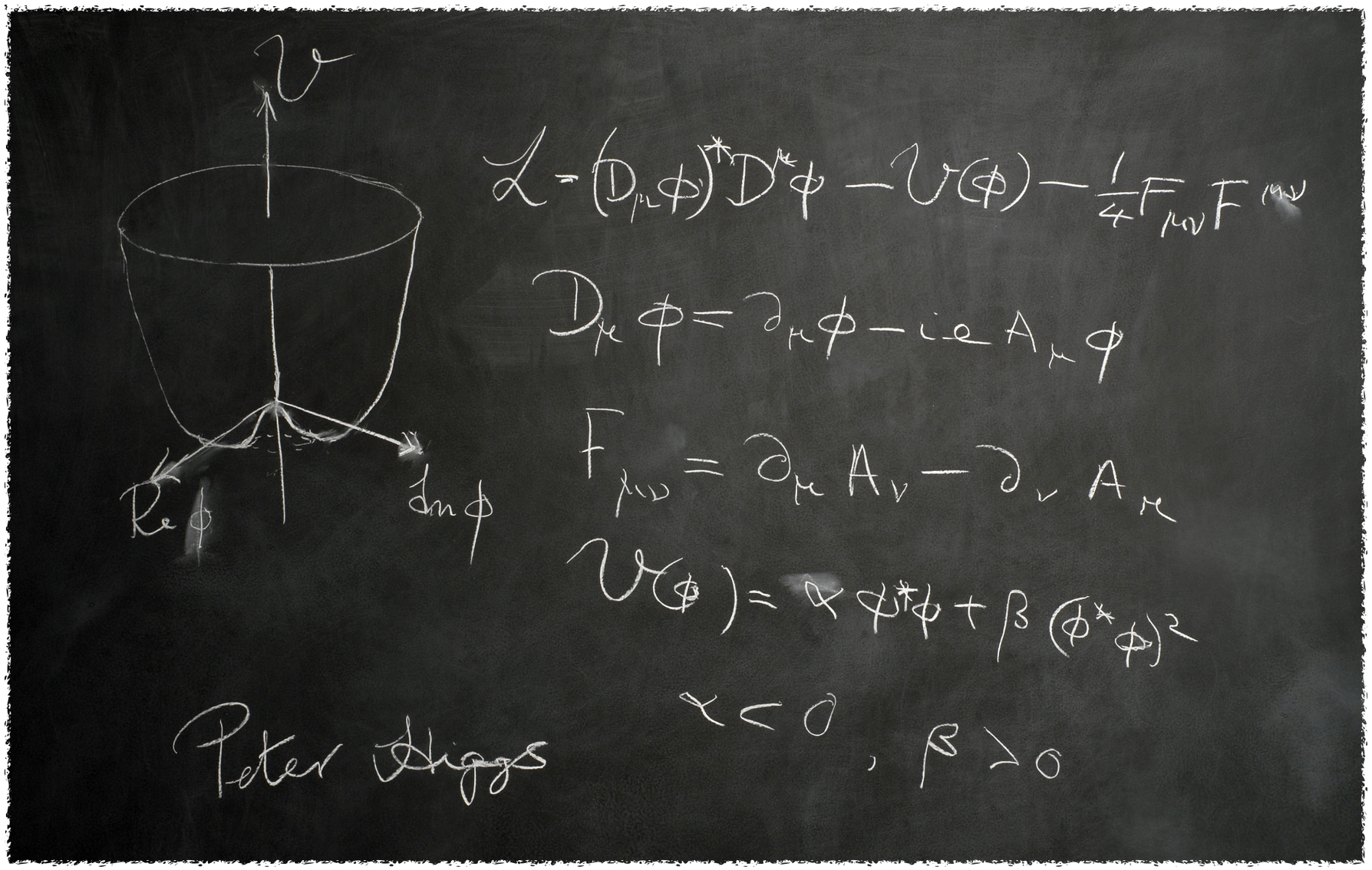
What Happened after the Big Bang?

Announcements of the 2013 Nobel Prizes

Physiology or Medicine:
Announced Monday 7 October
Physics:
Tuesday 8 October, 11:45 a.m. CET at the earliest
Chemistry:
Wednesday 9 October, 11:45 a.m. CET at the earliest
Literature:
Thursday 10 October 1.00 p.m. CET
Peace:

The conception: 1964

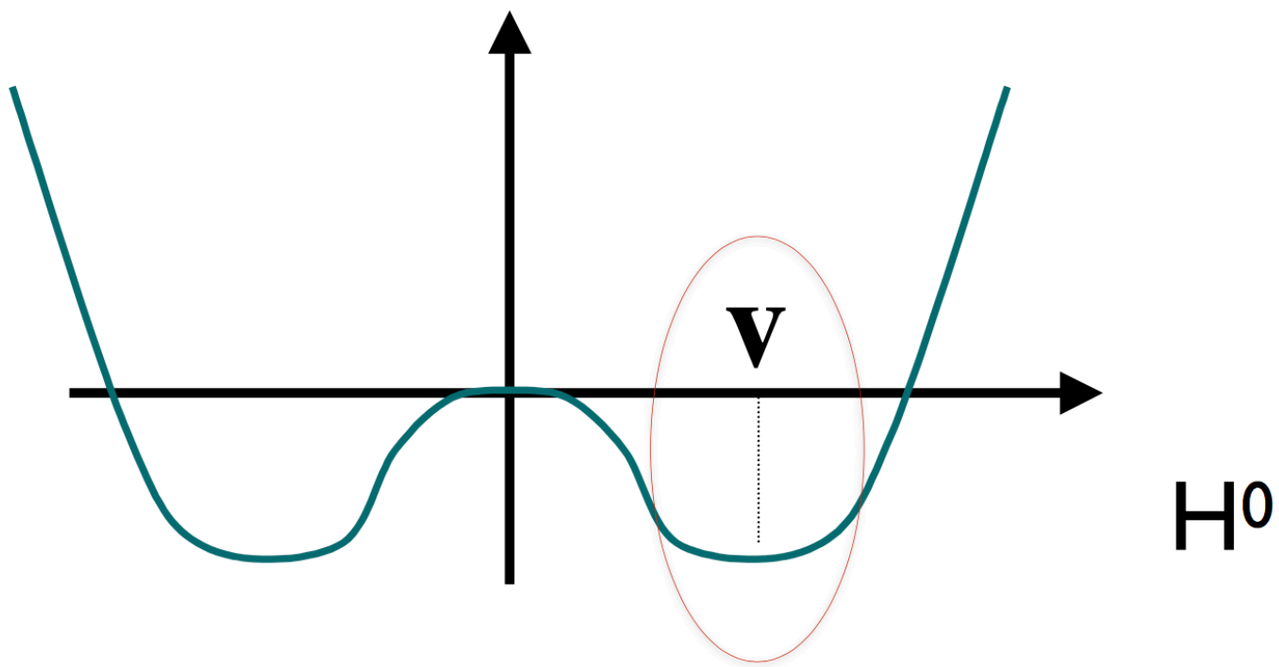
Electroweak symmetry breaking



With the Higgs particle present, all unwanted infinities disappeared …

☛ talk by t'Hooft

The Higgs potential

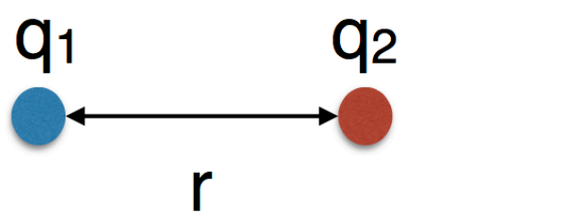


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

☛ talk by Mangano

The Higgs potential

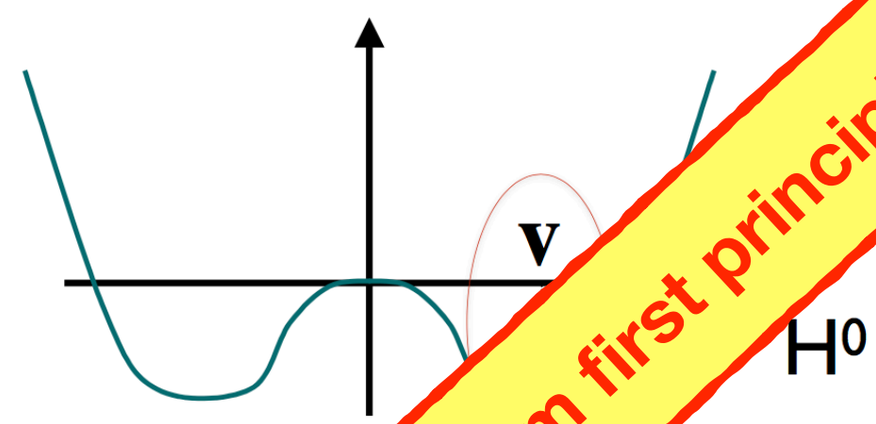


quantized, in units of fixed charge

$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem



Does not follow from first principles!

$$) = -\mu^2 |H|^2 + \lambda |H|^4$$

☛ talk by Mangano

The Higgs mechanism

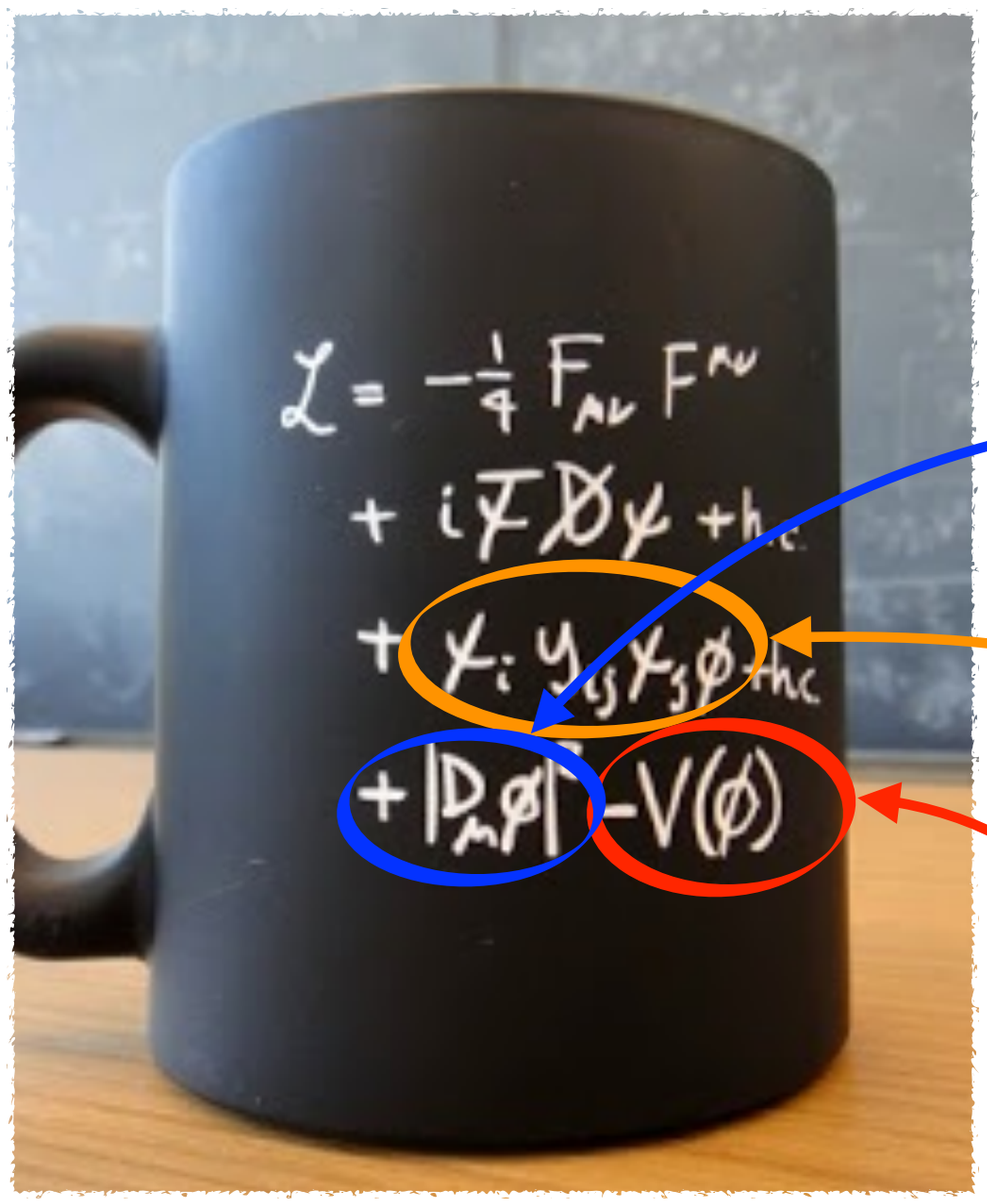
- The wonder: the Higgs discovery confirmed the mechanism of spontaneous symmetry breaking postulated by Brout, Englert and Higgs almost fifty years before

- The beauty of this discovery is that the underlying idea (and mathematics) is incredibly simple

- The power of the idea: the Higgs mass fixes everything in the Standard Model

The Higgs is special

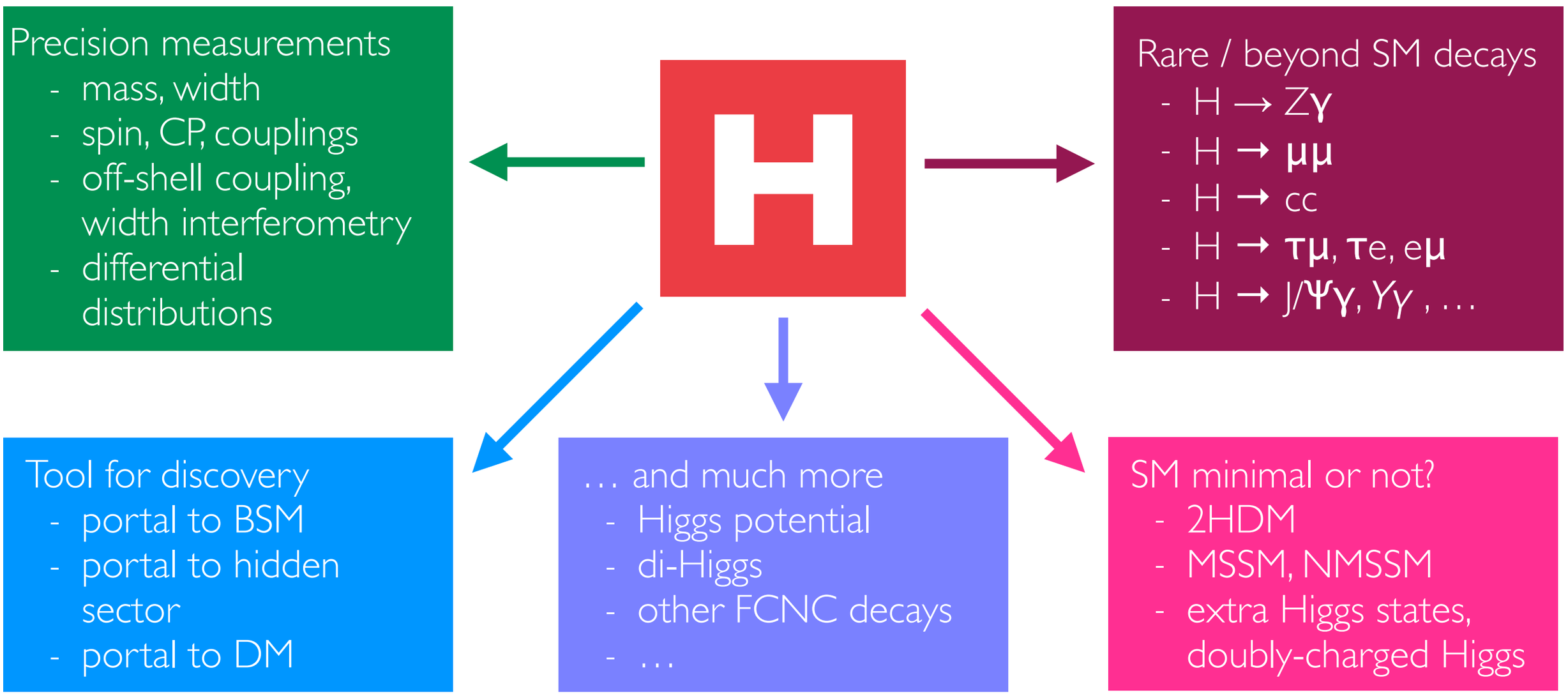
It is the only fundamental scalar with spin 0 we have seen so far



Discovery allows to access a new sector in the Lagrangian:

