Measurements of b quark production cross section at the Tevatron

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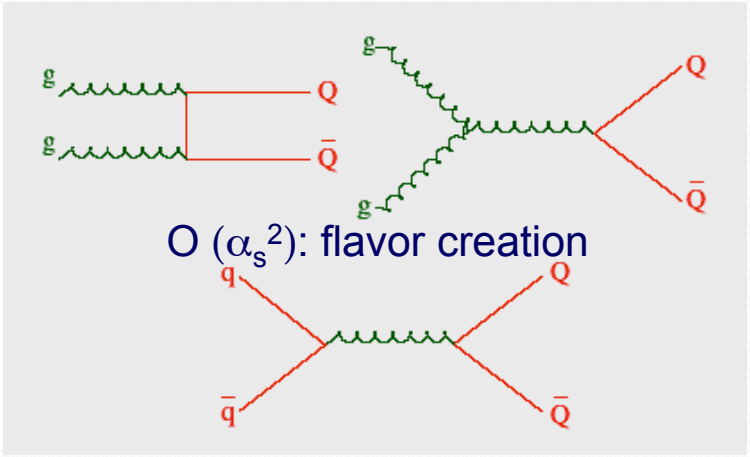
Cross section measurements

$$\sigma = \frac{N}{A \cdot \varepsilon \cdot L}$$

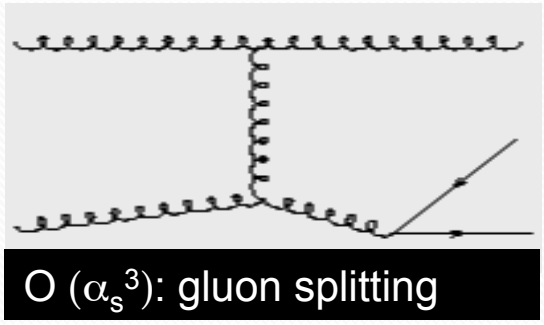
- N: number of selected events – possibly clear sample @ hadron collider
  - Leptons in the final state: J/ψ, semileptonic decays
  - Impact parameter of particles in jets
- A: acceptance – how many of the events that are generated actually end up in active parts of the relevant detectors?
- ε: efficiencies (the hard bit)
  - in detecting the particle passage though a detector
  - in reconstructing the observable at trigger level
  - for the trigger to select the event
  - for the offline reconstruction to reconstruct all quantities correctly
  - for the analysis cut to select the event
  - … and related to this we need also to know the purity of all the above, to remove unwanted contributions
- L: luminosity – there is always somebody calculating that for you…

Heavy Flavor Production at $p\bar{p}$

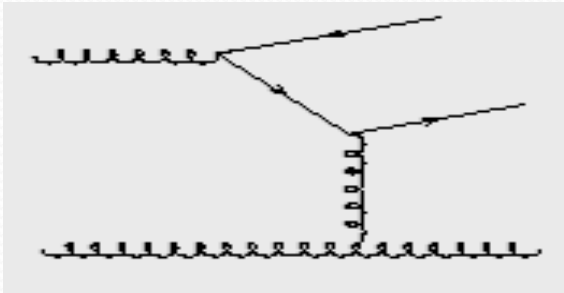
Leading Order Diagrams



Next to Leading Order Diagrams



O (α_s^3): gluon splitting



O (α_s^3): flavor excitation

σ_b is inferred from the measurement of the production rate as a function of p_T of the B_u hadrons or some of their decay products:

$$\frac{d\sigma\left(p\bar{p} \to B \to J/\psi, l\right)}{dp_T\left(B, J/\psi, l\right)} = \frac{d\sigma\left(qq/gg/qg \to bX\right)}{dp_T\left(b\right)} \otimes PDF^{p,\bar{p}} \otimes D^{b\to B} \otimes \text{EVT GEN}$$

measured — parton level calculation (NLO, FNLLO) — p structure — frag — decay

What we see today

- Single b cross section
  - Sensitive high order QCD effects
- Correlated bb cross section
  - Dominated by LO diagrams

Single b production

- Tev Run I: b-quark production higher than expected from NLO theory
- Big theoretical effort to understand discrepancies:
  FONLL + PDF + Frag. Fun. + α_s -> New prediction for Tevatron in 2002/3 [1]
- Discrepancies between different measurements [2]
- Tevatron RUN II: huge production of b quarks
  - First measurement of B-quark production using inclusive J/ψ [3]
    - Good agreement with FONLL
  - Precise measurement of the cross section in different modes
  - Check the pattern of the different experimental results

[1] M.Cacciari and P.Nason, PRL 89, 122003 (2002)
[2] F. Happacher et. al., PRD73, 014026 (2006)
[3] D. Acosta et al., PRD71 032001 (2005)

Single b production review [2]

Compare measurements to NLO calc. (NDE) [4]

channel (ex.)	R for p_T^{min} (GeV/c) = 6	8-10	12-15	19-21	≈29	R to FONLL
J/ΨK⁺ (CDF)		4.0±15%	(3.4)			1.5±15%
J/ΨK⁺ (CDF)		2.9±23%	(1.9)			
μX (CDF)				2.5±26%	(1.9)	
eX (CDF)			2.4±23%			
eD° (CDF)				2.1±34%		
J/ΨX (CDF)		4.0±10%	(3.4)			
J/ΨX (CDF2)		3.1±9%	(2.7)			1.1±9%
μX (DØ)	2.1±27%		(1.7)			
μX (DØ)	2.5±25%		(3.5)			
b jets(μ) (DØ)				2.4±20%		

$\langle R \rangle = \sigma(\text{data})/\sigma(\text{NLO}) = 2.8$, $RMS = 0.7$

Excluding J/Ψ $\langle R \rangle = 2.33$, $RMS = 0.19$

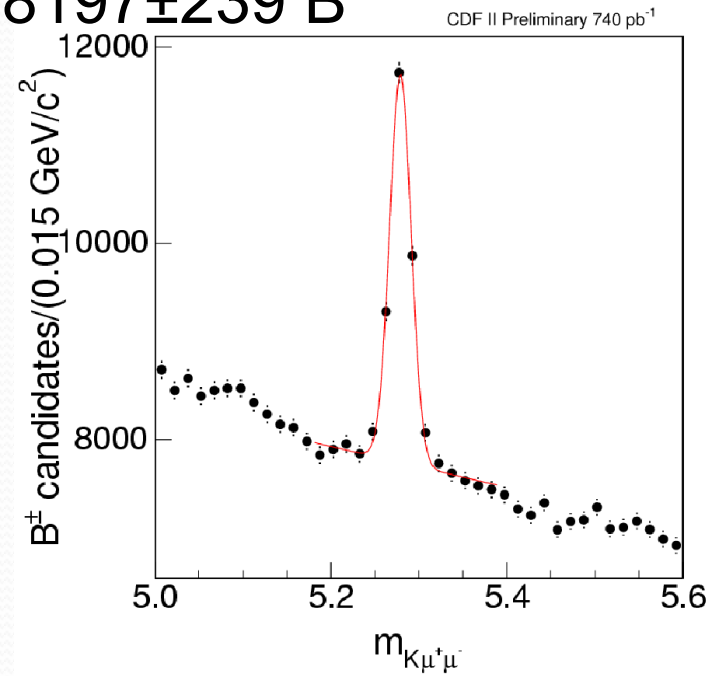
[4] P. Nason et. al., Nucl. Phys. B327, 49 (1998)

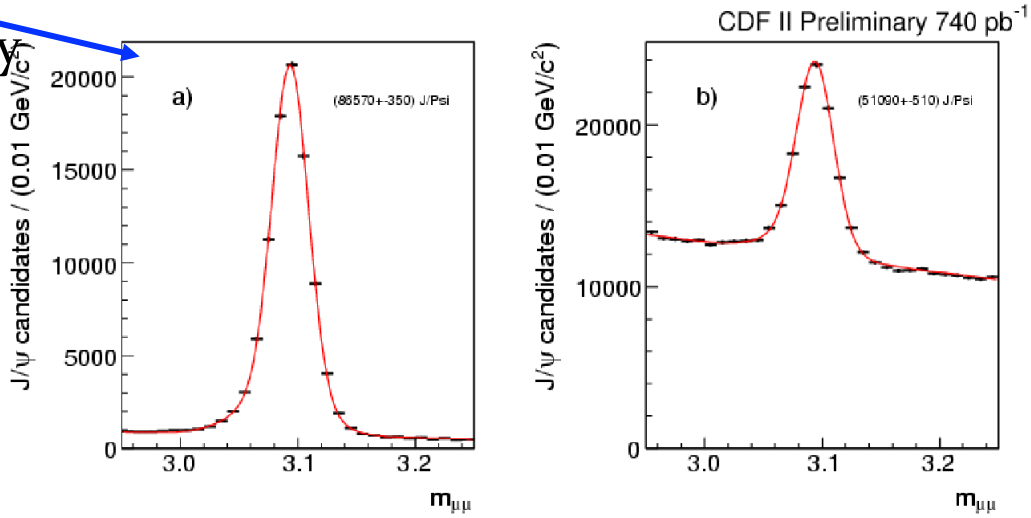
σ_B using $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+\mu^-$

PRD75, 012010 (2007)

- Fully reconstructed mode
- Reduce systematics
  - No L_{xy} cut systematics
- Kinematical cuts
  - $p_T(B^+) > 6$ GeV/c & $|y| < 1$
  - $p_T(\mu) > 2$ GeV/c & $|\eta(\mu)| < 0.8$
  - $p_T(K) > 1.25$ GeV/c & $|\eta(K)| < 1.3$
- Acc. times eff. from MC
- Correct efficiencies with data
- Dominant sys. 6% from luminosity

8197±239 B^+





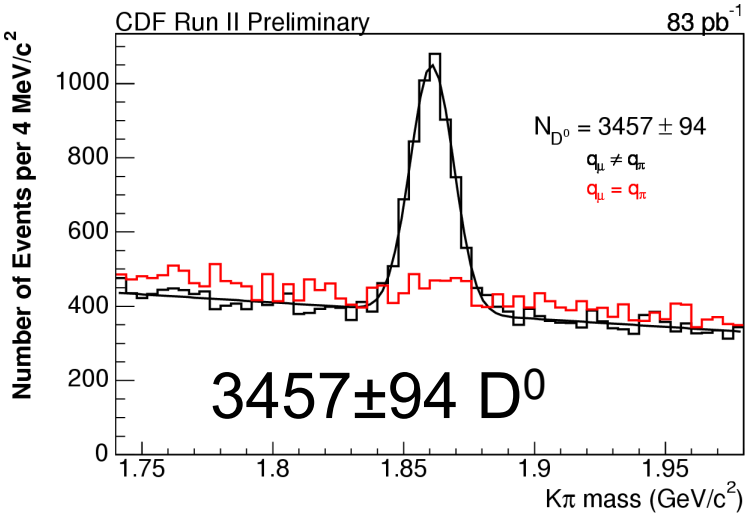
$$\sigma_{B^+}\left(p_T \geq 6.0\ \text{GeV}/c,\ |y| < 1\right) =$$

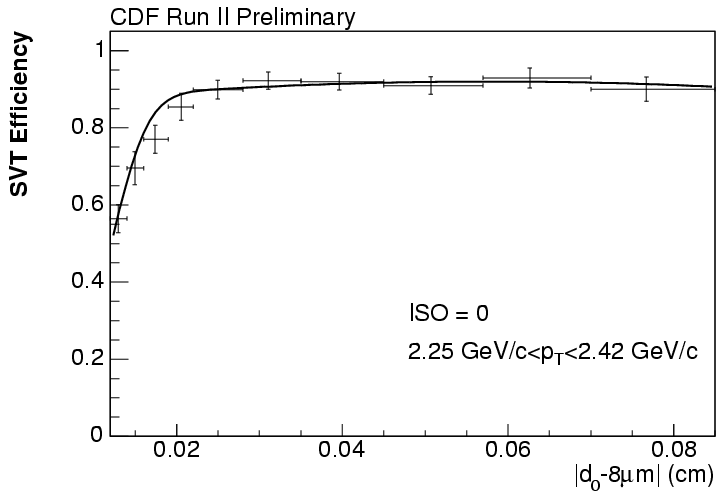
$$2.78\ \mu\text{b} \pm 0.24\ \mu\text{b}$$

σ_B using $H_b \rightarrow \mu\text{-}D^0X$, $D^0 \rightarrow K^-\pi^+$

PRD79, 092003 (2009)

- Clean mode low uncertainties
- SVT trigger: lepton + displaced track
- Kinematical cuts
  - $p_T(\mu D^o) > 9$ GeV/c & $|\eta(\mu D^o)| < 0.6$
- Calculate acceptance with MC
  - p_T-y spectrum from CDF meas. & NLO calc.
- Measure efficiencies with data
- Remove resonant bkg=12.0% ±3.2%
  - $c\bar{c}, b\bar{b}, B \rightarrow DD, B \rightarrow D\tau$
- Unfolding $p_T(\mu D^o) \rightarrow p_T(H_b)$ with MC input
- Result: $\sigma_B\left(p_T \geq 9.0 \text{ GeV/}c,\ |y| < 0.6\right)$





$$\sigma \times BR = 3.53\ \text{nb} \pm 0.20\ \text{nb (stat.)}\ ^{+0.34}_{-0.36}\ \text{nb (syst.)} \quad (D^0)$$

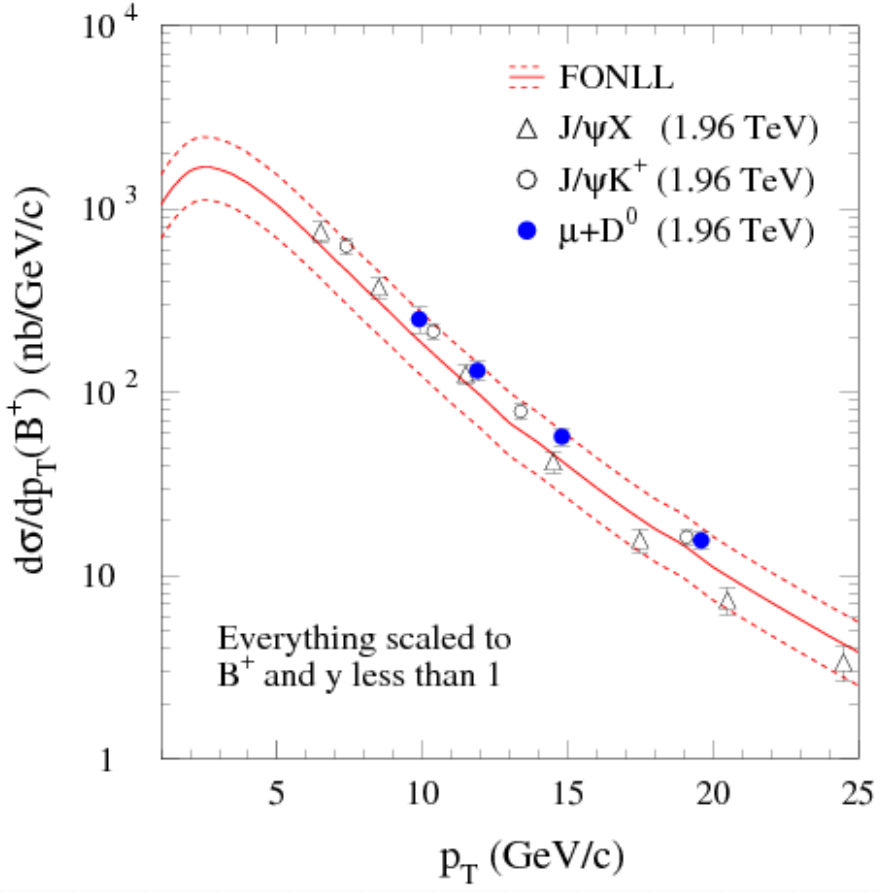
$$\sigma = 1.34\ \mu\text{b} \pm 0.08\ \mu\text{b (stat.)}\ ^{+0.13}_{-0.14}\ \mu\text{b (syst.)} \pm 0.07\ \mu\text{b (BR)} \quad (D^0)$$

$$\sigma = 1.47\ \mu\text{b} \pm 0.18\ \mu\text{b (stat.)}\ ^{+0.17}_{-0.19}\ \mu\text{b (syst.)} \pm 0.11\ \mu\text{b (BR)} \quad (D^{*+})$$

sub sample

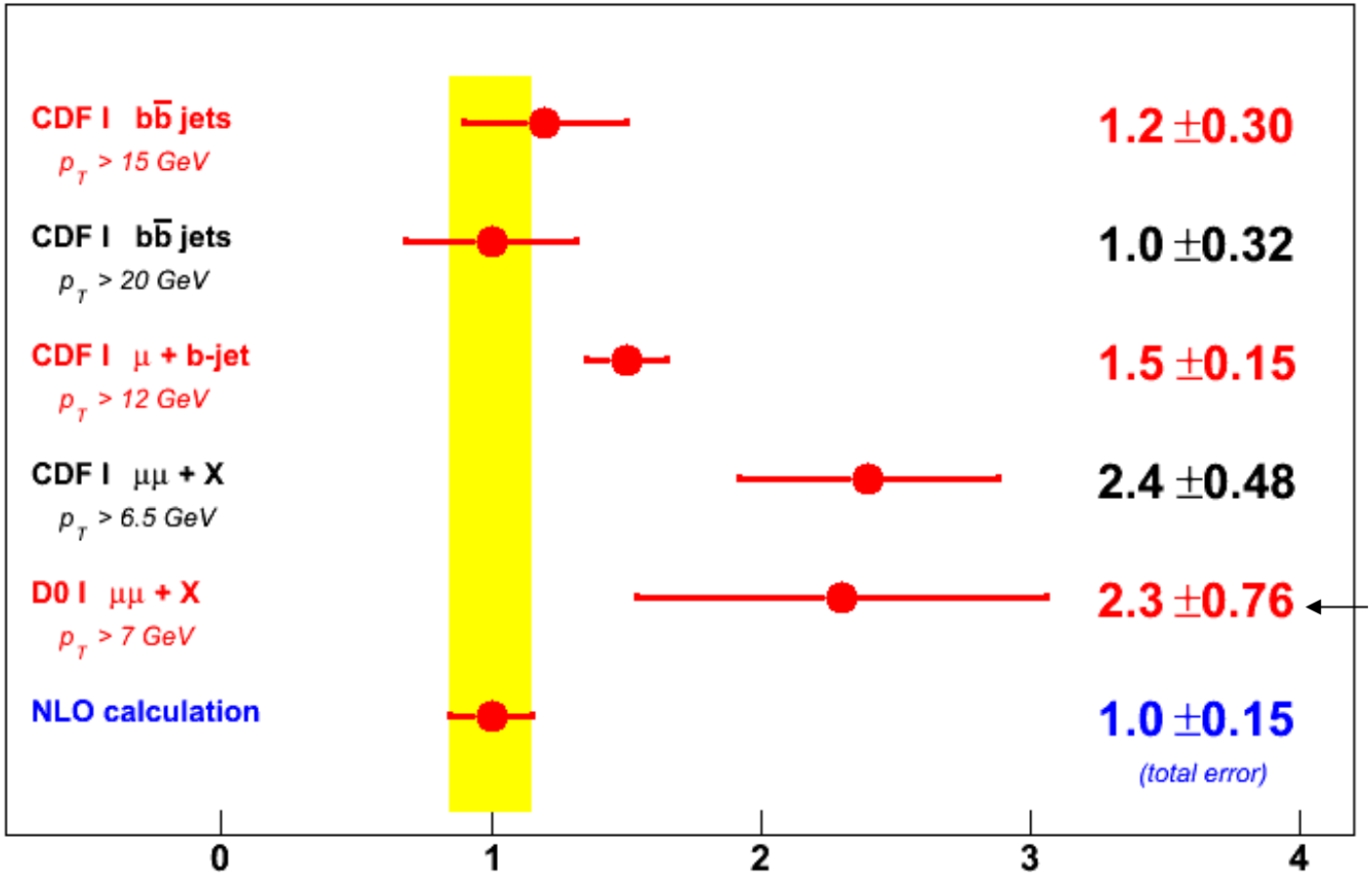
Single b production CDF Run II

- 3 separate measurements
- Improved precision down to ~10%
- Allow a reliable test of theory
- Consistent with FONLL



$b\bar{b}$ correlations review [2]

Run I $b\bar{b}$ xsection increasing with # of muons?