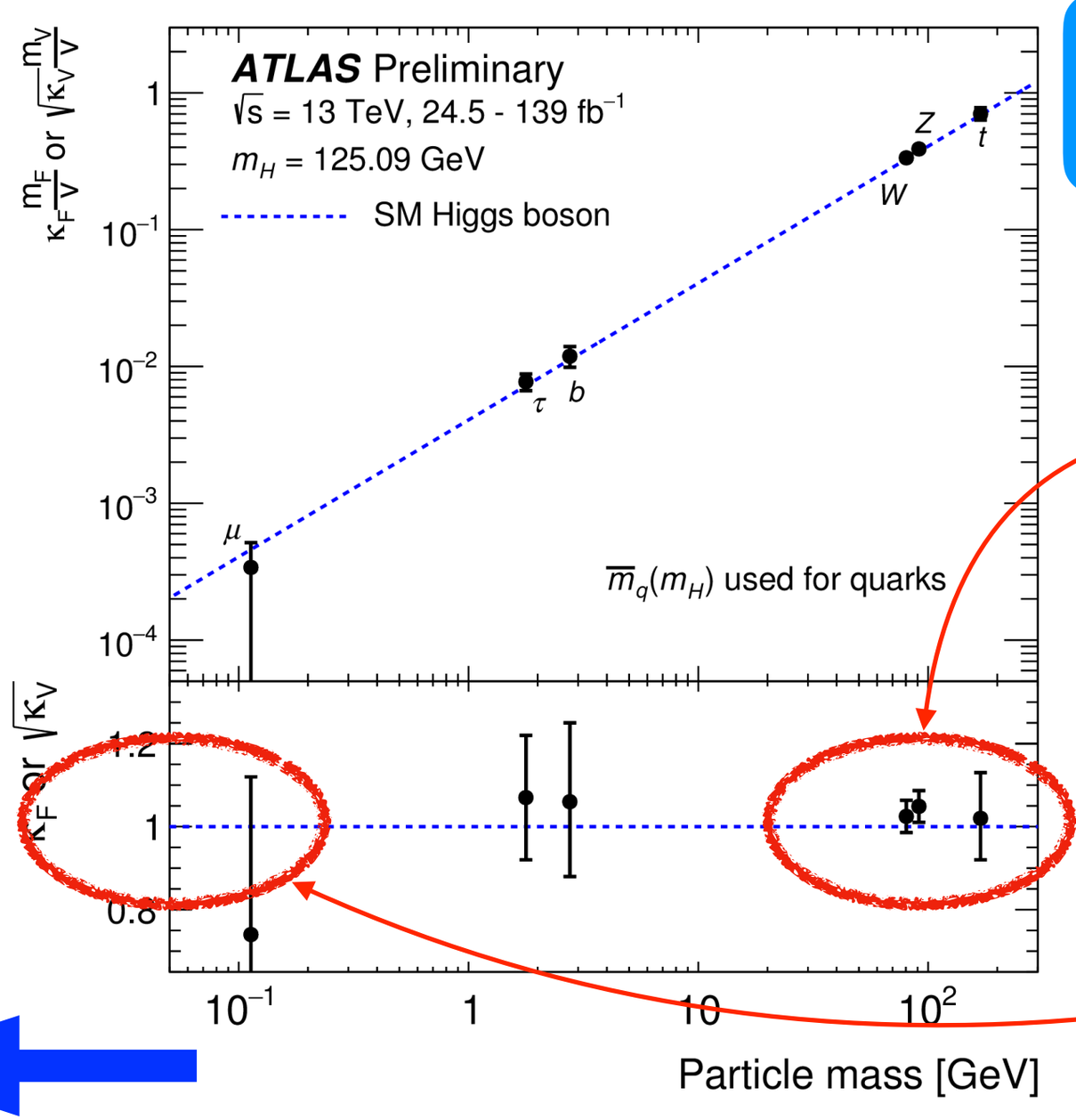
- Scalar-Gauge boson interactions
- Yukawa couplings (new type of interaction)
- Higgs potential: cornerstone of BEH mechanism, not yet probed experimentally

An incredibly rich program



After ten years of Higgs Hunting

Higgs couplings



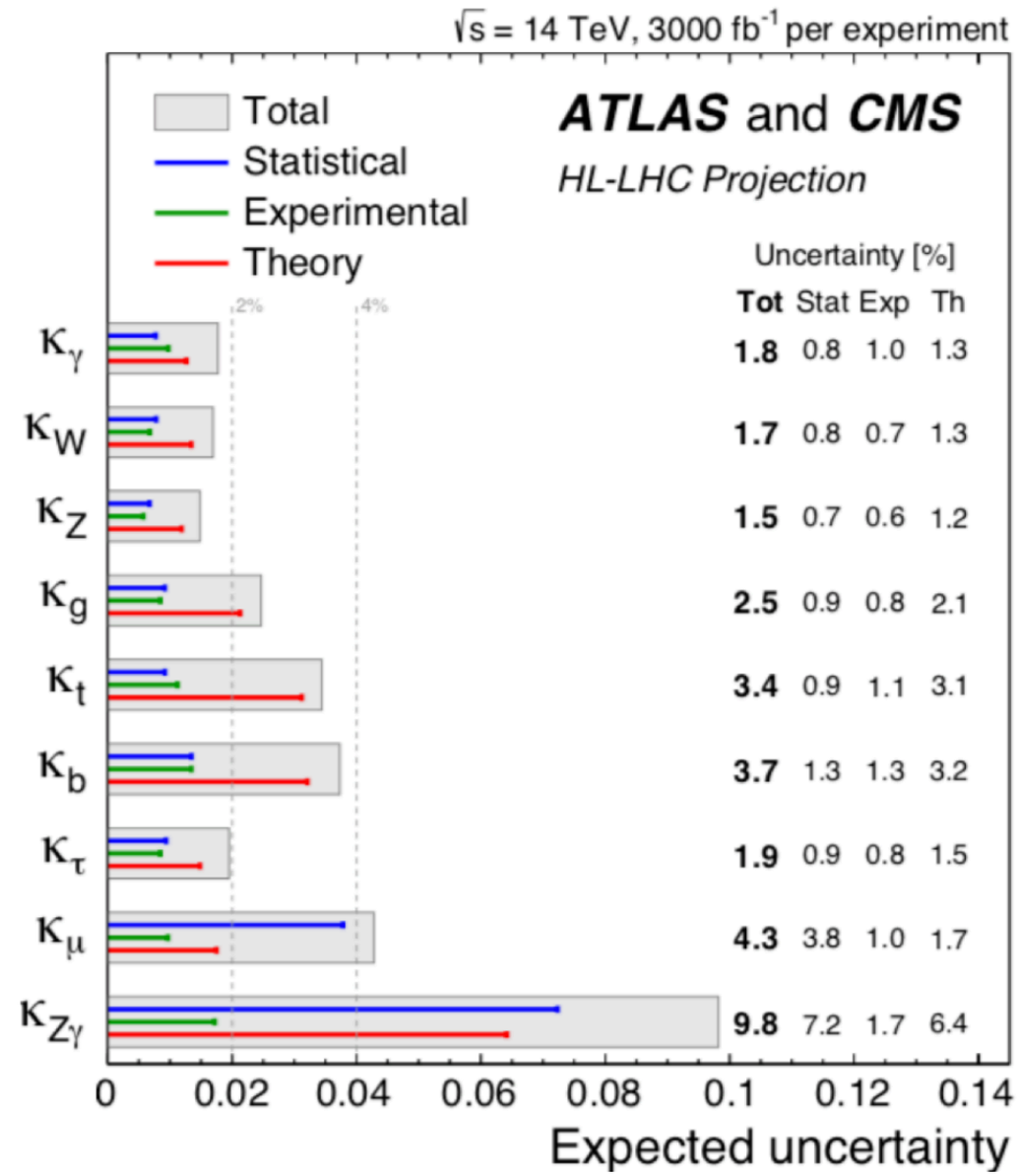
Footprint of SM Higgs: mass versus coupling correlation

SM predictions for the couplings of heavier particles (gauge bosons, 3rd generation fermions) tested to about 10%

No stringent tests for lighter particles yet (1st and 2nd generation fermions)

Electron, light quarks, neutrinos

Largest contribution from theory

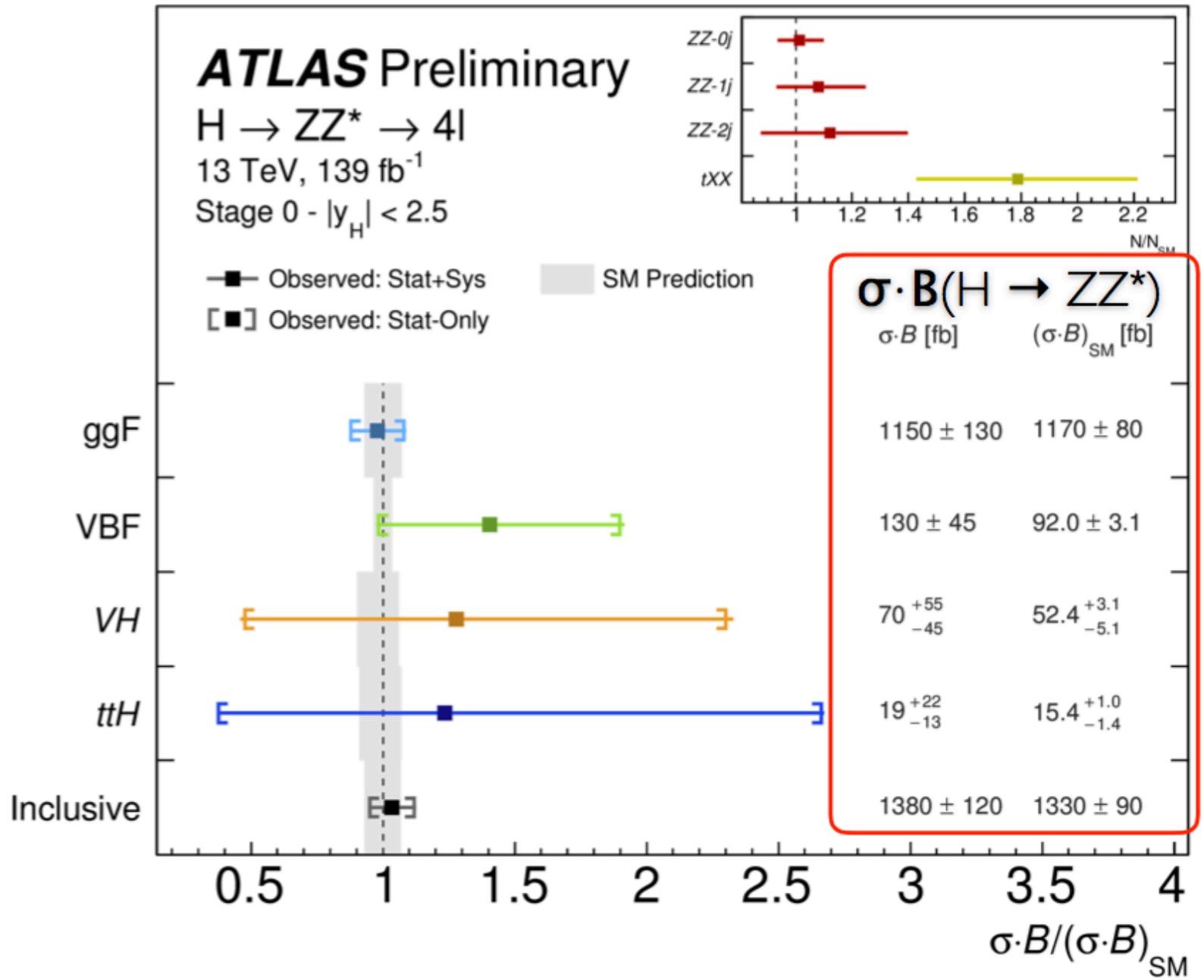


Given the detailed projections from the experiments substantial further progress will be needed from theory calculations if these are not to become a limiting factor in interpreting a wide range of High-Luminosity LHC (HL-LHC) data

ggF Higgs

Looking at the present:

- $H \rightarrow ZZ^* \rightarrow 4\ell$
  - Still statistics limited with 140 fb^{-1}
  - ggF measurement precision reaches precision of SM prediction



☛ talk by Köneke

ggf Higgs at N^{3}LO

σ	δ(PDF)	$\delta(\alpha_s)$	δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(tbc)$	$\delta(1/m_t)$	
48.58	± 0.90	$^{+1.27}_{-1.25}$	$^{+0.10}_{-1.15}$	± 0.18	± 0.56	± 0.49	± 0.40	± 0.49	pb
	± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	± 1	%

☛ progress: talks by Caola, Furlan

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)(\text{PDF} + \alpha_s)$$

(+2%)
(-3%)

If theory errors combined quadratically

Dominant uncertainties (PDF & α_s) will be reduced by new data and new input from lattice for α_s (PDG error on α_s already reduced from 0.015 to 0.011)

⇒ A reduction of the uncertainty by a factor 2 seems realistic

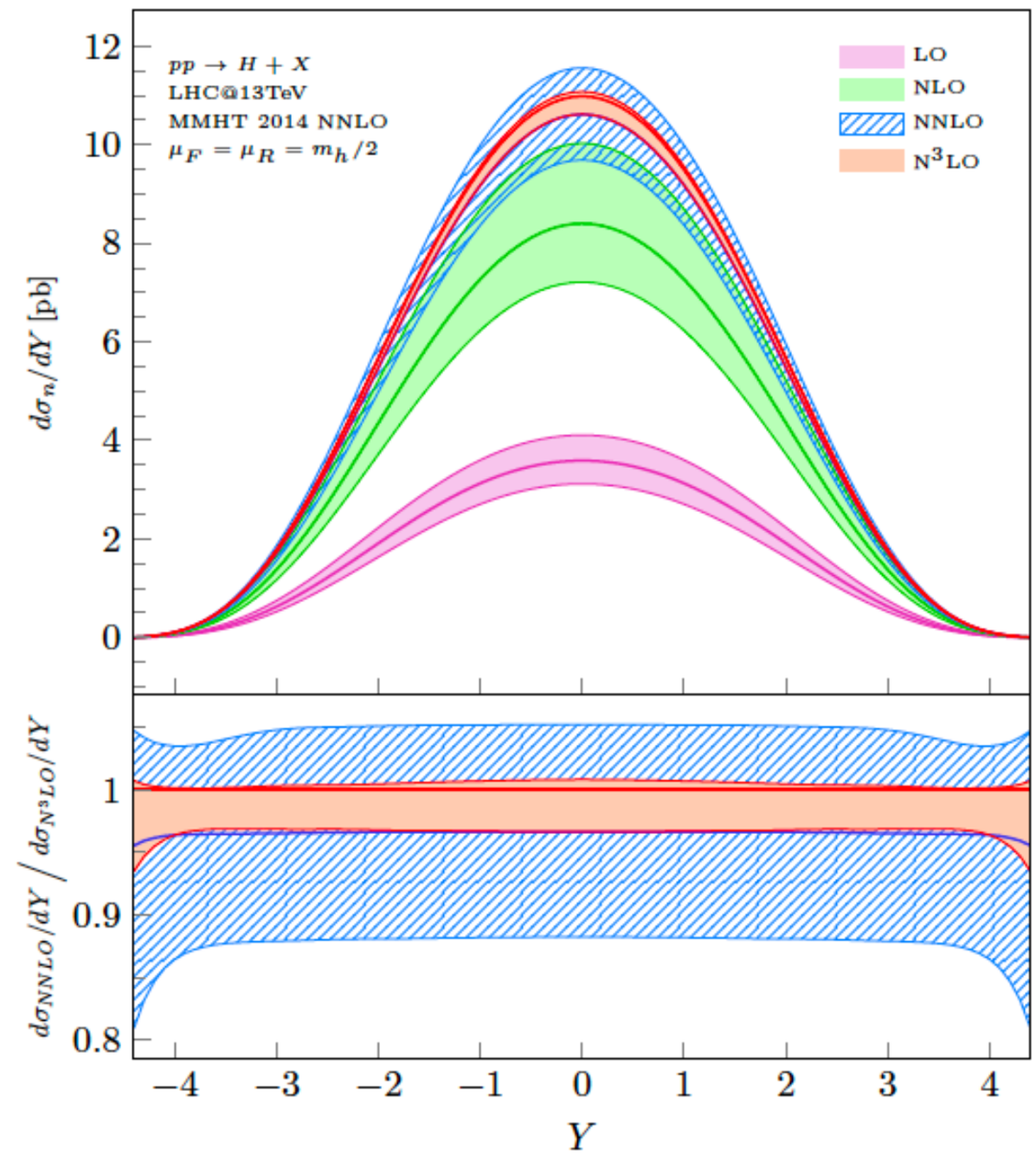
Rapidity at N³LO

New at N³LO:

Higgs rapidity (using a threshold expansion)

All ingredients available to have fully differential Higgs production at N³LO accuracy

⇒Remarkable stability of perturbative expansion

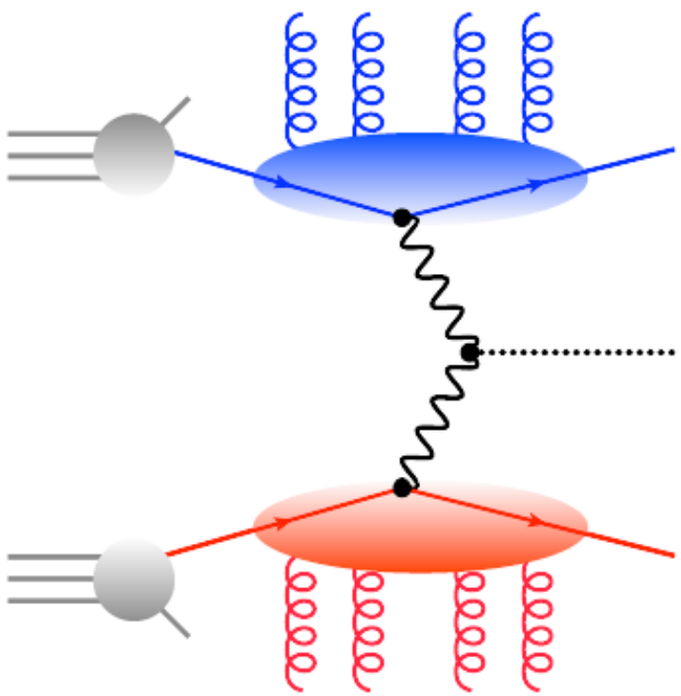


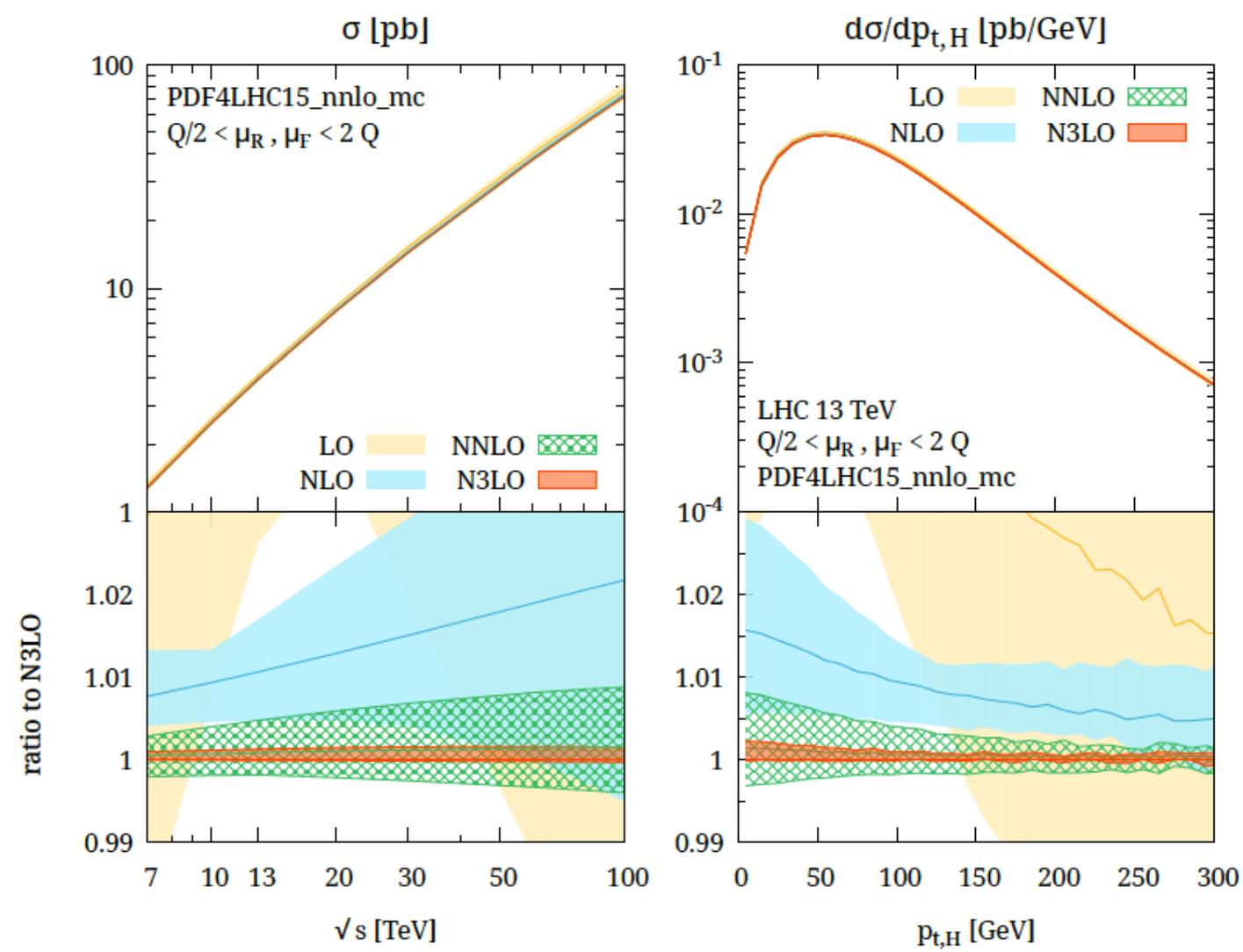
Dulat, Mistlberger, Pelloni 1810.09462

VBF Higgs at N^{3}LO

Inclusive Vector Boson Fusion Higgs cross-section (DIS approx.)