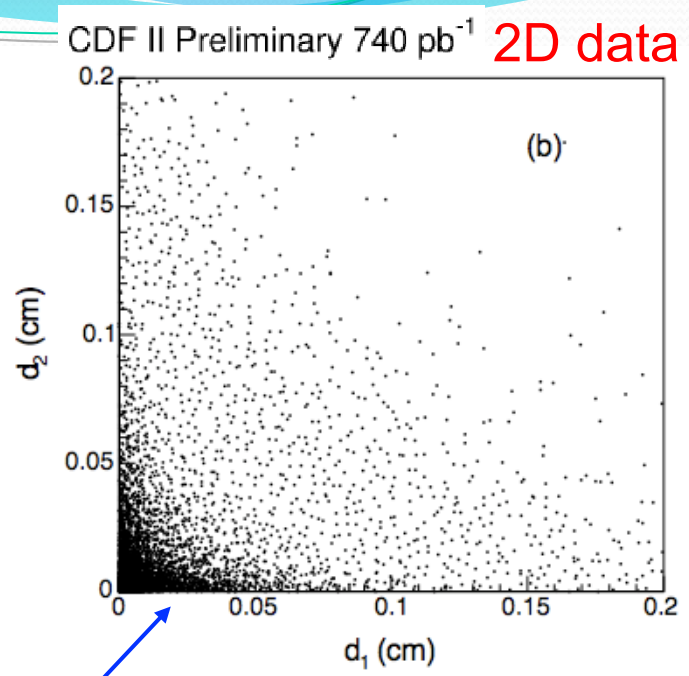


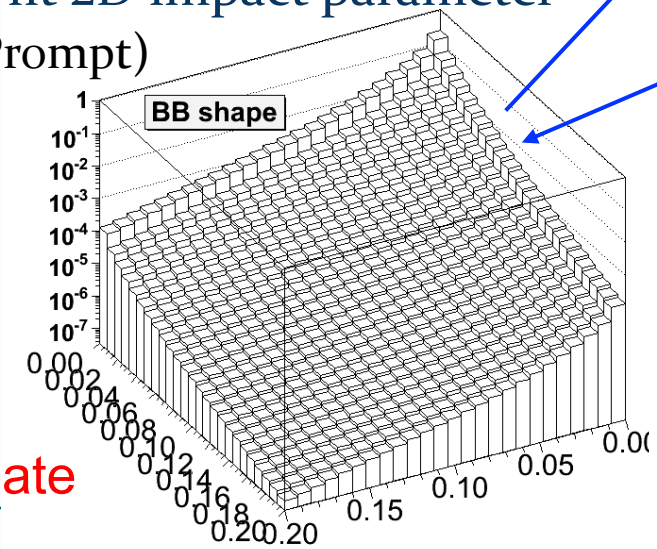
$< R_{2b} > = \sigma(\text{data})/\sigma(\text{NLO}) = 1.8$ with RMS = 0.8

σ_{bb} using inclusive $\mu\mu$ events

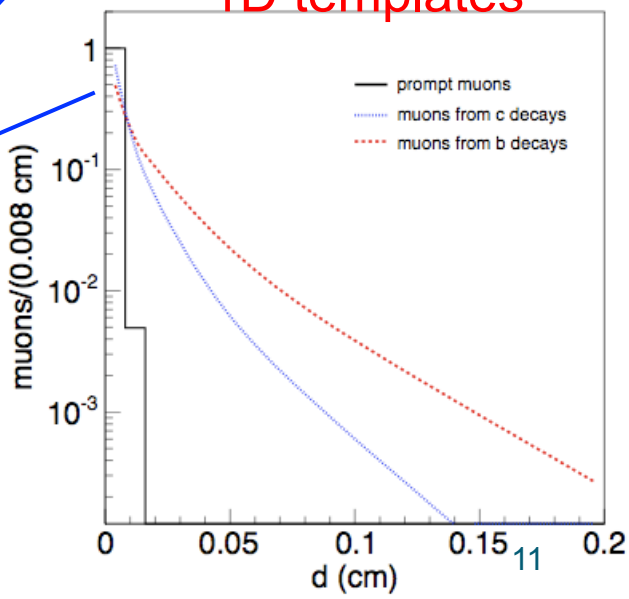
PRD77, 072004 (2008)

- Select $\mu\mu$ events
  - $p_T \geq 3$ GeV/c && $|\eta| \leq 0.7$ && $5 < m_{\mu\mu} < 80$ GeV/c²
- Dimuon events are produced by:
  - Decays of heavy flavor quark pairs (bb, cc)
  - Prompt Drell Yan processes
  - Charmonium, bottomonium, K and π decays
  - Misidentification of K and π mesons
- Sample composition --> fit 2D impact parameter
  - templates from Data (Prompt)
  - templates from tuned Herwig simulation