Dreyer & Karlberg 1606.00840





NB: NNLO non-factorizable effects sub-percent

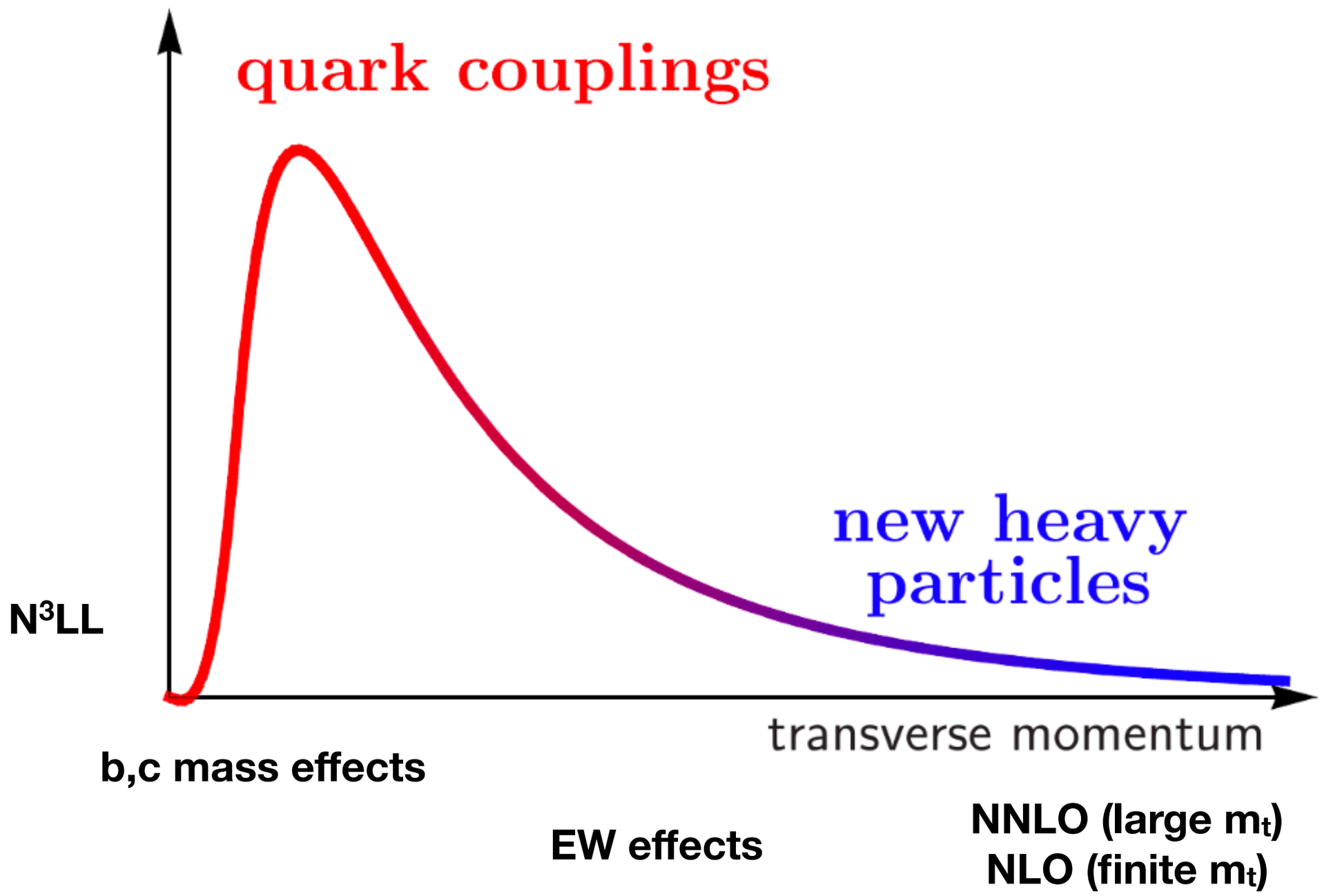
Liu et al. 1906.10899

N^3LO: future prospects?

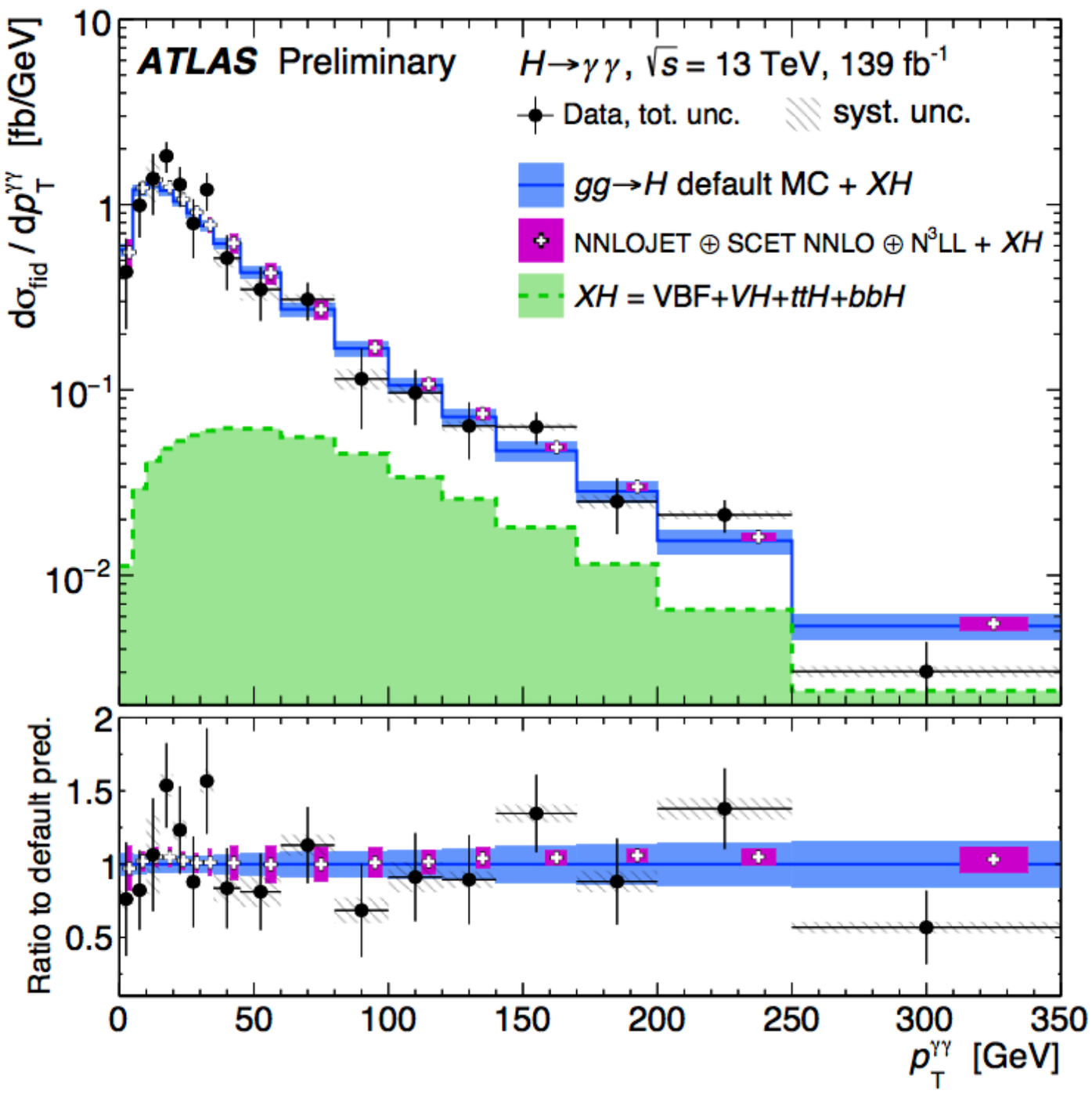
In the two cases where N^3LO results are known, the series shows a remarkable convergence and stability:

- it will be interesting to see whether the same pattern holds for e.g. associated Higgs production and other Higgs background processes (WW, ZZ, etc)
- it will be interesting to see how stable the picture is with realistic LHC fiducial cuts (e.g. Higgs cross-section with jet-veto)

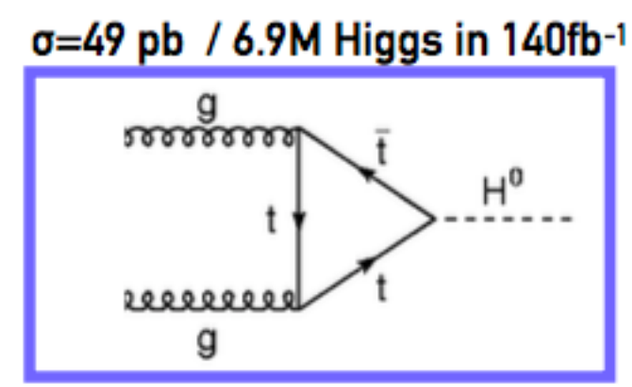
Higgs transverse momentum



Higgs transverse momentum

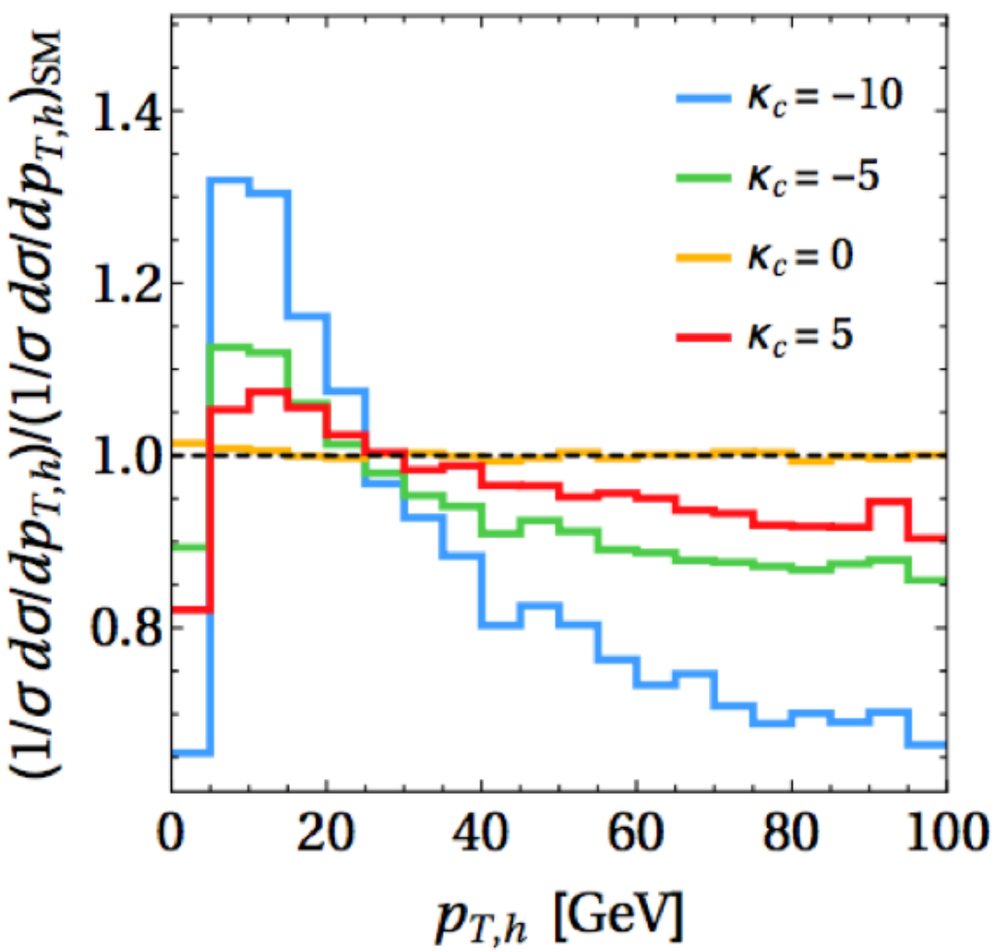


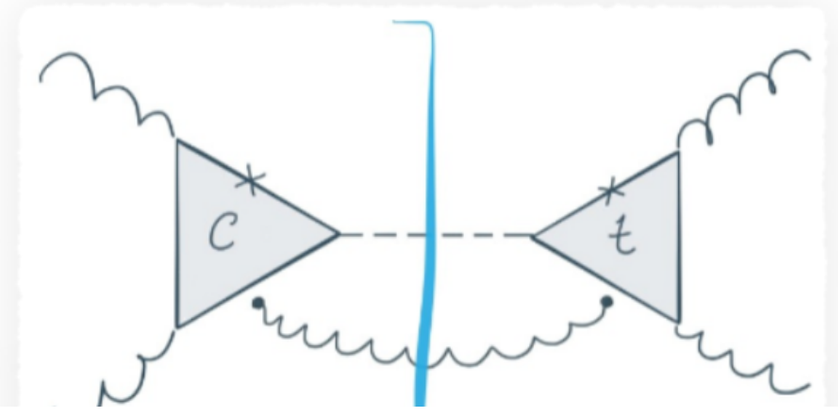
Today impressive level of sophistication (NNLO+N^{3}LL), still theory uncertainty about 20%

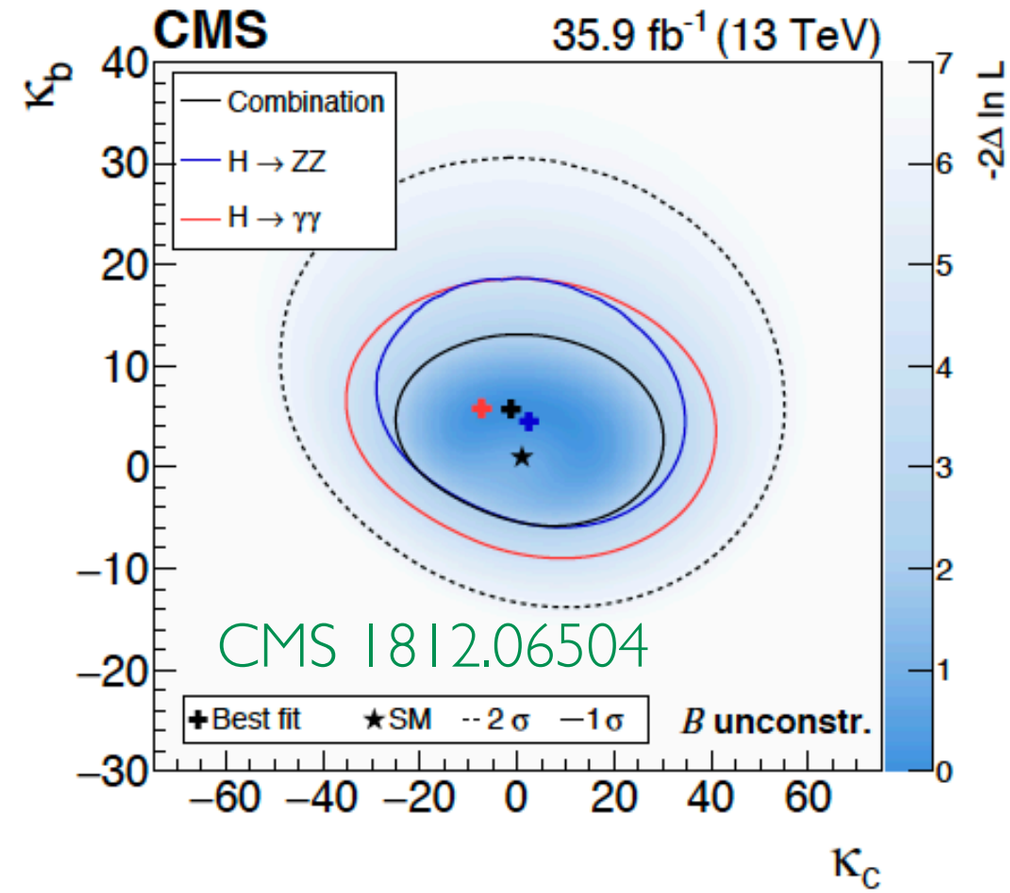


Higgs transverse momentum

<u>Low transverse momentum:</u> sensitivity to light Yukawa coupling (b and 2nd generation)