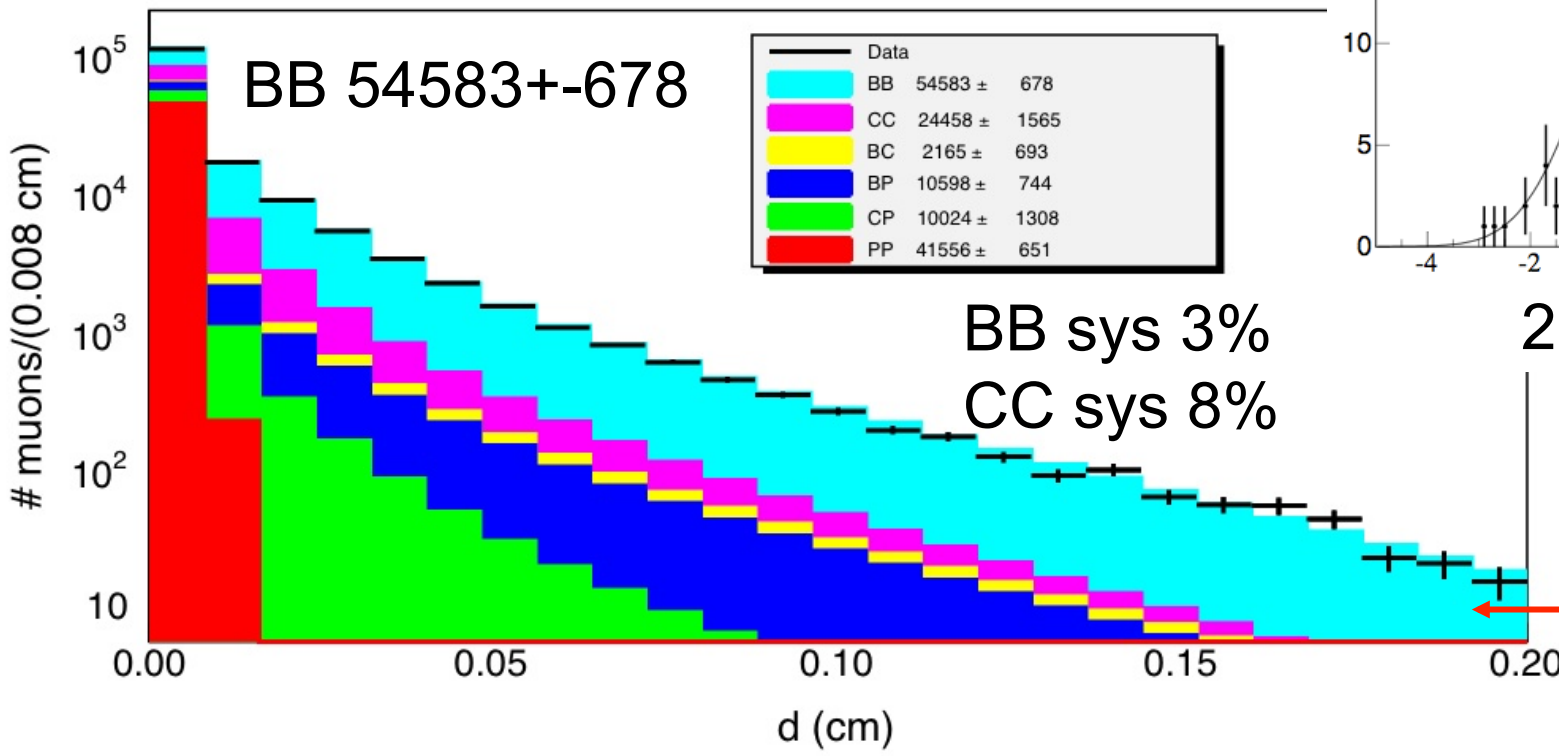




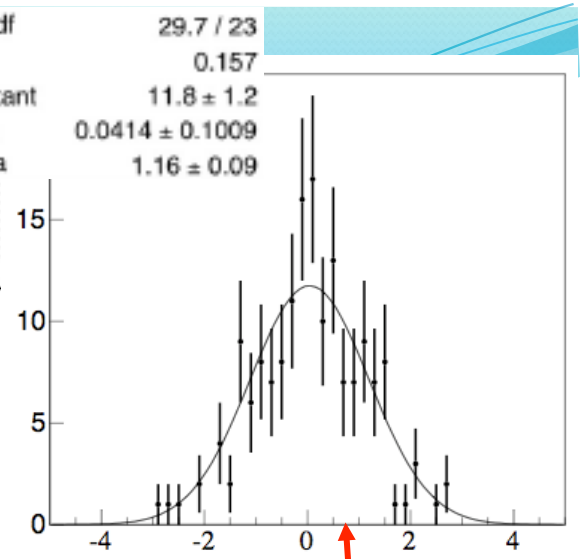
1D templates



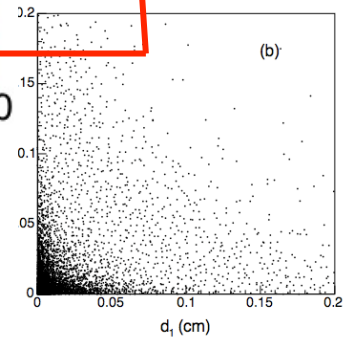
1D i.p. projection

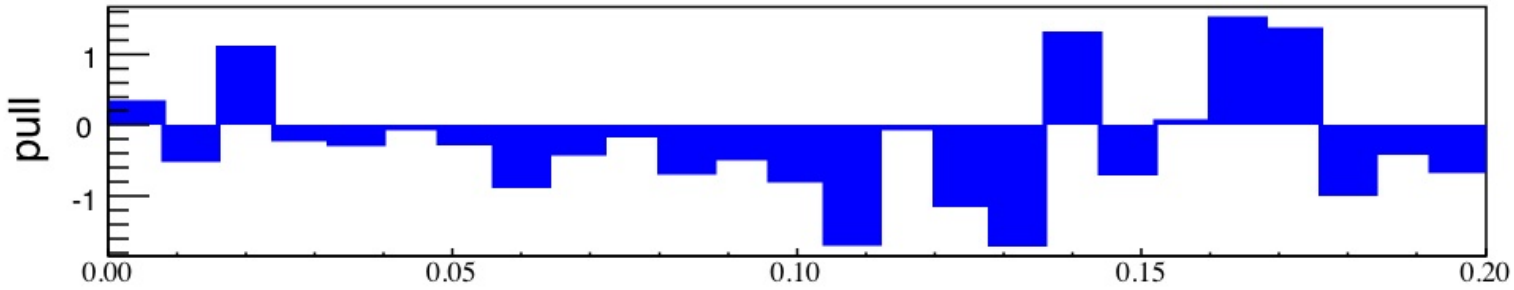


BB sys 3%
CC sys 8%



2D fit pulls





$\sigma_{b\to\mu,b\to\mu}$ $\sigma_{c\to\mu,c\to\mu}$

Remove fake muons

Measure acceptance & efficiency

Dimuon purity

bb : 0.96+-0.04

cc : 0.81+-0.09

Component	$\mathcal{A}_{\rm corr}$ (%)	No. of Events
BB	4.56 ± 0.15	52400 ± 2278
CC	4.28 ± 0.17	19811 ± 2540

L=740pb^{-1}

$$\sigma = \frac{N}{L \times A_{corr}}$$

$$\sigma_{b\to\mu,b\to\mu} = \sigma_{bb} \cdot BR(bb \to \mu\mu X) \cdot A(p_T^{\mu} > 3GeV,\ |\eta^{\mu}| < 0.7,\ 5 < m_{\mu\mu} < 80GeV)$$

$\sigma_{b\to\mu,b\to\mu}$ = 1549+-133 pb

$\sigma_{c\to\mu,c\to\mu}$ = 624+-115 pb

Data vs NLO

NLO = MNR + MRST98 + Peterson + EvtGen

$$\sigma_{b\to\mu,b\to\mu} = \sigma_{bb} \cdot BR(bb \to \mu\mu X) \cdot A(p_T^{\mu} > 3GeV,\ |\eta^{\mu}| < 0.7,\ 5 < m_{\mu\mu} < 80GeV)$$

NLO: 15% uncertainty

	$\sigma_{b\to\mu,b\to\mu}$	$\sigma_{c\to\mu,c\to\mu}$
Data	1549+-133 pb	624+-104 pb
NLO Peterson	1293+-55 pb ε=0.006	230+-16 pb ε=0.06
NLO Peterson	1543 pb ε=0.002	383 pb ε=0.02

- R1 = data/NLO - experimental and BR uncertainties only
  - $R1_{b\to\mu,\ b\to\mu}(\varepsilon=0.006) = 1.20+-0.11$

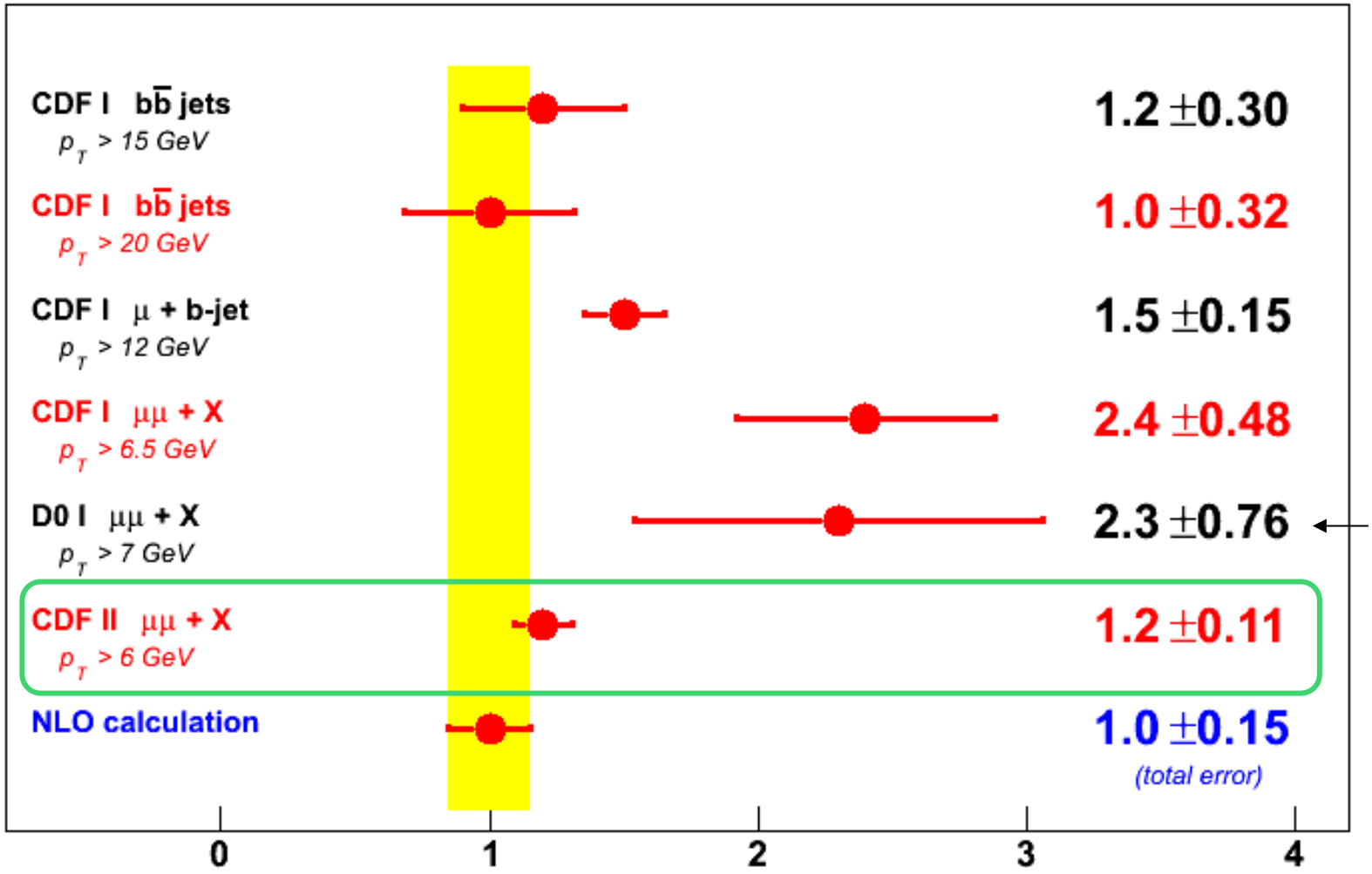
R1

NLO prediction: 1348 +- 209 nb

$$\sigma_{b\bar{b}}(p_T \geq 6\ \mathrm{GeV/c}, |y| \leq 1) = 1618 \pm 148\ \mathrm{nb}$$

$b\bar{b}$ correlations

High di-muon cross-section NOT observed in Run II



Ratio to HVQJET

$< R_{2b} > = \sigma(\text{data})/\sigma(\text{NLO})$

The common denominators

- Keep things as simple as possible to reduce systematics
  - Some cuts are strongly related to the measurement we want to perform
- Rely as little as possible on MC
  - Check how cuts on reconstructed analysis propagates back to the production spectra
- Rely on data to adjust all efficiencies
  - Several unbiased samples are needed
  - At least 4 trigger paths used for each analysis

Summary

- Single b quark xsec in Run I → higher than theory
- Interplay between theory and measurement fundamental to understand nature
- Run II improved precision
  - 3 measurements agree within 10%
  - they are compatible with FONLL