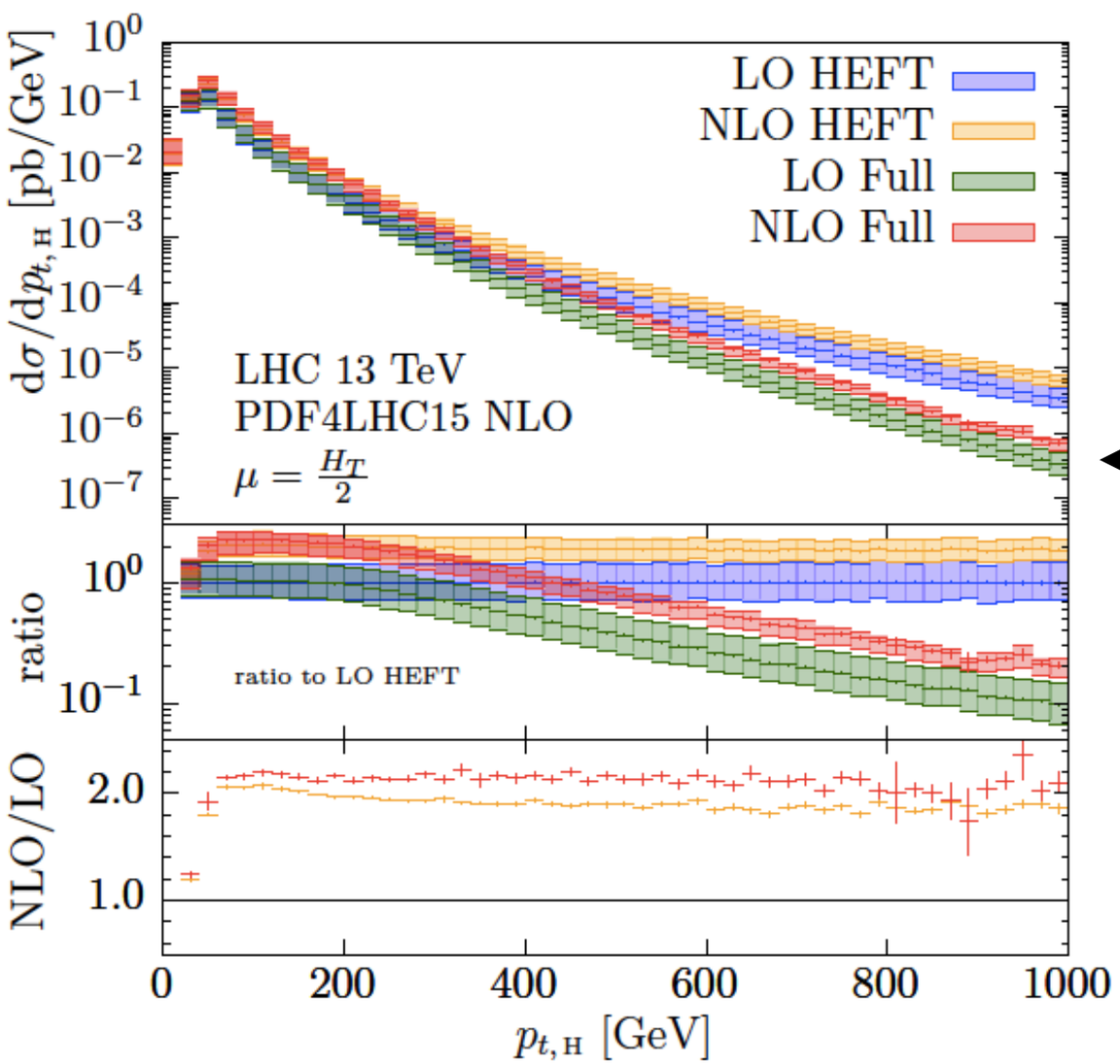




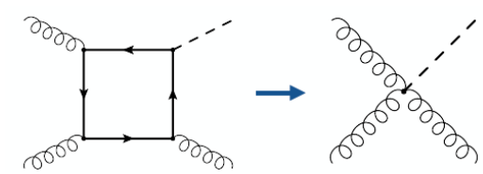


Higgs transverse momentum

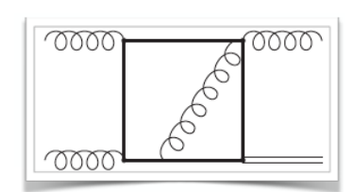
<u>High transverse momentum:</u> sensitivity to New Physics (resolve heavy particles circulating in loops)



HEFT: $m_t \to \infty$ limit



NLO loop-induced: different scaling behaviour at large p_T

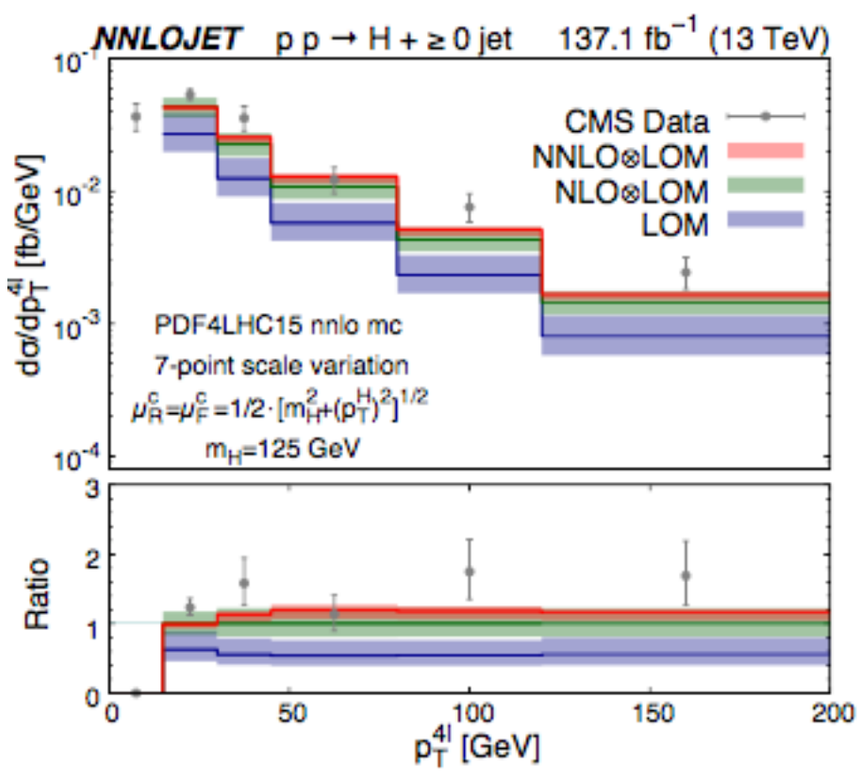


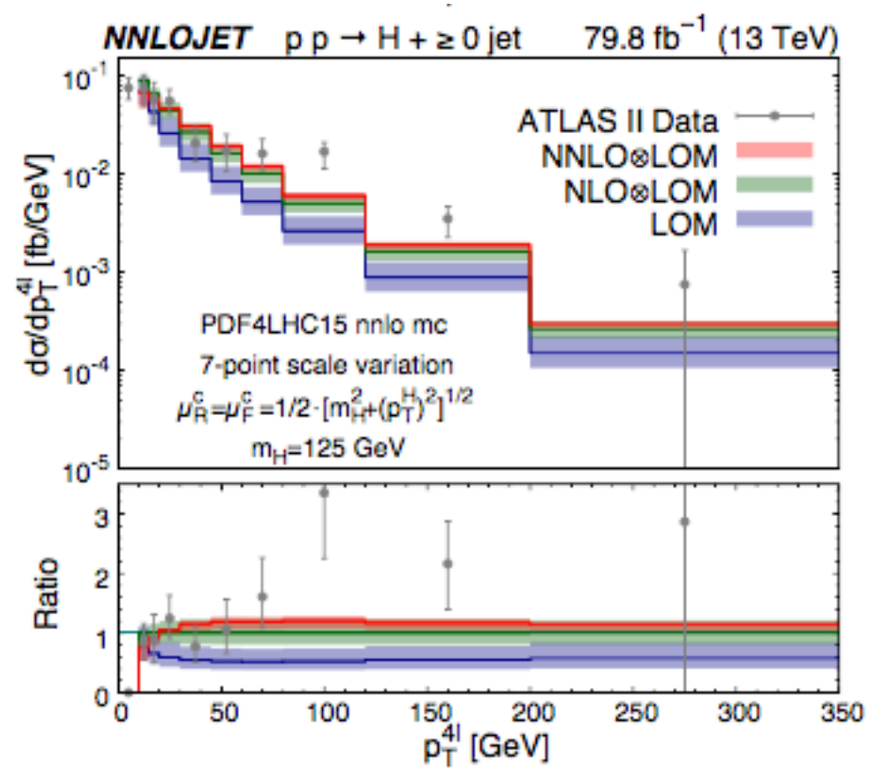
Similarly to top-loops, new particles will largely affect the shape at high p_T

H(→4l)+jet @ NNLO

Chen, Gehrmann, Glover, Huss 1905.13738

Good agreement with ATLAS and CMS data (within their larger errors)





<u>ATLAS lepton isolation:</u> removal of non-isolated jet

<u>CMS lepton isolation:</u> removal of non-isolated lepton → worse convergence of acceptance at fixed-order

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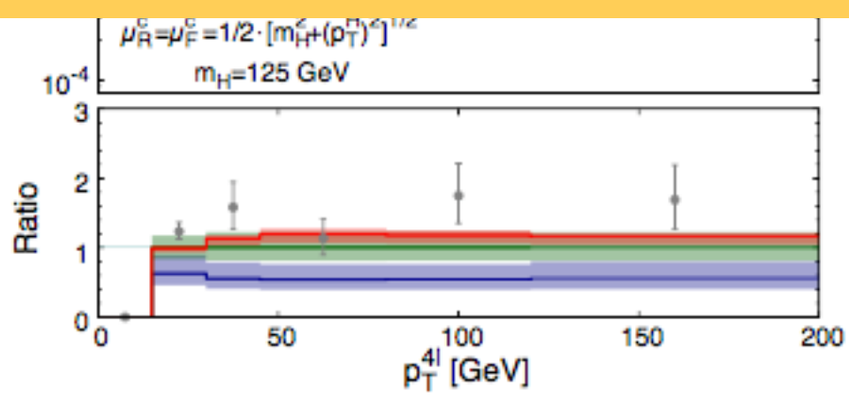
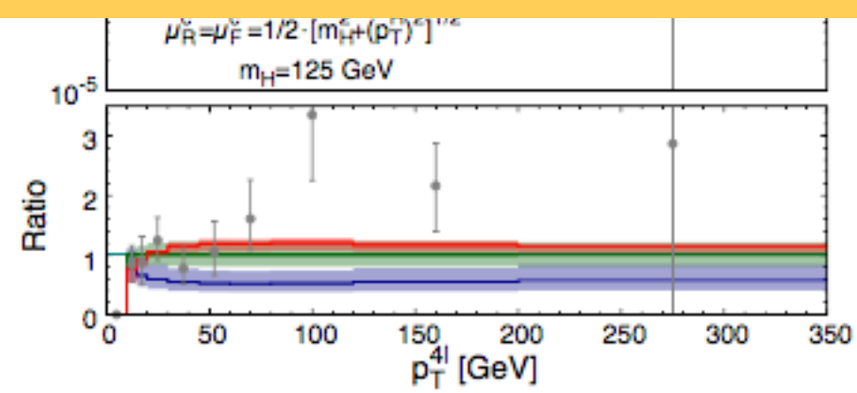
Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)





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Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)

But example also illustrates shortcomings of NNLO calculations, where only 2 leptons from the Higgs decay are present

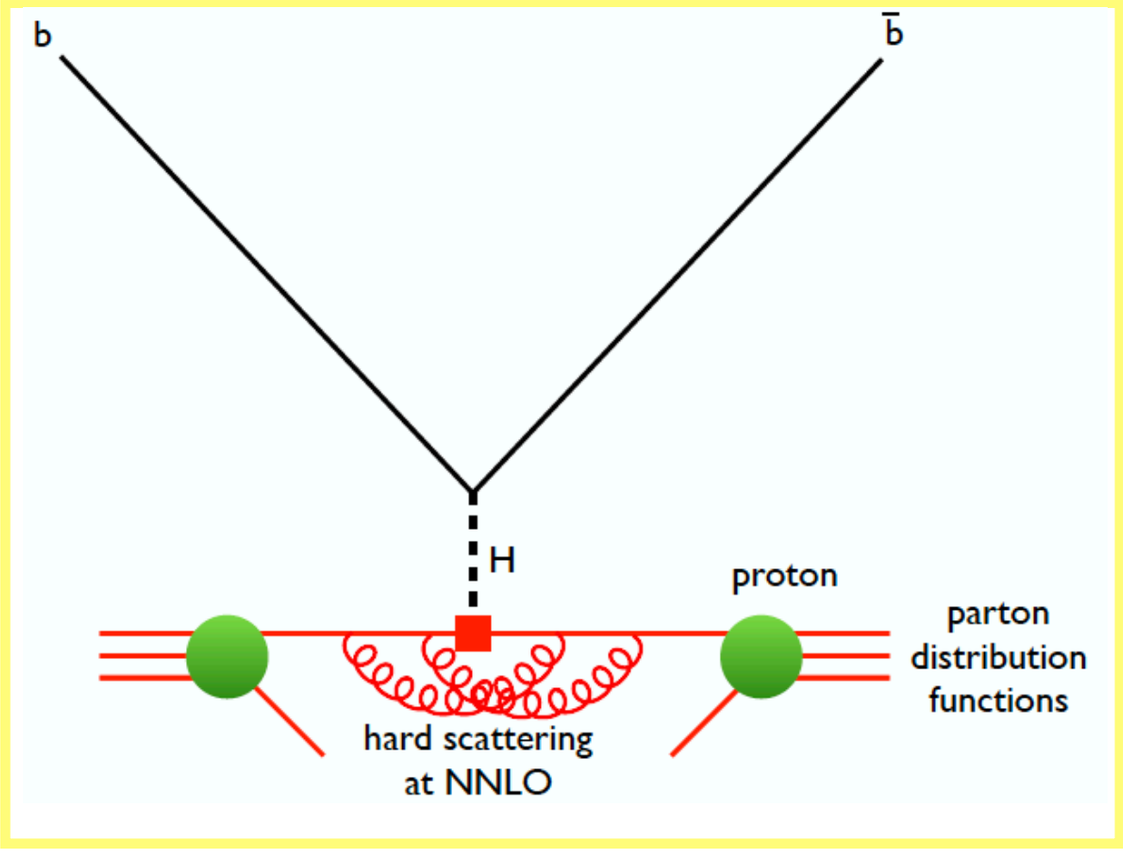
ATLAS

CMS lepton isolation: removal of non-isolated lepton → worse convergence of acceptance at fixed-order

NNLO or PS?

NNLO:

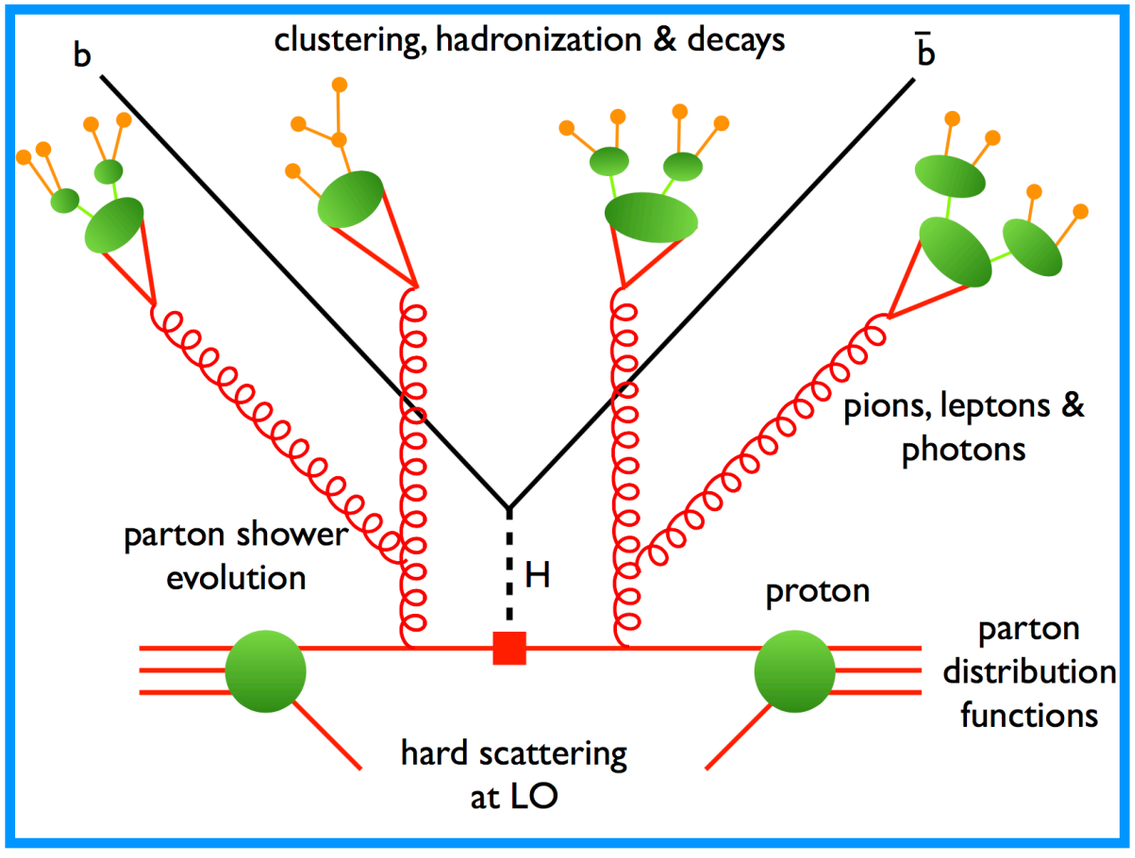
good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only



?