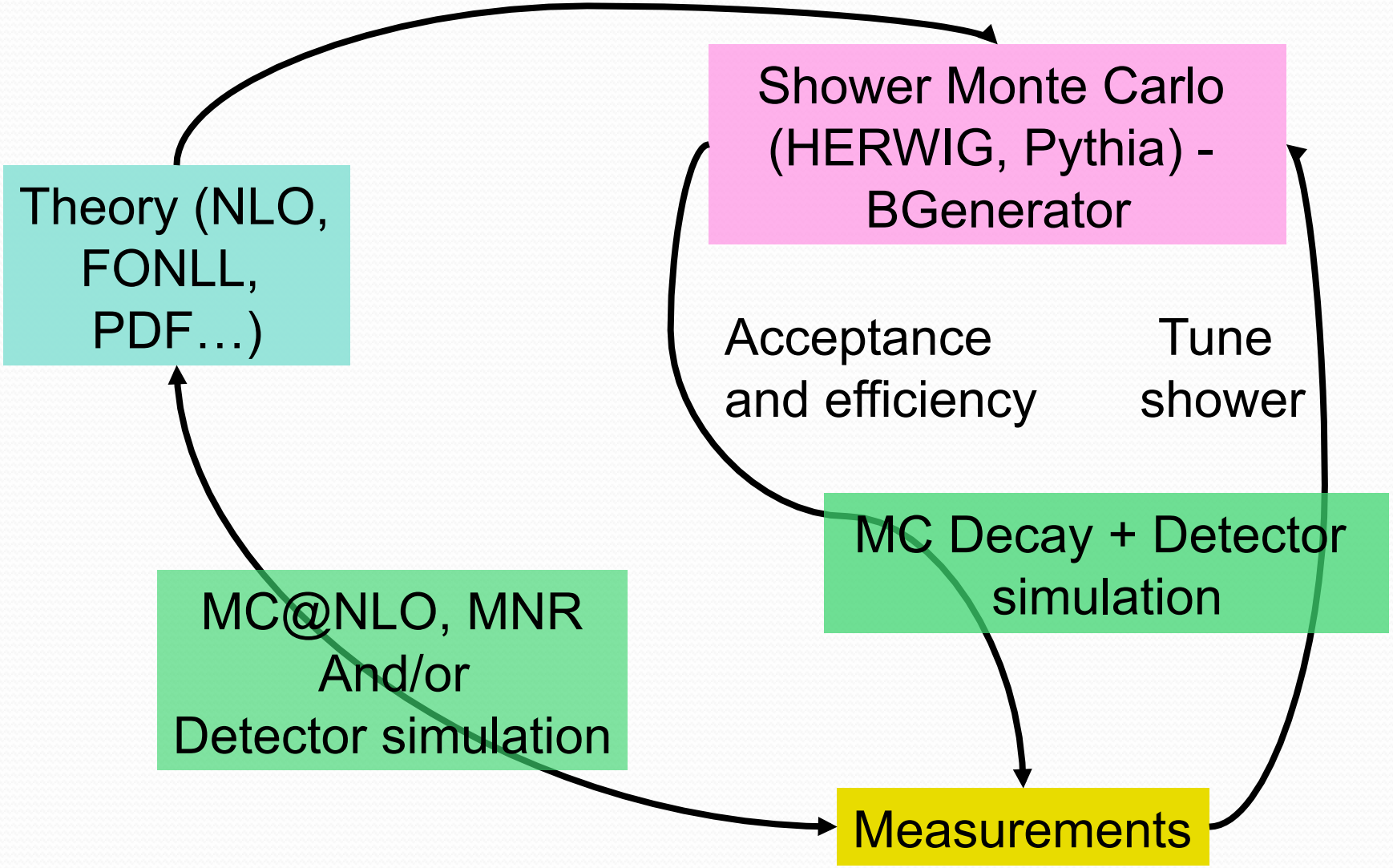
- Run I: correlated $b\bar{b}$ xsec increases w/ # of leptons (?)
- Run II: $\sigma(p\bar{p} \rightarrow \mu\mu + X)$ compatible with NLO
  - Indicates no issues with bb xsec

- We now have a clear picture of b cross sections!

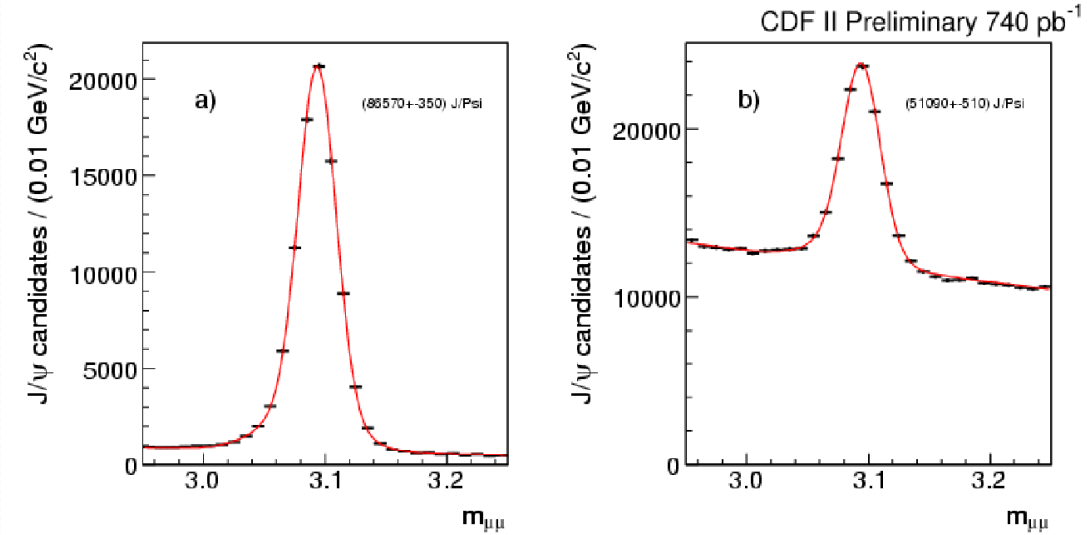
- Now it is time to leave the stage to LHC … on this …

BACKUP

The players of the game



Efficiency correction



Source	Data	Simulation	Corr.
COT tracking	$(0.996 \pm 0.006)^3$	$(0.998 \pm 0.002)^3$	1.00 ± 0.02
Kaon interaction			1.000 ± 0.003
CMU acc. and eff.	$(0.6251 \pm 0.0047)^2$	$(0.6439 \pm 0.0004)^2$	0.942 ± 0.014
L1 CMU primitives	$(0.9276 \pm 0.0005)^2$	$(0.8369 \pm 0.0004)^2$	1.228 ± 0.002
L1 eff.	0.9879 ± 0.0009	0.9868	1.0011 ± 0.0009
L2 eff.	0.9948 ± 0.0001	0.9939	1.0009 ± 0.0001
L3 eff.	$(0.997 \pm 0.002)^2$	1	0.994 ± 0.004
Total	0.328 ± 0.008	0.283 ± 0.002	1.152 ± 0.029

Single b xsec w/ $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+\mu^-$

$$\frac{d\sigma(B^+)}{dp_T} = \frac{N/2}{\Delta p_T \times \mathcal{L} \times \mathcal{A}_{\rm corr} \times BR}$$

$\sigma_{B^+}(p_T \geq 6$ GeV/c, $|y| < 1) =$ (2.78 ± 0.24) μb (4% stat)

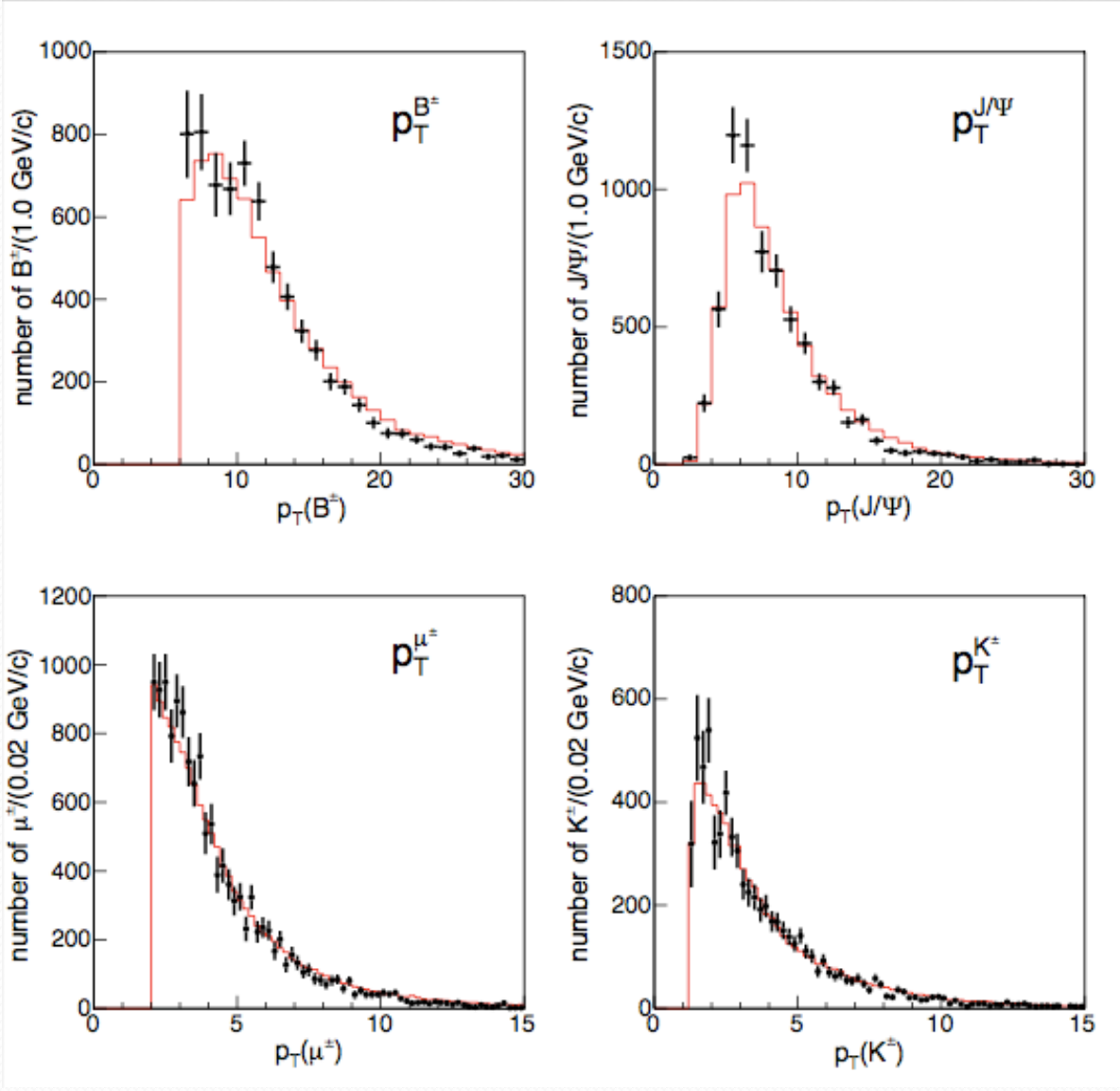
Ratio w.r.t. NLO: 2.80 ± 0.24

In agreement with RUN II J/ψX measurement

$< p_T >$ (GeV/c)	Events	Acceptance (%)	$d\sigma/dp_T$
7.38	2792 ± 186	1.780 ± 0.045	591.7 ± 59.0 (39.3 stat.)
10.38	2373 ± 110	4.405 ± 0.111	203.2 ± 17.8 (9.4 stat.)
13.39	1365 ± 66	6.872 ± 0.173	74.9 ± 6.6 (3.6 stat.)
19.10	1390 ± 63	10.16 ± 0.25	15.5 ± 1.3 (0.7 stat.)
≥ 25	277 ± 44	14.42 ± 0.36	

MC

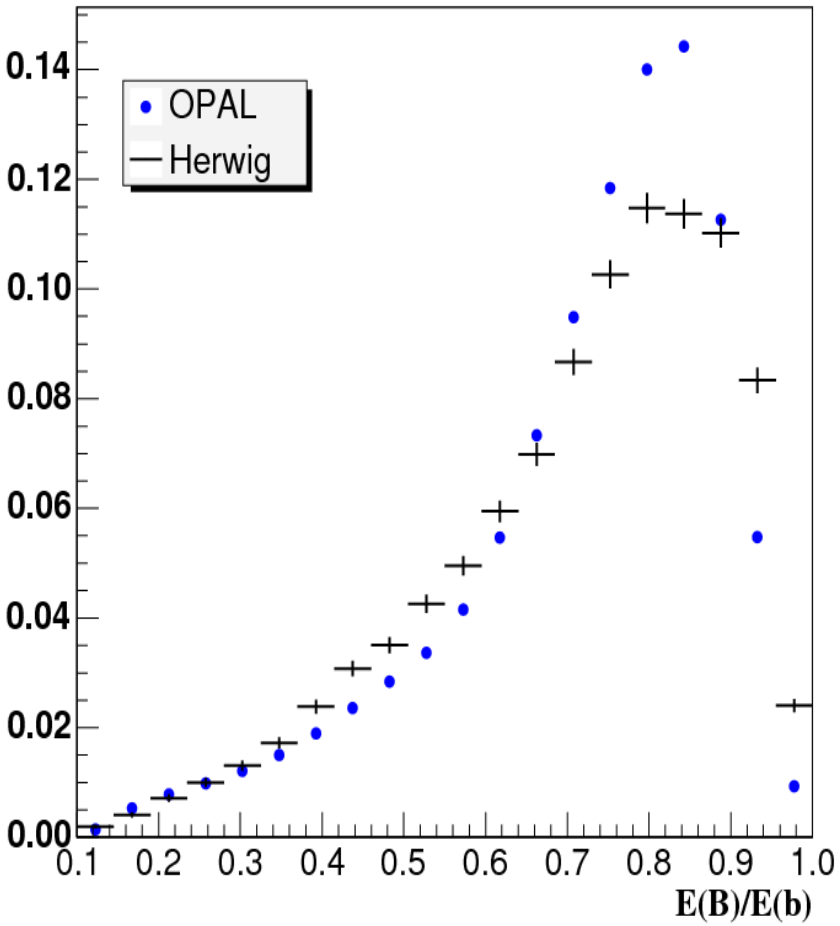
- Generate events based on NLO calculation
- PDF: MRSDo
- Decay B using EvtGen for B decays
- GEANT simulation of CDF
- Simulation of L1 and L2 primitives and algorithms

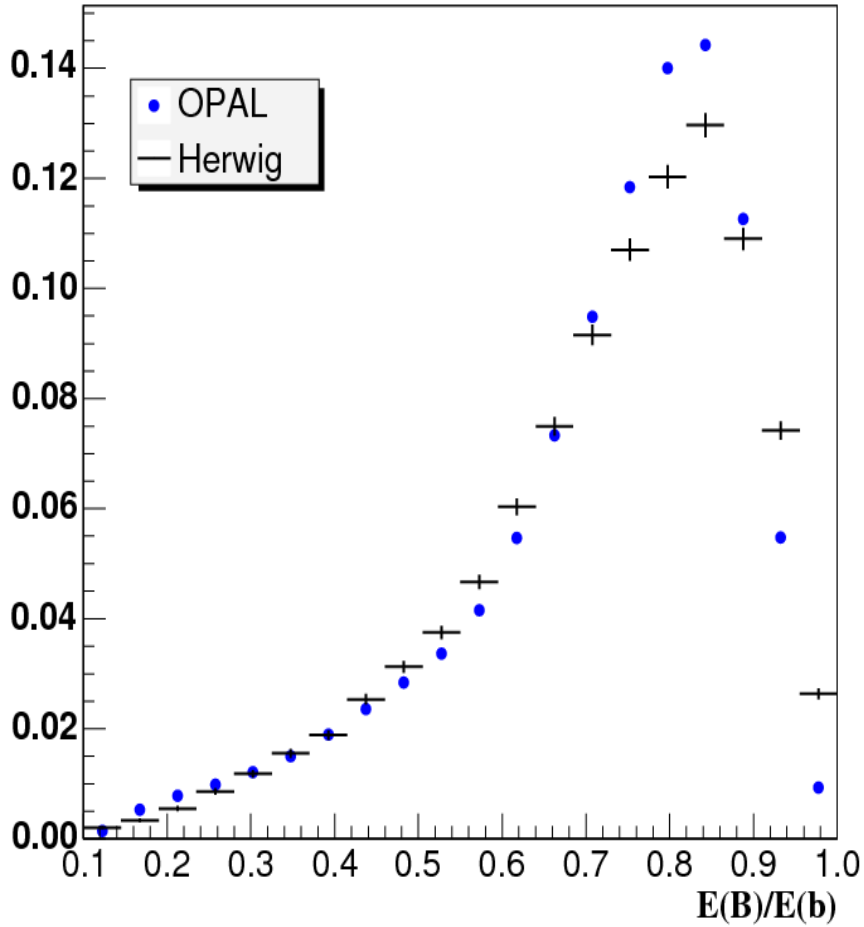


Fragmentation fractions

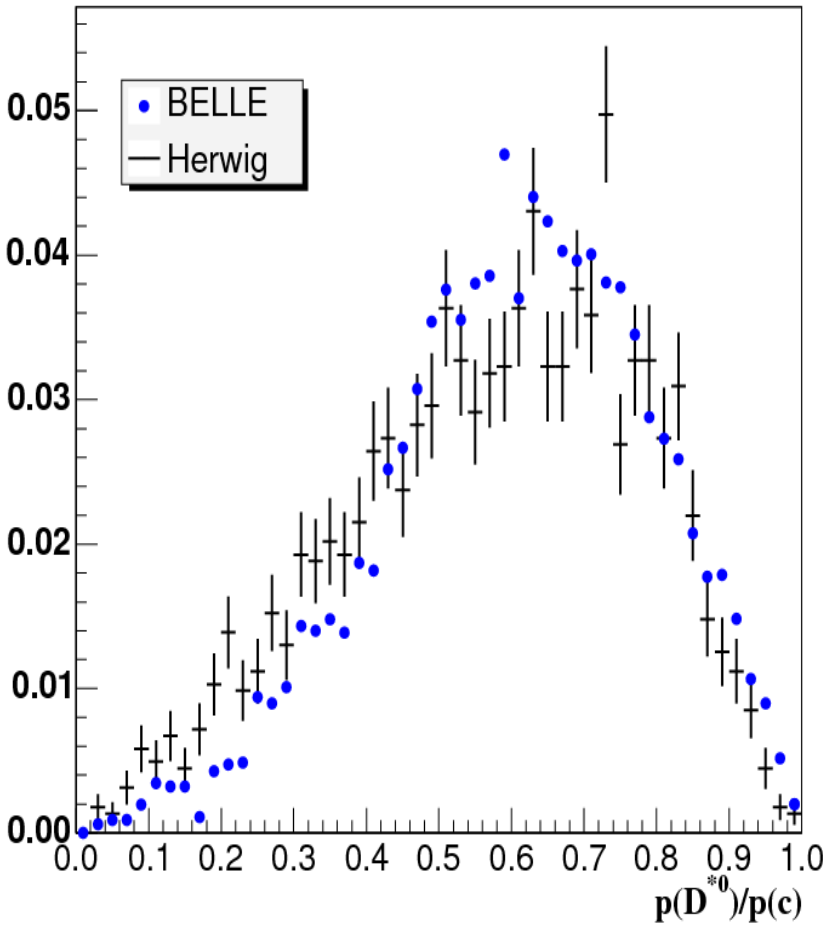
	expectation		HERWIG
$f_u = f_d$	=	$(39.7 \pm 1.0)\%$	39.6%
f_s	=	$(10.7 \pm 1.1)\%$	11.2%
f_{baryon}	=	$(9.9 \pm 1.7)\%$	9.6%
$f(c \to D^+) = f(c \to D^0)$	=	$(16.4 \pm 2.3)\%$	16.9%
$f(c \to D^{*+}) = f(c \to D^{*0})$	=	$(22.8 \pm 2.5)\%$	22.5%
$f(c \to D_s + D_s^*)$	=	$(12.1 \pm 2.5)\%$	11.5%
$f(c \to \text{baryons})$	=	$(9.5 \pm 4.0)\%$	9.7%