Parton shower:

less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects



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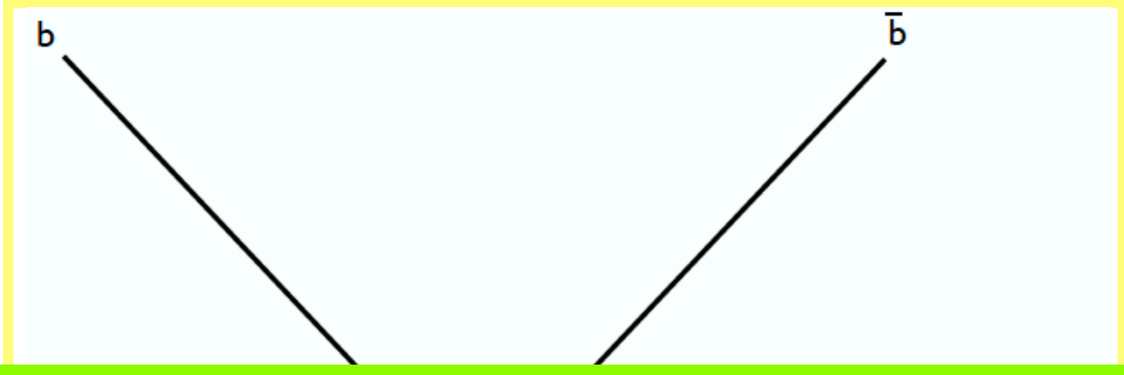
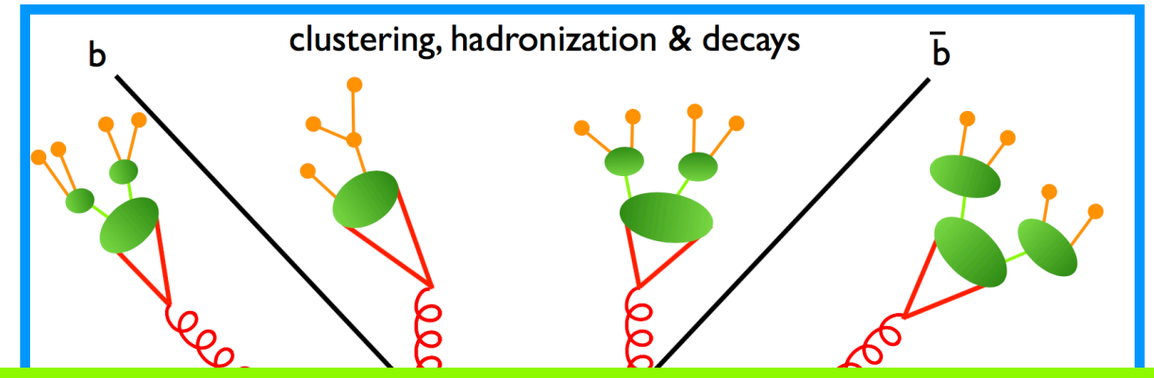




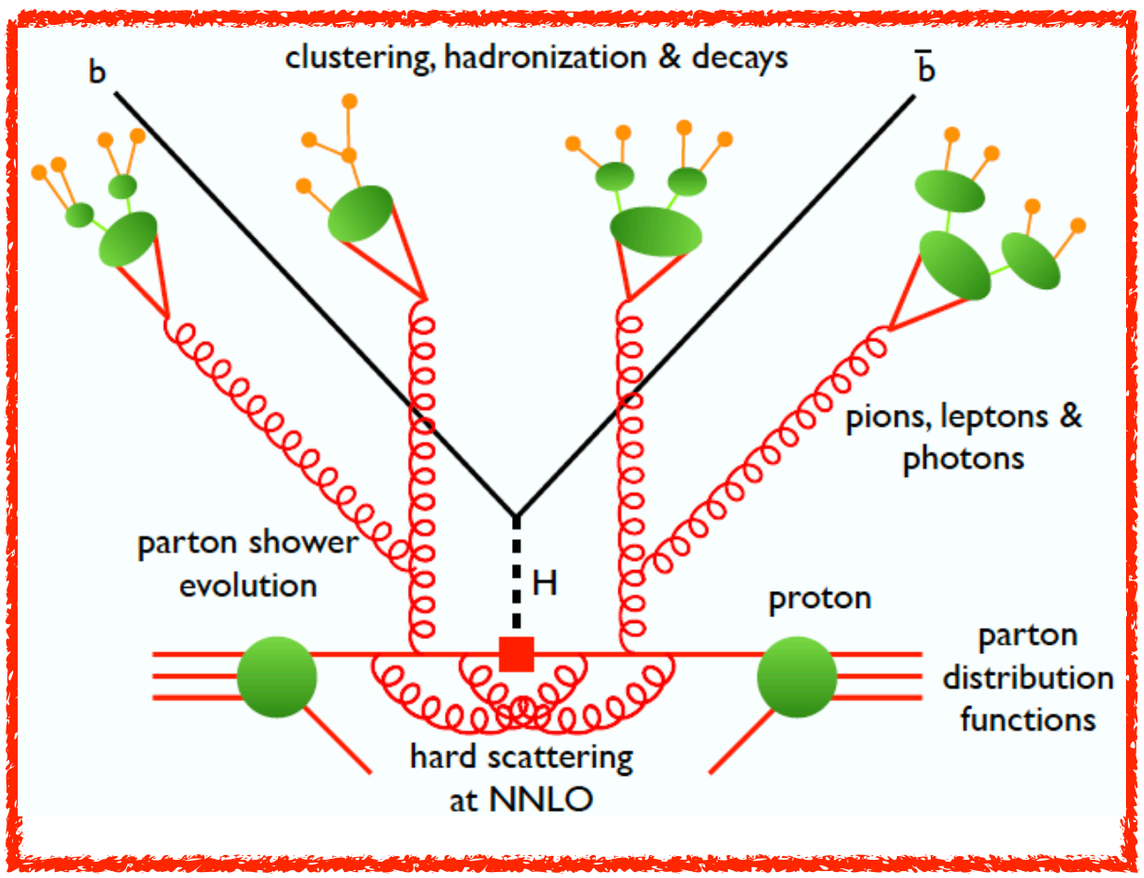
Matching of NLO & parton shower achieved in seminal papers about 15y ago

Nason hep-ph/0409146; Frixione & Webber hep-ph/0204244

Today: NLO+PS codes (MC@NLO, POWHEG, Sherpa) well-established and used in all advanced LHC analyses

NNLOPS

Matching of NNLO and parton shower (=NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final



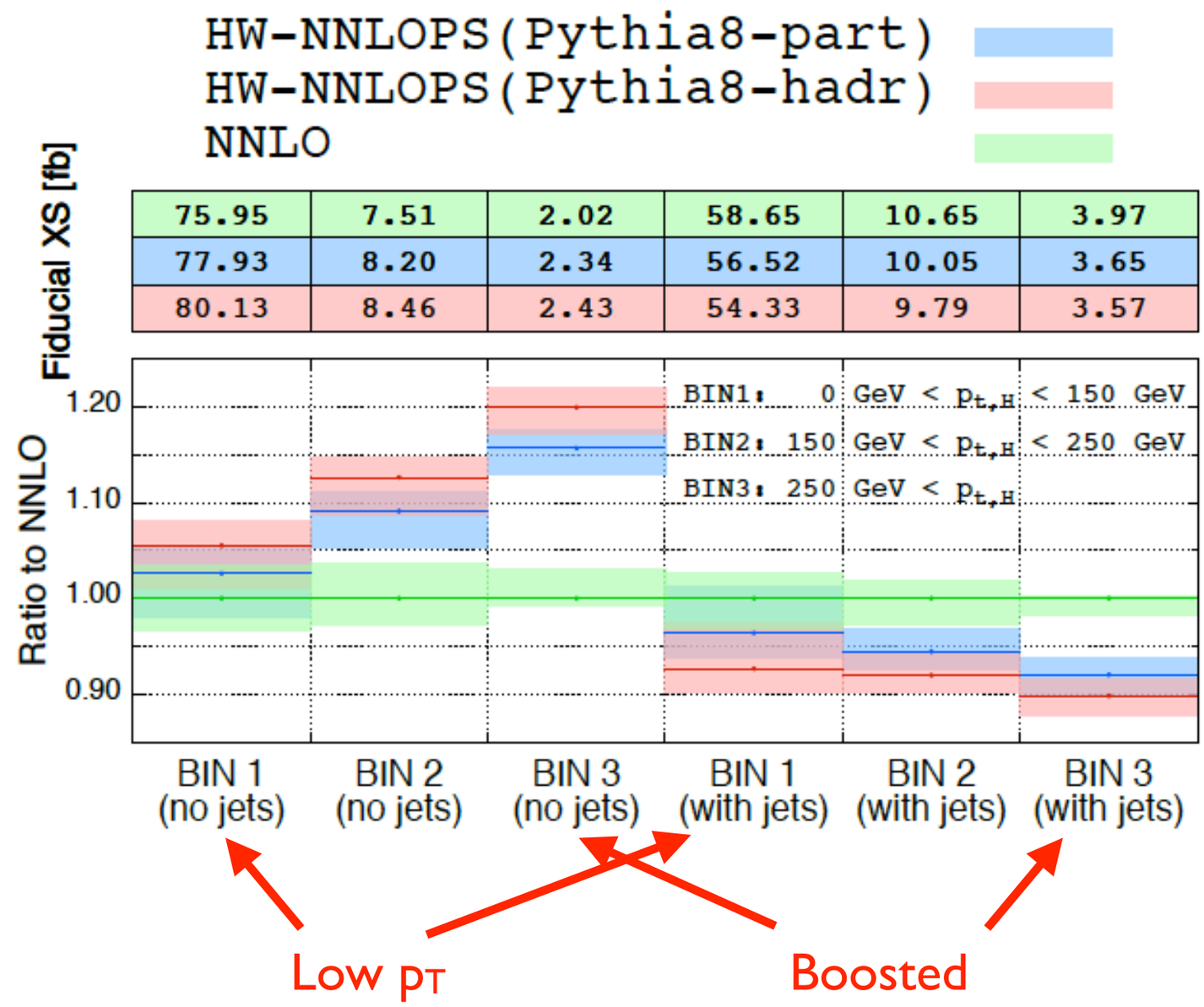
NNLOPS: currently three methods exist (UNNLOPS, Geneva, MiNLO) but very hard to extend to generic 2 → 2 processes.

Hoeche, Li,Prestel [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh [Geneva]

NNLOPS

Example: associated HW production with cuts used by HXSWG

- PS and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables

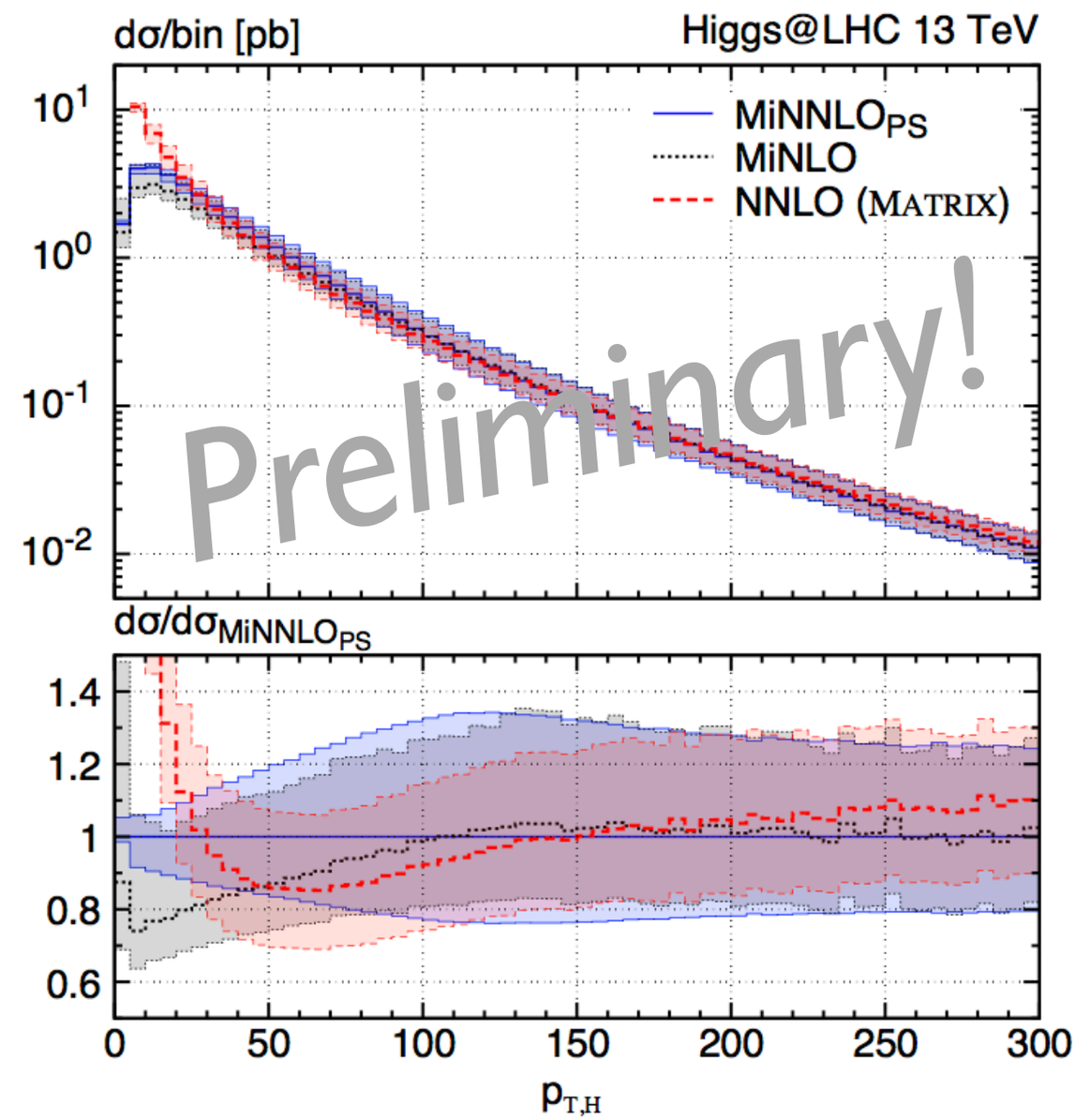


Bizon et al. 1603.01620

NNLOPS without reweighing

MiNNLOPS: NNLO at generation time (no additional) reweighing

$$\frac{d\sigma}{d\Phi_{FJ}} = \exp[-\tilde{S}(p_T)]\left\{\frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}}\right]^{(1)}\left(1+\frac{\alpha_s(p_T)}{2\pi}[\tilde{S}(p_T)]^{(1)}\right)\right.$$
$$\left.+\left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}}\right]^{(2)}+\left(\frac{\alpha_s(p_T)}{2\pi}\right)^3[D(p_T)]^{(3)}F^{corr}(\Phi_{FJ})\right\}$$
$$\times\left\{\Delta_{pwg}(\Lambda)+\int d\Phi_{rad}\Delta_{pwg}(p_{T,rad})\frac{R(\Phi_{FJ},\Phi_{rad})}{B(\Phi_{FJ})}\right\}+\mathcal{O}(\alpha_s^3)$$



Monni, Nason, Re, Wiesemann, GZ in preparation

MC uncertainty: example ttH

☛ talk by Caola

Dominant background from ttbb:

Selection	Tool	σ_{NLO} [fb]	$\sigma_{\mathrm{NLO+PS}}$ [fb]	$\sigma_{\mathrm{NLO+PS}}/\sigma_{\mathrm{NLO}}$
$n_b \geq 1$	SHERPA+OPENLOOPS	$12820^{+35\%}_{-28\%}$	$12939^{+30\%}_{-27\%}$	1.01
	MADGRAPH5_AMC@NLO		$13833^{+37\%}_{-29\%}$	1.08
	POWHEL		$10073^{+45\%}_{-29\%}$	0.79
$n_b \geq 2$	SHERPA+OPENLOOPS	$2268^{+30\%}_{-27\%}$	$2413^{+21\%}_{-24\%}$	1.06
	MADGRAPH5_AMC@NLO		$3192^{+38\%}_{-29\%}$	1.41
	POWHEL		$2570^{+35\%}_{-28\%}$	1.13

Needs to be understood!

Shower effects large and MC dependent in Higgs region!

Recoil effect? Bin migration? b-definition? g → bb contamination… ?

Resummed calculations crucial to validate logarithmic accuracy of parton showers

Resummations

Current status: in several cases, the accuracy of all-order resummed predictions pushed to NNLL or even N^3LL, properly matched to fixed order

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- On one side, once an accurate fixed order result is available, the impact of the resummation is limited to regions of low transverse momenta, see e.g.

> 3) NNLO QCD computations work in "hard kinematic regions". For an object with the invariant mass O(100) GeV, "hard" means down to transverse momenta O(30) GeV. This requires NNLO. Resummations are important but with NNLO results available, they become relevant at low(er) transverse momenta;
>
> Melnikov LHCP 2019

Resummations

Current status: in several cases, the accuracy of all-order resummed predictions pushed to NNLL or even N^3LL, properly matched to fixed order

- On one side, once an accurate fixed order result is available, the impact of the resummation is limited to regions of low transverse momenta, see e.g.