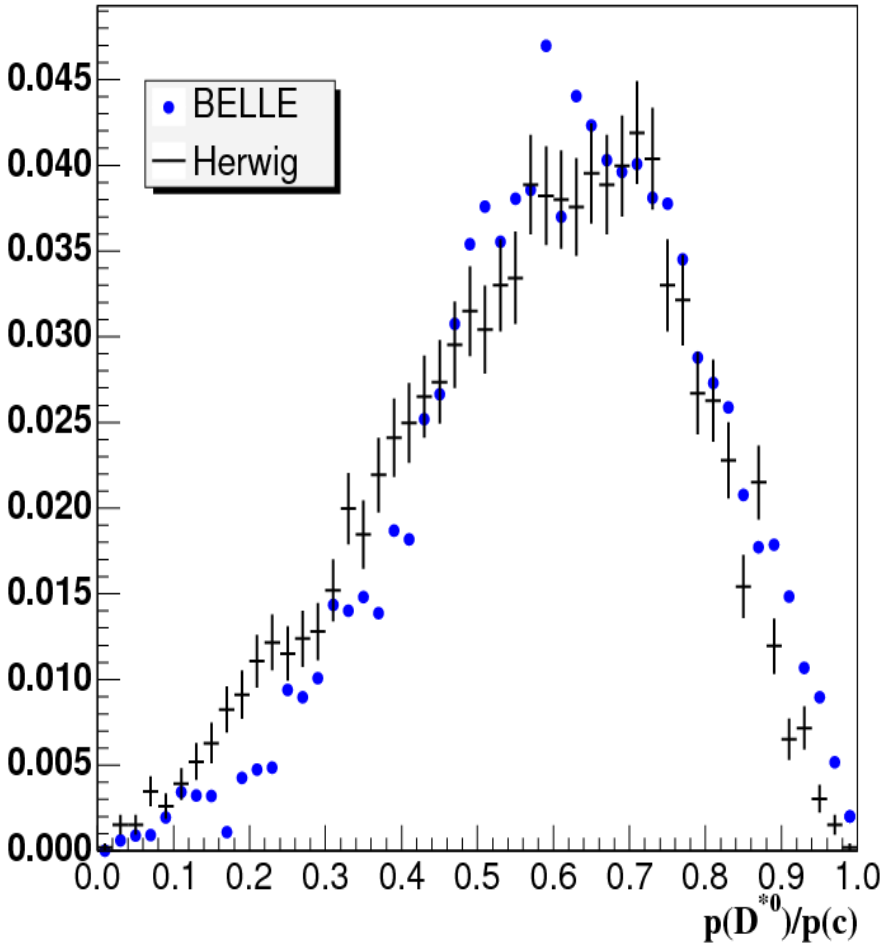
B fragmentation function



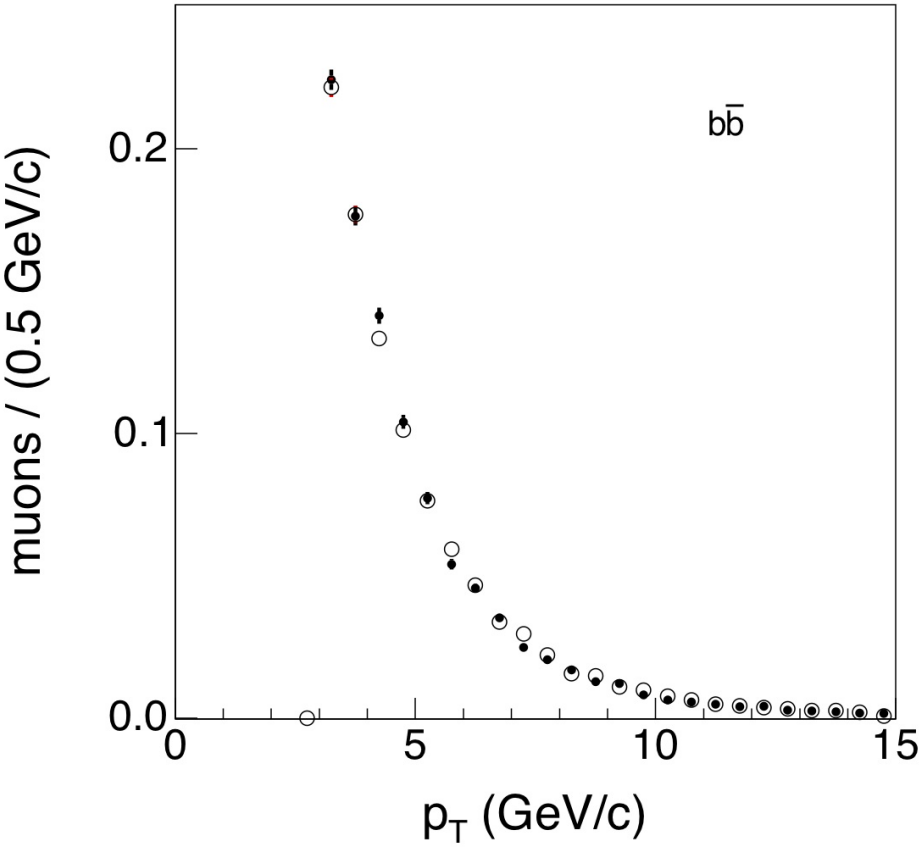


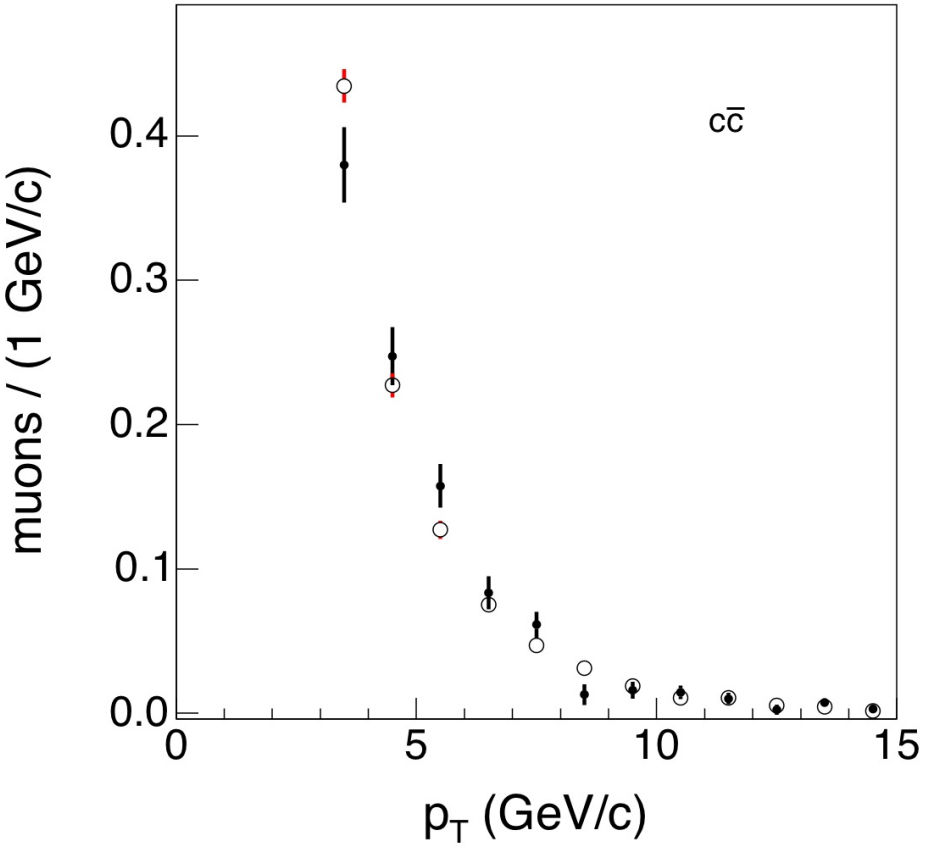
C fragmentation function





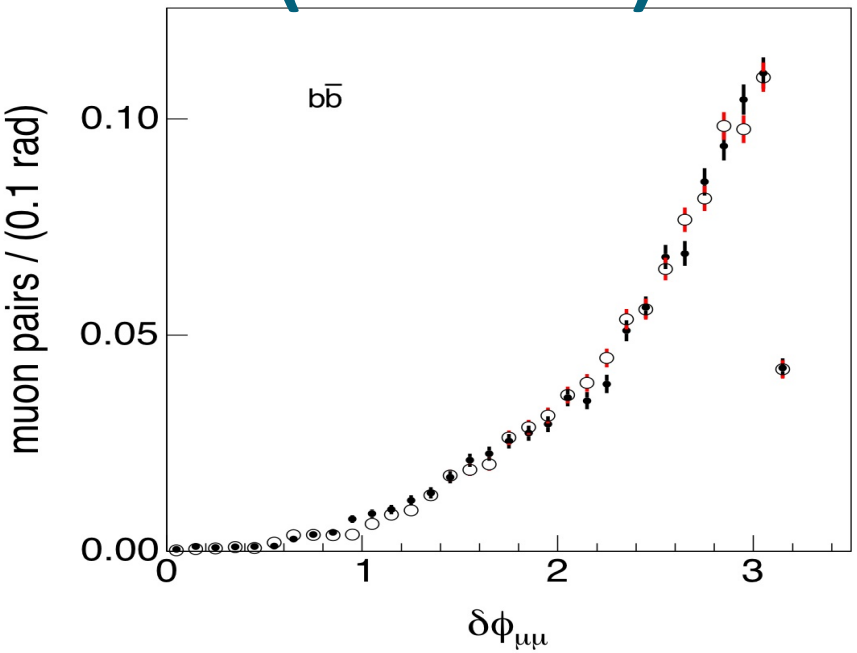
Data (sPlots[9]) vs MC (herwig)

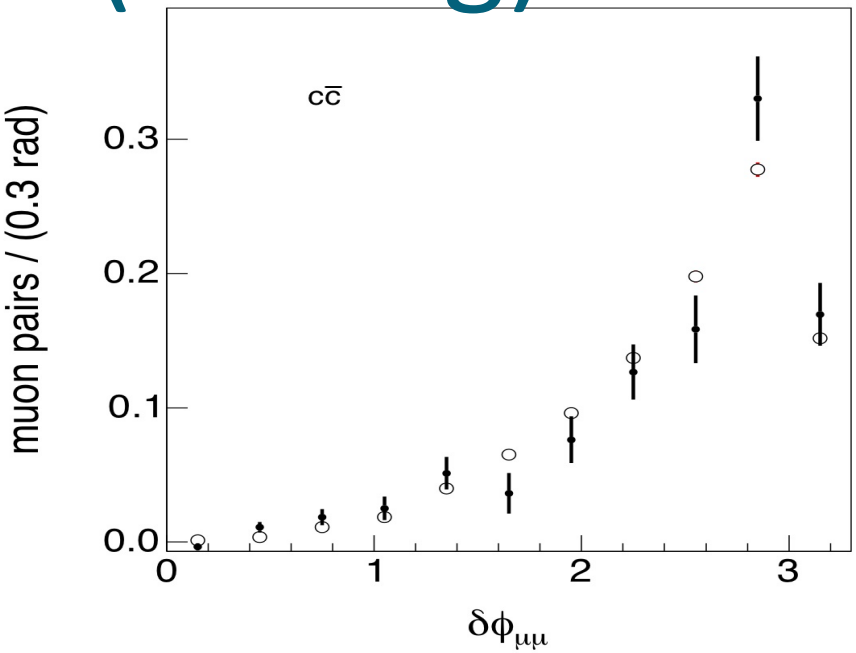


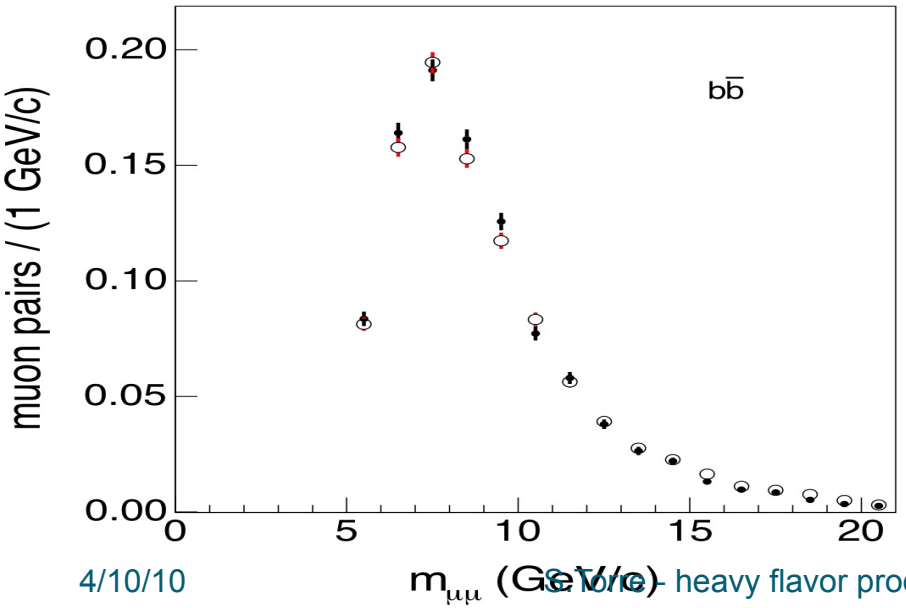


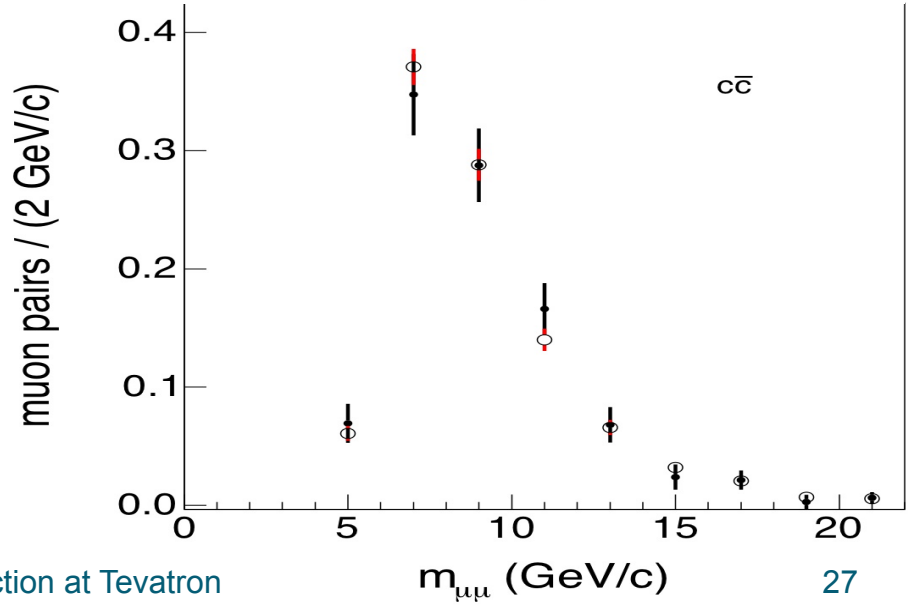
[9] M. Pivk and F. R. Le Diberder, NIM A555, 356 (2005)

Data (sPlots) vs MC (herwig)



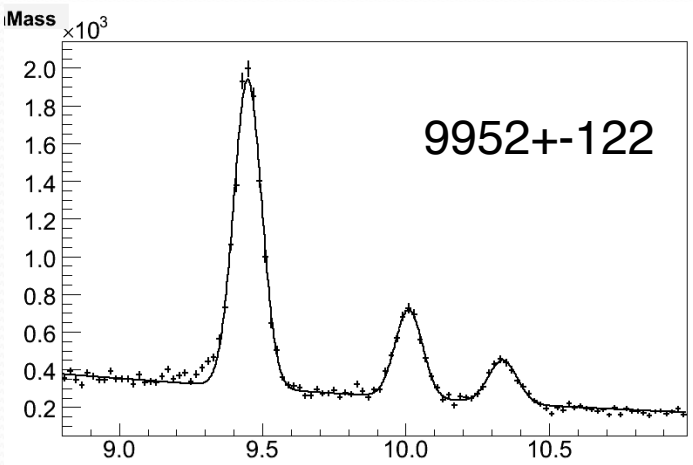
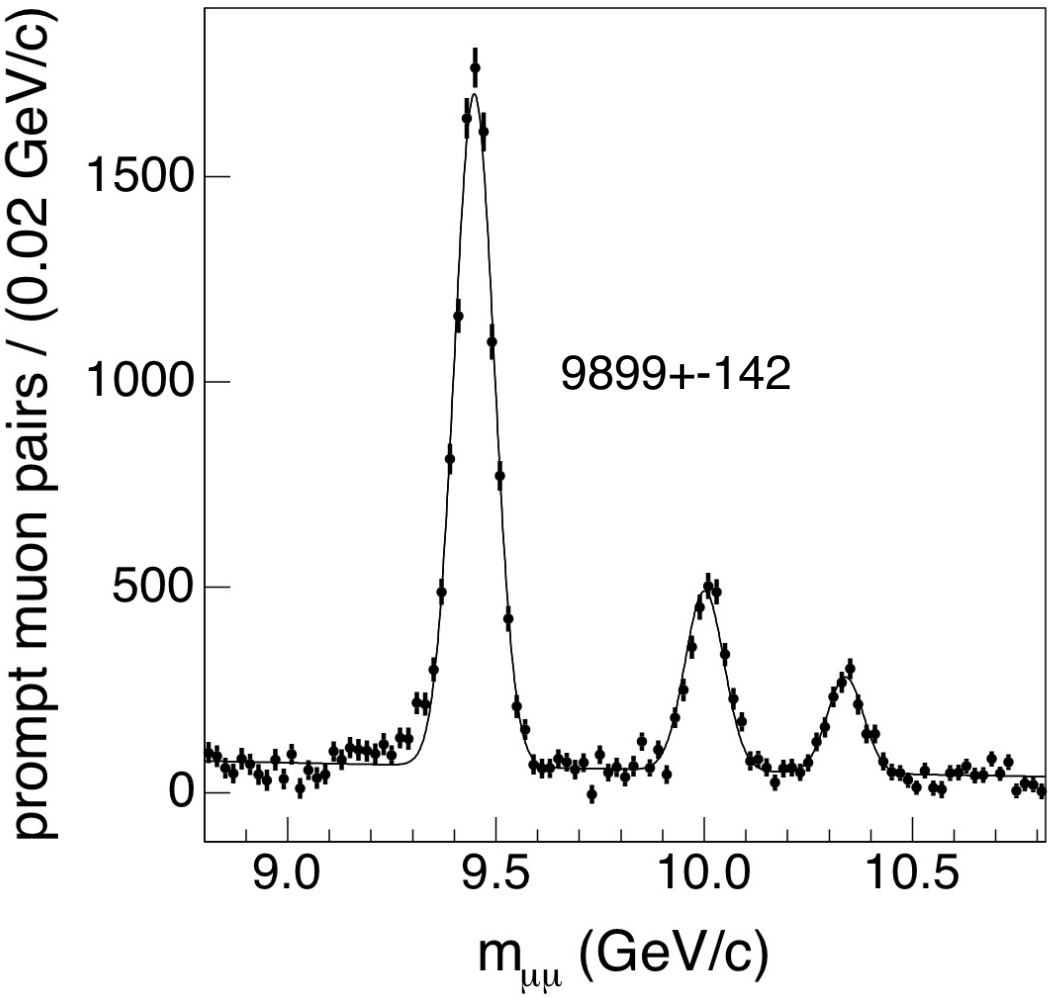






Υ in prompt

All data



Prompt sPlots