> 3) NNLO QCD computations work in "hard kinematic regions". For an object with the invariant mass O(100) GeV, "hard" means down to transverse momenta O(30) GeV. This requires NNLO. Resummations are important but with NNLO results available, they become relevant at low(er) transverse momenta;
>
> Melnikov LHCP 2019

- On the other side, resummed predictions are often inclusive and do not allow for fiducial cuts. This limits the applicability of resummed calculations

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> Melnikov LHCP 2019

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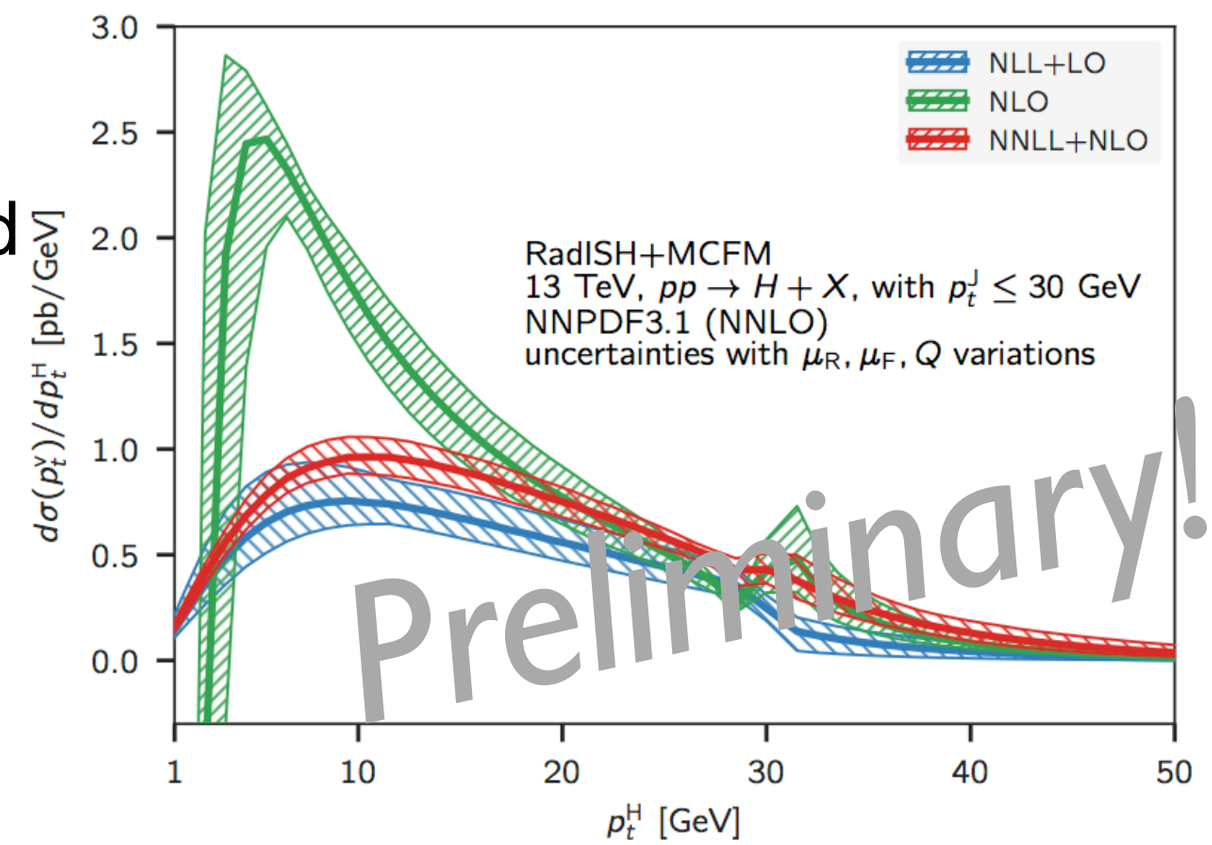
Both points seem to imply that resummations are not quite that useful. I want to argue that this is not true.

Resummations

Even if the hard scale if O(100 GeV), fiducial cuts can push all the kinematics at low transverse momentum values, e.g. for Higgs production the bulk of the cross section lies *well below 30 GeV*

Double differential resummed predictions, e.g. NNLL resummed predictions for the Higgs transverse momentum with a veto on jets



Monni et al. '19

Reminder: jet-veto is required in the WW decay channel to suppress top background

Other joint resummations

Increasing interest in resummations in more exclusive regions

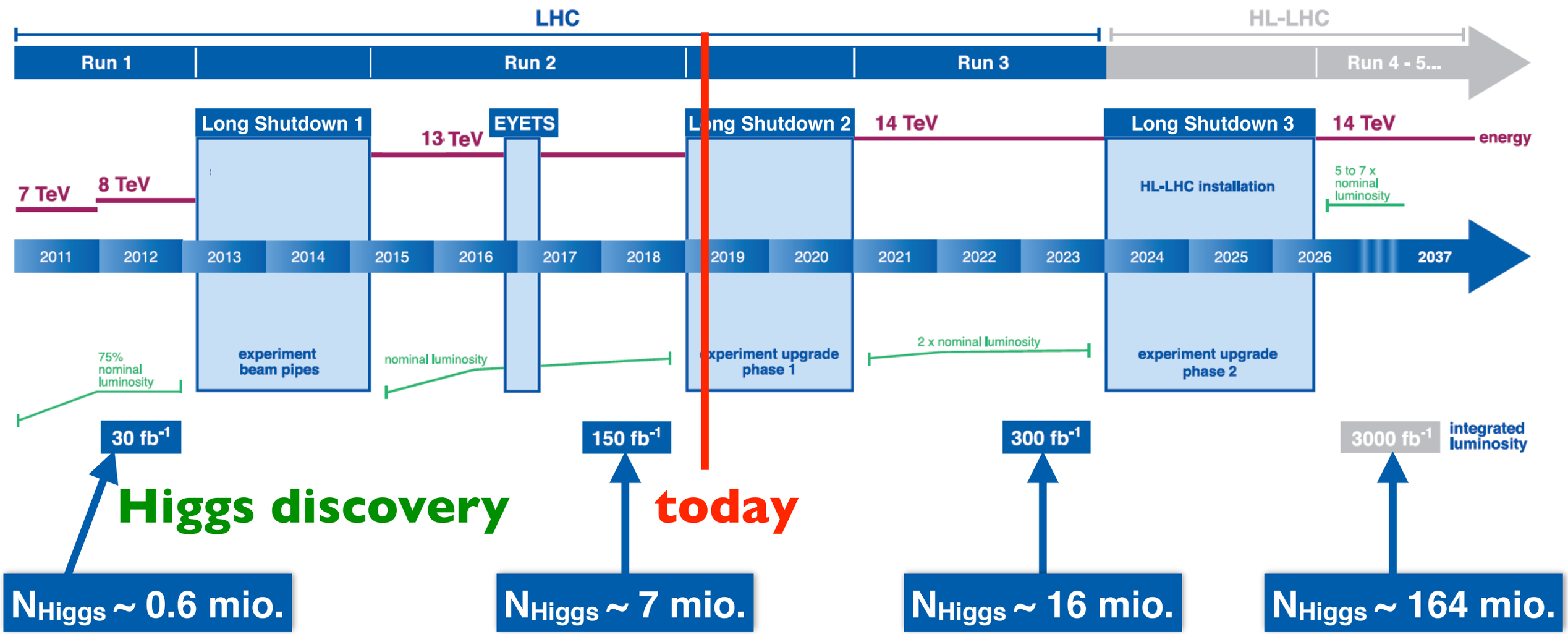
- $p_{t,H}$ and small-x — Laenen et al hep-ph/0010080; Kulesza et al hep-ph/0309264
- $p_{t,H}$ and large-x — Lustermans et 1605.027400; Muselli et al. 1701.01464
- small-x and large-x — Marzani 1511.06039; Forte and Muselli 1511.05561
- $p_{t,H}$ and jet-radius — Bonvini and Marzani 1802.07758
- $p_{t,V}$ and 0-jettiness — Banfi et al. 1511.02886
- 2 angularities — Lustermans et al. 1901.03331; Larkoski et al. 1501.4458; Procura et al. 1806.10622

Resummations no longer limited to inclusive observables

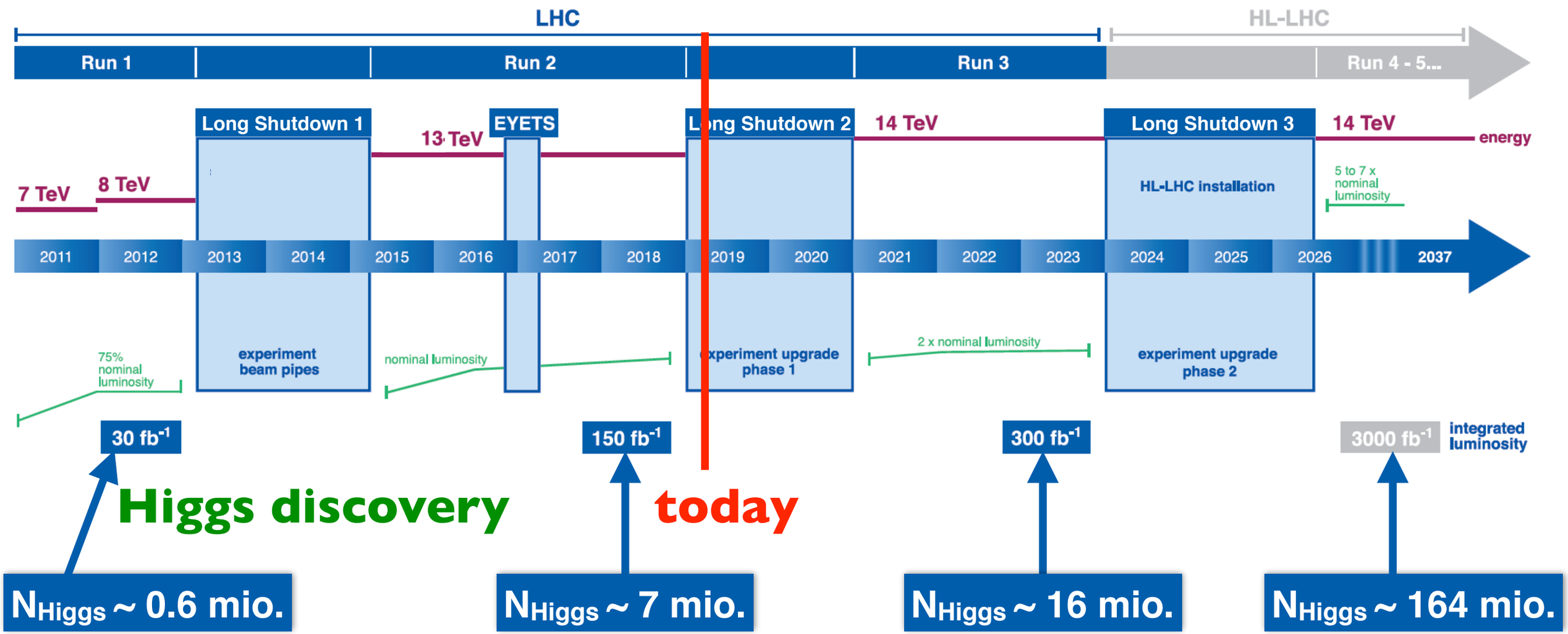
⇒ closer connection between resummed predictions and measurements

Ahead?

Our Higgs factory



Our Higgs factory



Did you know that? *About 10^6 Higgs bosons are produced every year from proton cosmic rays in our atmosphere! We just don't have detectors to see them…*

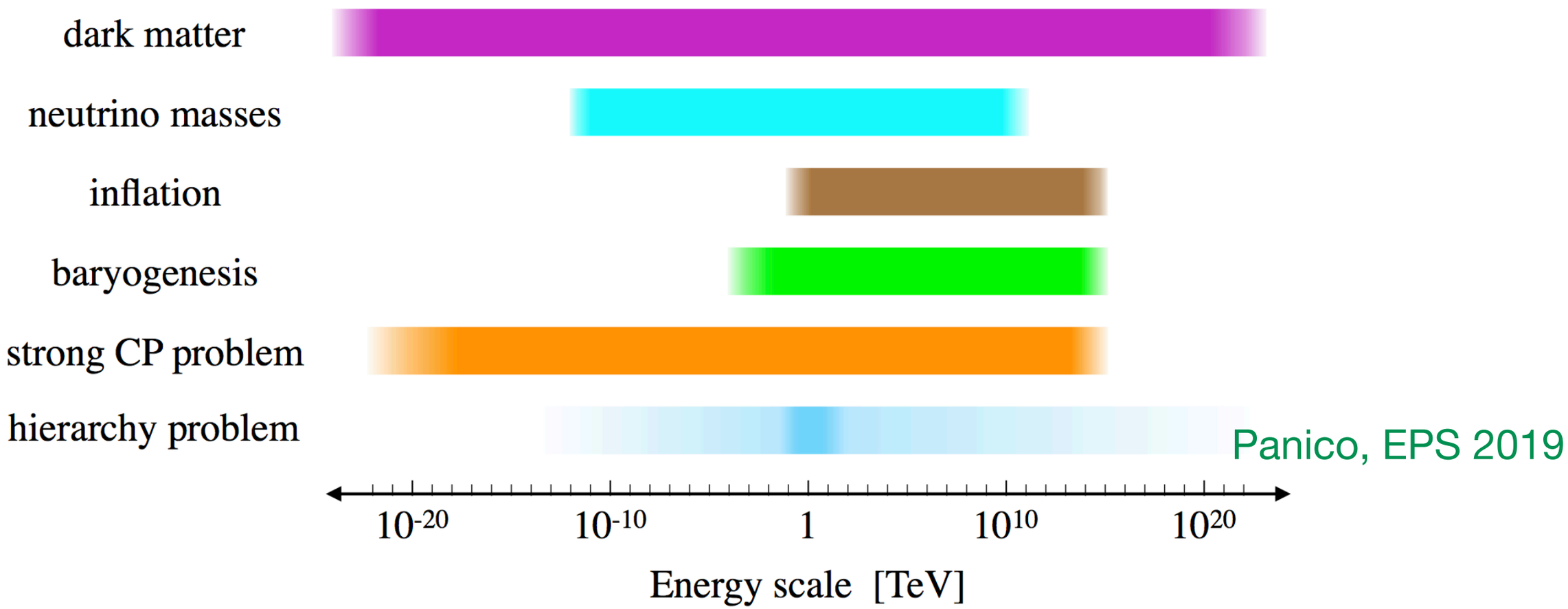
Beyond the Standard Model

Many open questions imply physics Beyond the Standard Model:

- The hierarchy problem
- Neutrinos are not massless
- Dark matter is not accounted for
- No explanation for the baryon asymmetry in the universe
- Solution to the strong CP problem?
- Gauge-coupling unification does not work (is it a hint?)
- No explanation for the inflationary period of the early universe
- Gravity not included in the picture

Beyond the Standard Model

Many open questions imply physics Beyond the Standard Model:



Only the hierarchy problem suggest a scale for New Physics

Higgs BSM

- Pedagogical review (crisis, opportunities, fringy perspective?)

  ☛ talk by Perez

- Higgs as a portal to new dynamics

  ☛ talk by Contino

- Axiflavon: flavour hierarchies with pNBG Higgs

  ☛ talk by Blasi

- Composite Higgs and Dark Matter

  ☛ talks by Ruhdorfer

- Electroweak baryogengesis above the weak scale

  ☛ talk by Giloti

- Prospects of multi-Higgs production in the 2HDM at the LHC

  ☛ talk by Munir

- Exotic Higgs decays

  ☛ talk by Shelton

Higgs without the Higgs

- What can be learnt on the Higgs from measurements in other sectors?
- What can be learnt on the other sectors from Higgs measurements?

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

☛ talk by Zhang

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$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
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$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

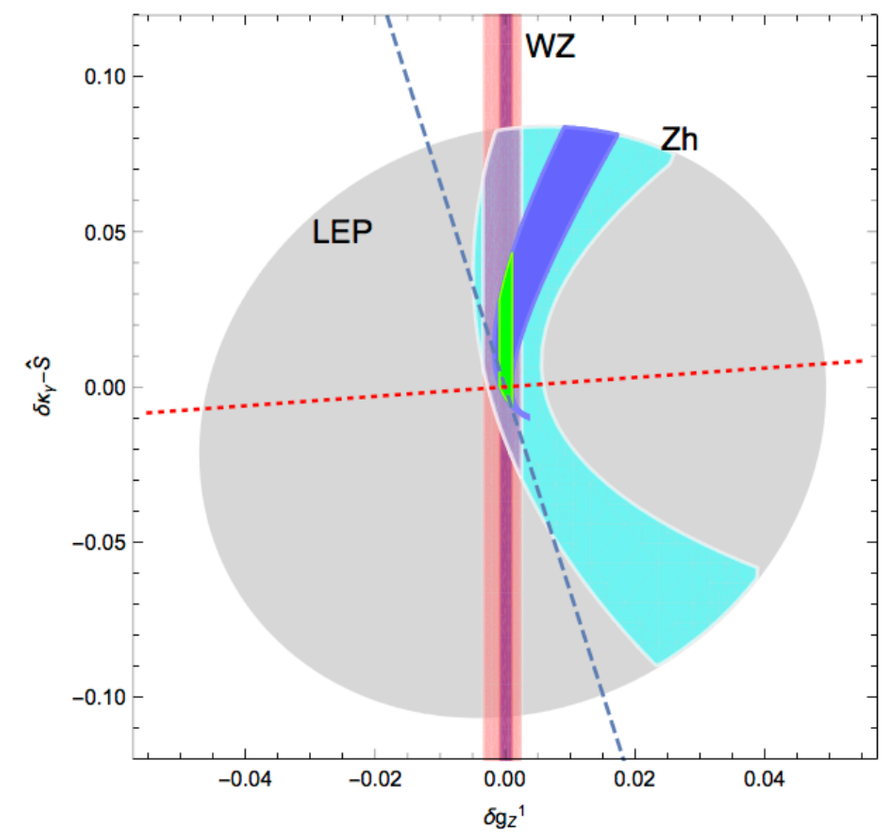
☛ talk by Zhang

With more and more precise LHC measurements and future collider programs, start to see clearly the connections between different sectors. It is then useful to think what we can learn from them.

Higgs without the Higgs

☛ talk by Banerjee

	Our Projection 300 fb^{-1} (3 ab^{-1})	LEP Bound
$\delta g^Z_{u_L}$	± 0.002 (± 0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	± 0.003 (± 0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	± 0.005 (± 0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	± 0.016 (± 0.005)	0.016 ± 0.0052
δg^Z_1	± 0.005 (± 0.001)	$0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	± 0.032 (± 0.009)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.003 (± 0.001)	0.0000 ± 0.0006
Y	± 0.032 (± 0.009)	0.0003 ± 0.0006



Precision and energy reach

New physics likely heavy ⇒ use effective field theory (EFT)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6}$$

scale of new physics

- At low energy, e.g. Higgs couplings

$$g = g_{\rm SM}\left(1 + c\frac{v^2}{\Lambda^2}\right)$$

- At high energy (E), e.g. oblique parameters in $V_L V_L$ scattering (V=W, Z, h)

$$g = g_{\rm SM}\left(1 + c\frac{E^2}{\Lambda^2}\right)$$

Precision and energy reach

New physics likely heavy ⇒ use effective field theory (EFT)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6}$$

scale of new physics

per-mille accuracy at LEP ≈ 10% accuracy at 1 TeV
1% accuracy at 1 TeV ≈ 10% accuracy at 3 TeV
0.1% accuracy at 1 TeV ≈ 10% accuracy at 10 TeV

V_L

$$g = g_{\rm SM}\left(1 + c\frac{v^2}{\Lambda^2}\right)$$

$$g = g_{\rm SM}\left(1 + c\frac{E^2}{\Lambda^2}\right)$$

Precision and energy reach

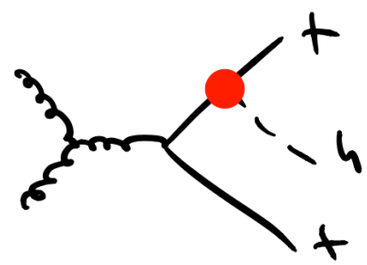
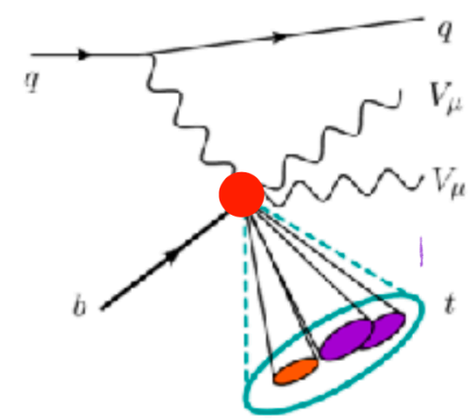
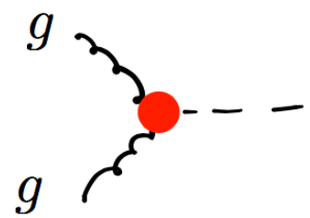
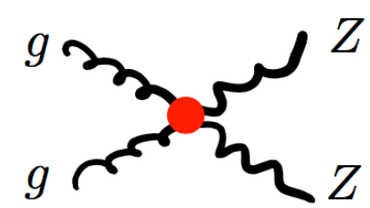
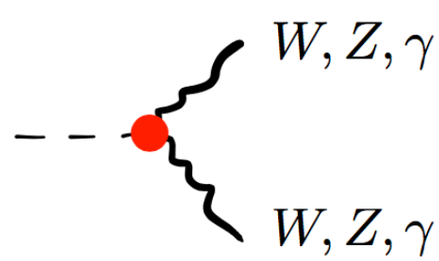
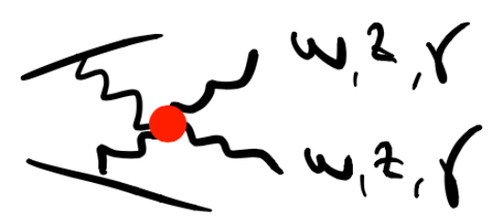
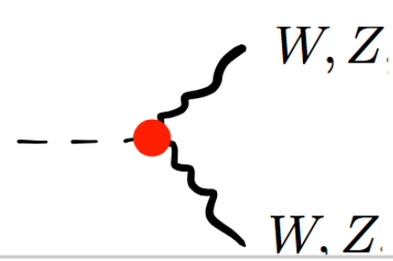
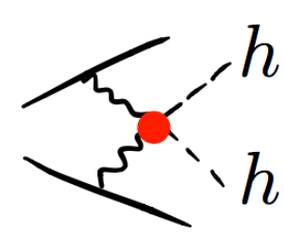
☛ talk by Zhang

A. When large energy is accessible, we identify the specific channels in which the amplitude grows with energy. i.e. trading high energy for precision.

B. When high precision can be reached, we use loop effects to open up more opportunities in our measurements.

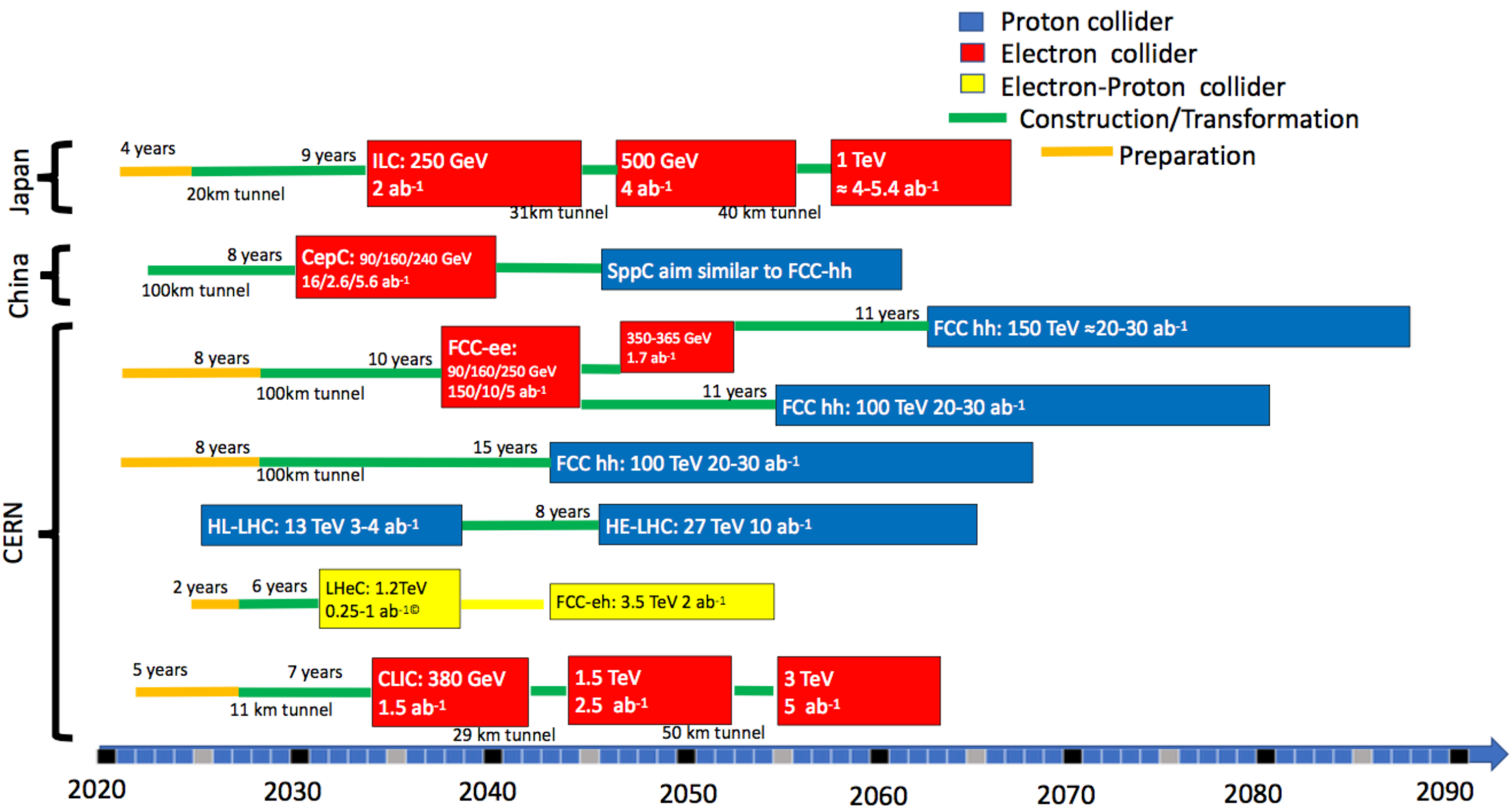
Have we pushed these ideas to their limits?

Complementarity

	$\sim const$	$\sim E^2$
κ_t $\quad \lvert H\rvert^2 Q\tilde{H}t_R$		
κ_G $\quad \lvert H\rvert^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\quad \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\kappa_{Z\gamma}$ $\quad \lvert H\rvert^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V $\quad \lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

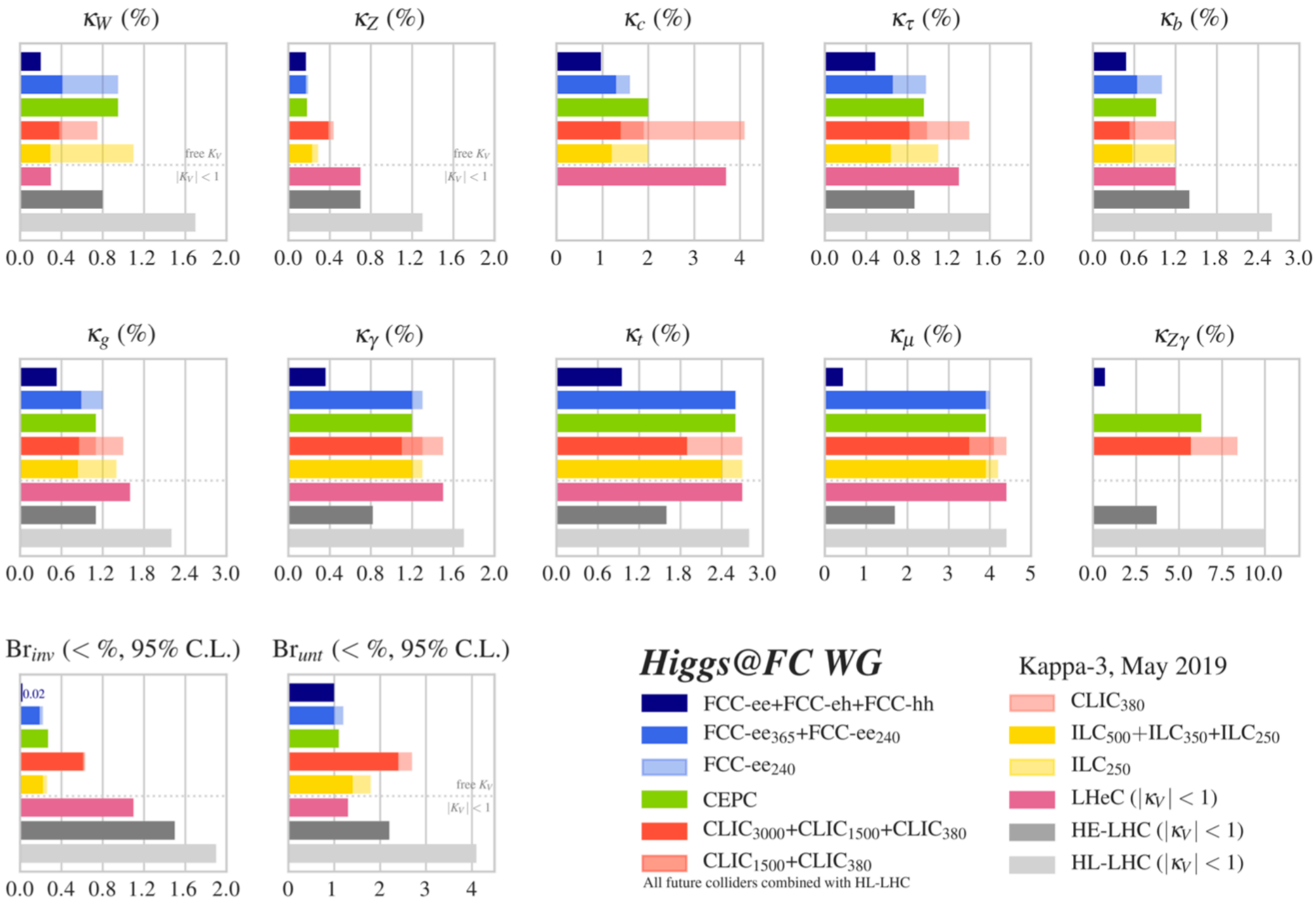
Henning, Lombardo, Rimbau, Riva ’18

Possible future colliders



From Ursula Bassler, Granada 2019

Possible future constraints



Blas et 1905.0374

Deep learning for Higgs

Impact of Machine Learning on the discovery and study of the Higgs Boson

Analysis	Data collection year	No ML sensitivity | p-value	ML sensitivity | p-value	Relative data gain | factor
CMS $H \to \gamma\gamma$ [25]	2011-2012	2.2 | 0.014	2.7 | 0.0035	51% | 4.0
ATLAS $H \to \tau^+\tau^-$ [43]	2011-2012	2.5 | 0.0062	3.4 | 0.00034	85% | 18
ATLAS VH→bb[99]	2011-2012	1.9 | 0.029	2.5 | 0.0062	73% | 4.7
ATLAS VH→bb [41]	2015-2016	2.8 | 0.0026	3.0 | 0.00135	15% | 1.9
CMS VH→bb[100]	2011-2012	1.4 | 0.081	2.1 | 0.018	125% | 4.5

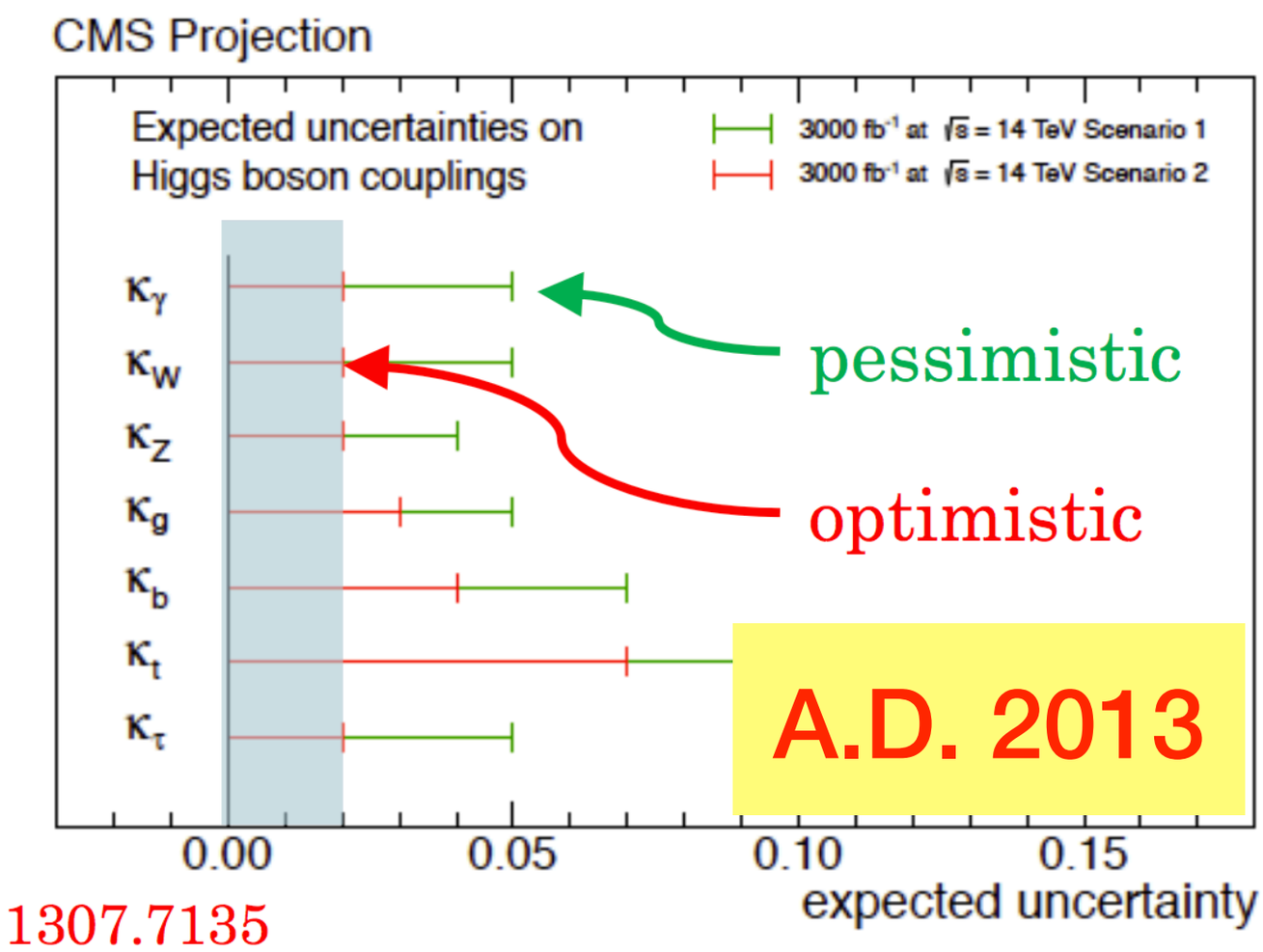
Nature 560 (2018) 41-48

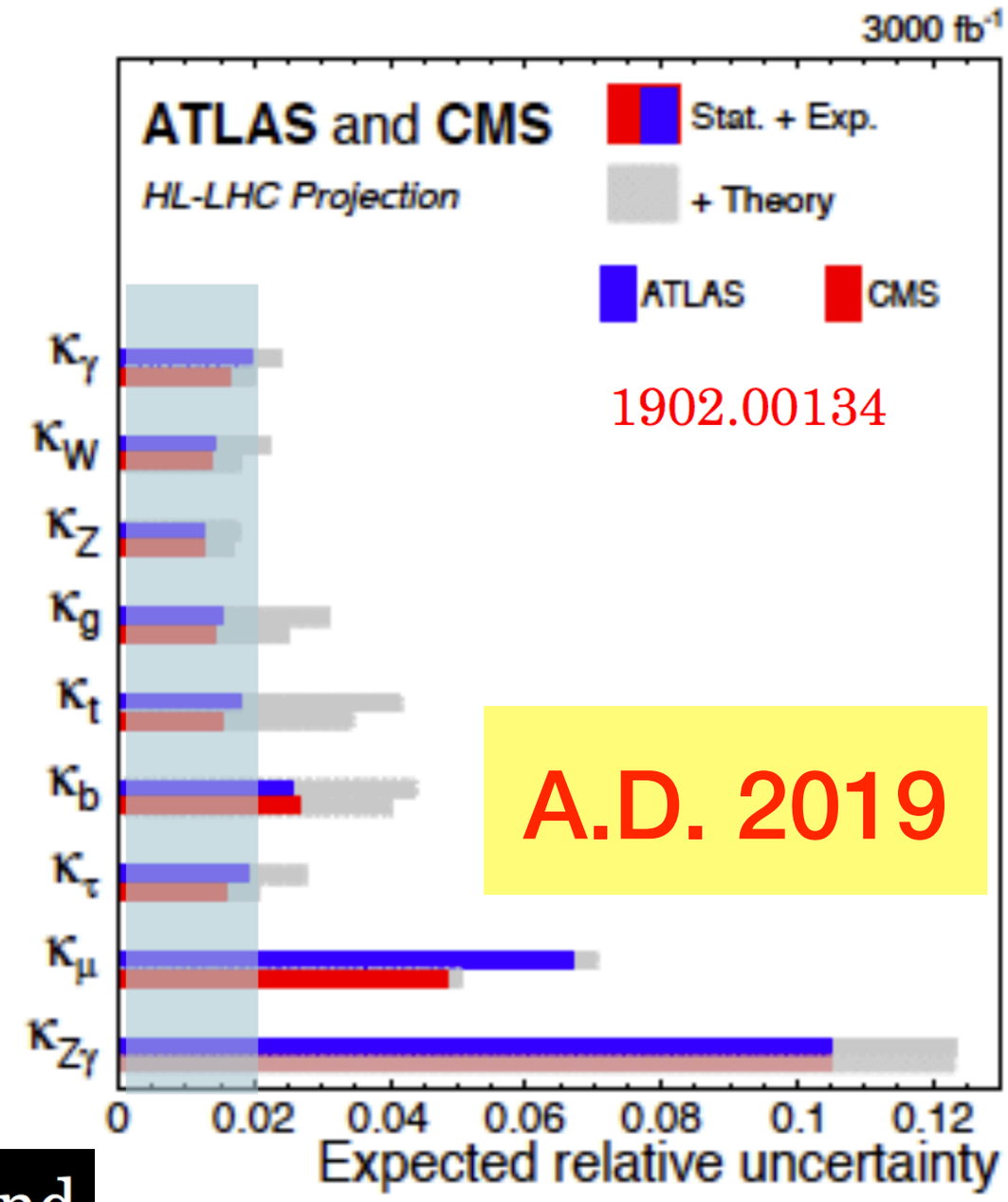
?

Additional amount of data needed to reach the ML-sensitivity without ML

About 15-125% gain on LHC running. Further improvements?

Projections for HL-LHC





Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

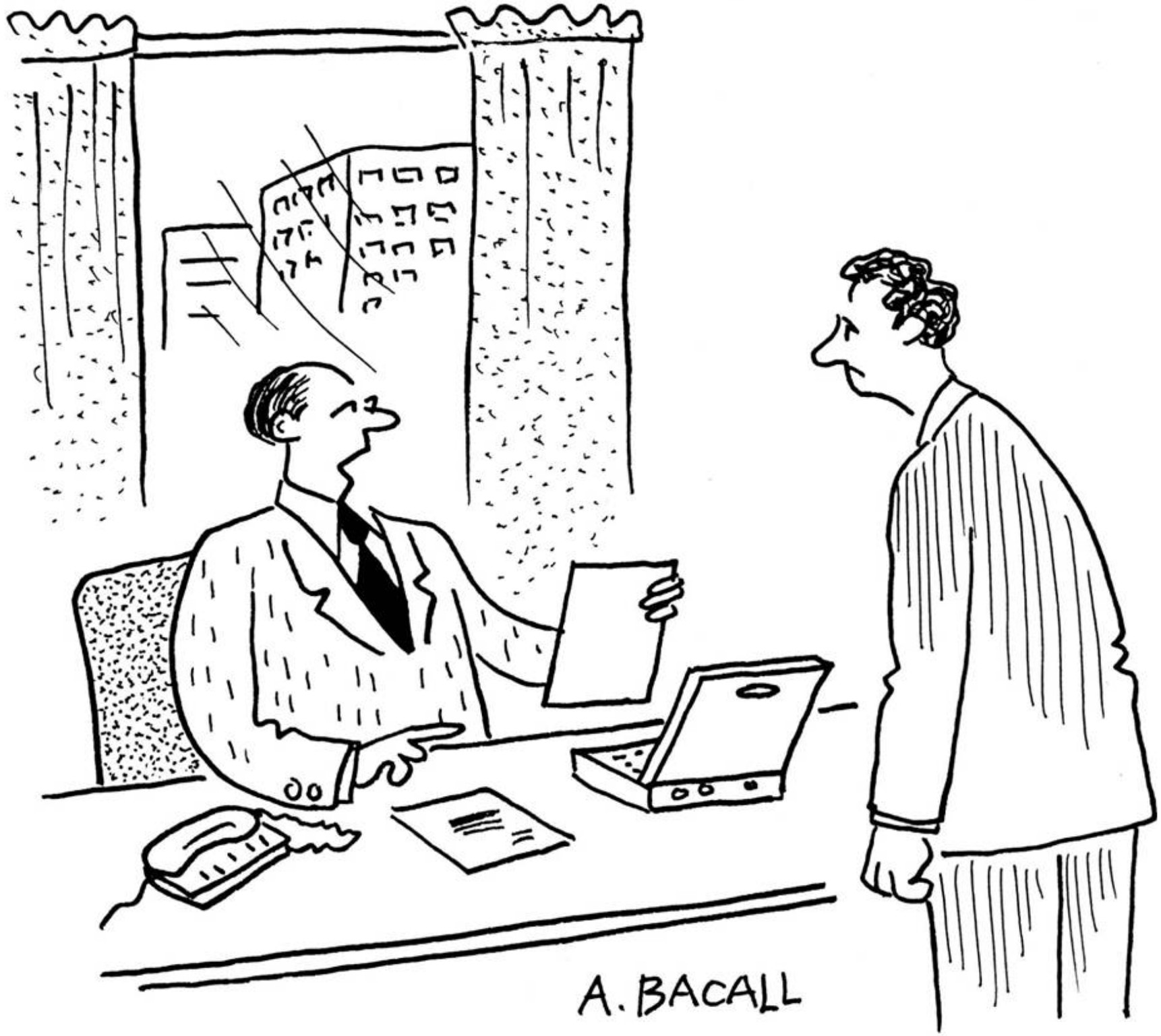
☛ talk by D'Hondt

New opportunities

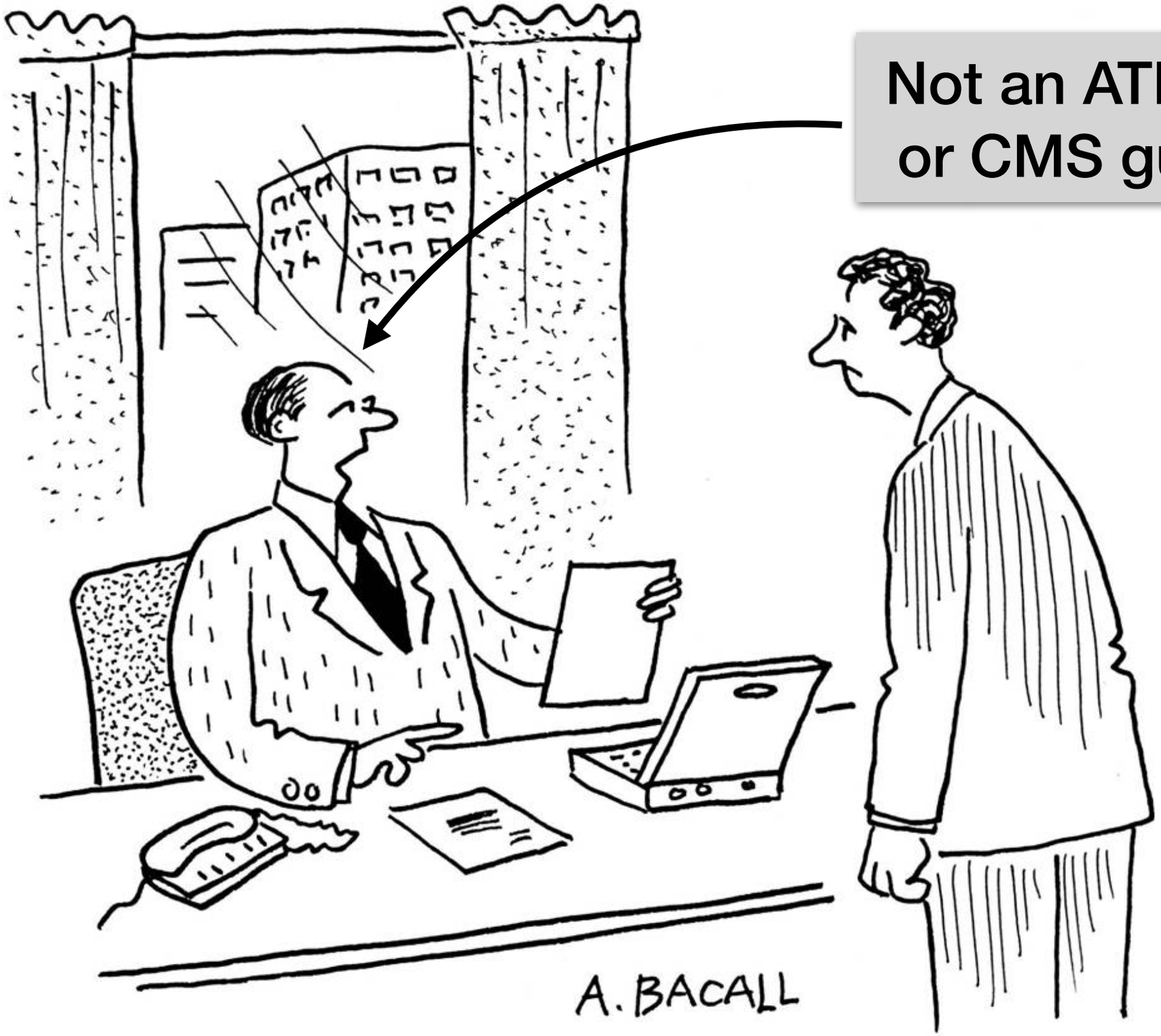
Examples of where precision and theoretical ingenuity brought in new opportunities:

- ☑ Higgs width from ratio off-shell to on-shell cross-section
- ☑ Constraints on light Yukawa from Higgs p_t spectrum
- ☑ Constraints on Higgs-self coupling from single Higgs production modes

All theoretical ideas implemented in experimental analyses and provided new experimental bounds



Your proposal is innovative. Unfortunately, we won't be able to use it because we've never tried something like this before."



Your proposal is innovative. Unfortunately, we won't be able to use it because we've never tried something like this before."

New ideas wanted!!

Conclusions

- Higgs studies are just out of their infancy. So far, the Higgs looks very much Standard Model like
- The scalar sector is connected to profound questions (naturalness, vacuum stability, flavour)
- The discovery allows us to explore a new sector with a broad experimental program that will extend over decades
- There is much more, fundamental to learn about the Higgs sector in the years to come

Stay healthy and live long

Grojean EPS 2019

Stay healthy and live long

Grojean EPS 2019

+

Sharpen your axe!

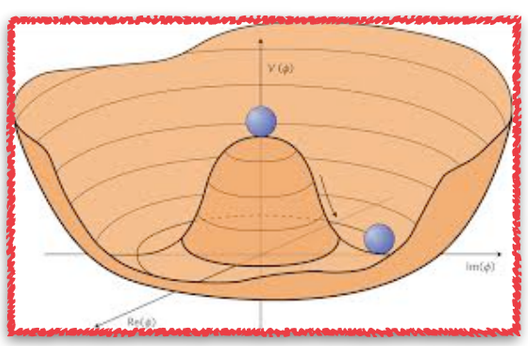
Give me six hours to chop down a tree and I will spend the first four sharpening the axe.

A. Lincoln

The Higgs potential

The Higgs boson is responsible for the masses of all particles. Its potential, linked to the Higgs self-coupling, is predicted in the SM, but we have not tested it so far

$$V_{\mathrm{SM}} = \frac{m_h}{2}h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

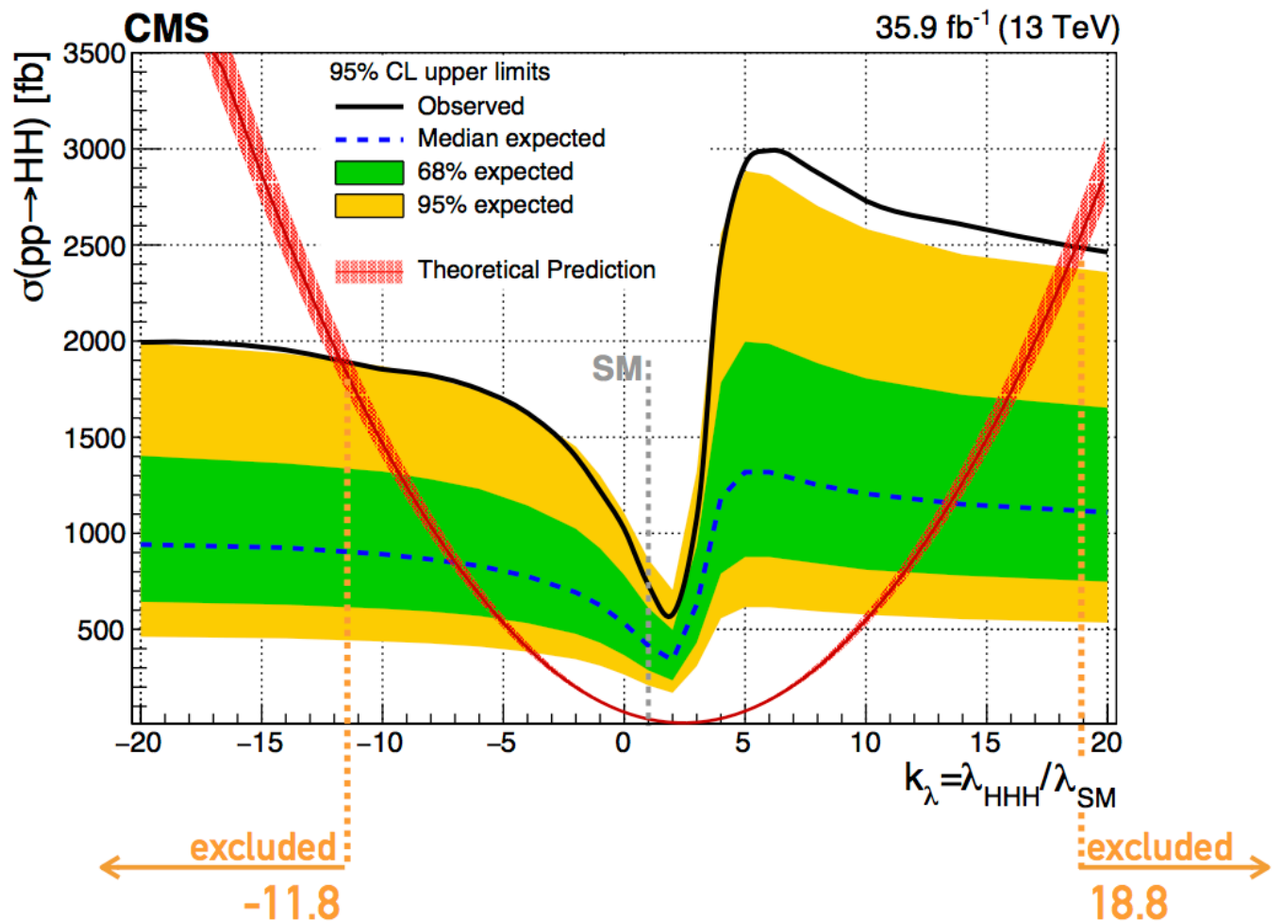


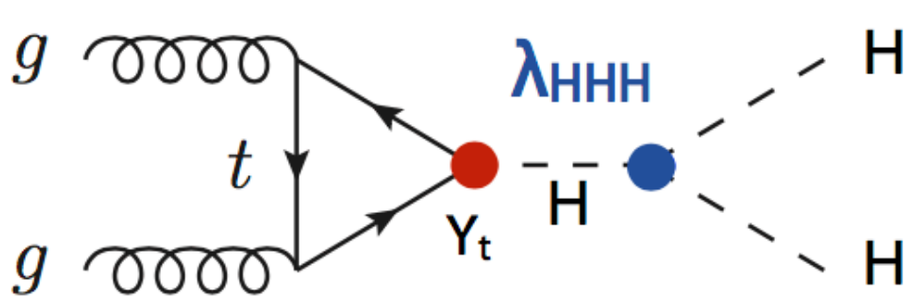
- ☑ Single Higgs — done — O(7 millions)
- ☐ Double Higgs — very hard — O(7000)
- ☐ Triple Higgs — out of reach — O(15)

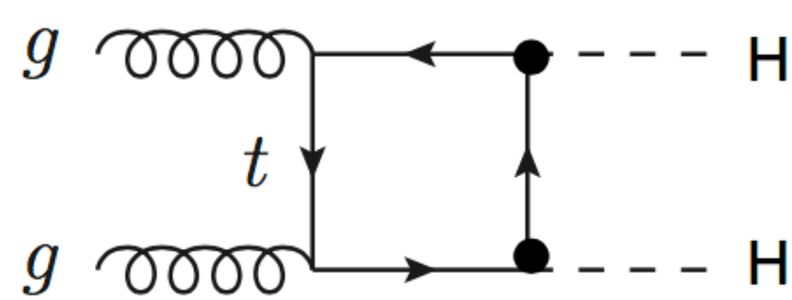
events produced so far

The Higgs self-coupling

Double-Higgs production is directly sensitive to the self-coupling







The Higgs self-coupling

Single-Higgs production modes indirectly sensitive to the self-coupling through electro-weak effects