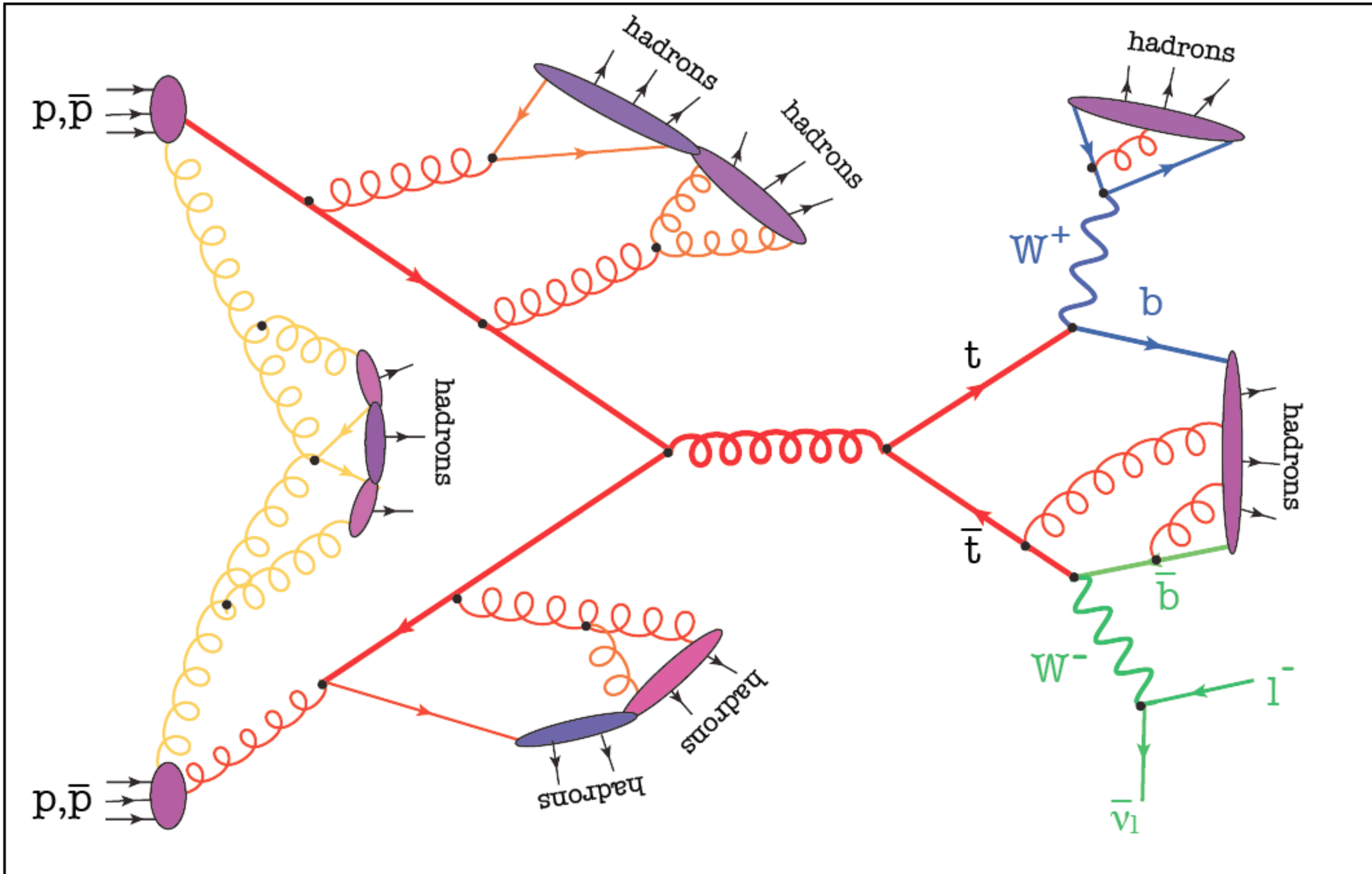
Heavy quark physics with LHCb

Rhorry Gauld

HEP Seminar
University of Liverpool - 04/03/15

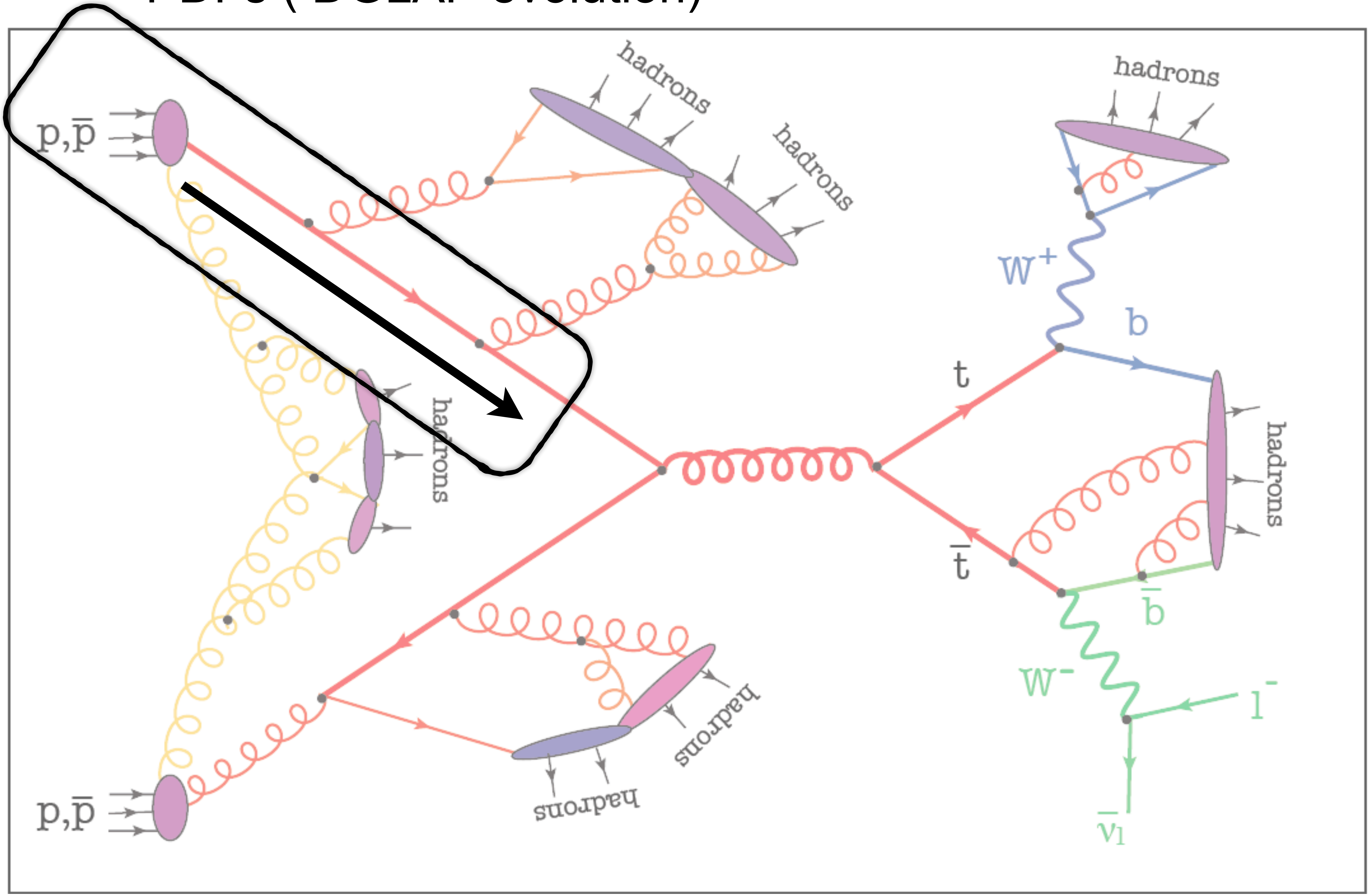
Overview

- Introduction and motivations
- Cross-section measurements
  - Results from 7 TeV data and implications
  - Prospects for 13/14 TeV
- Production asymmetry measurements
  - Results from 7 TeV (& new SM predictions)
  - Prospects for 13/14 TeV



Drawing by Keith Hamilton

PDFs (DGLAP evolution)



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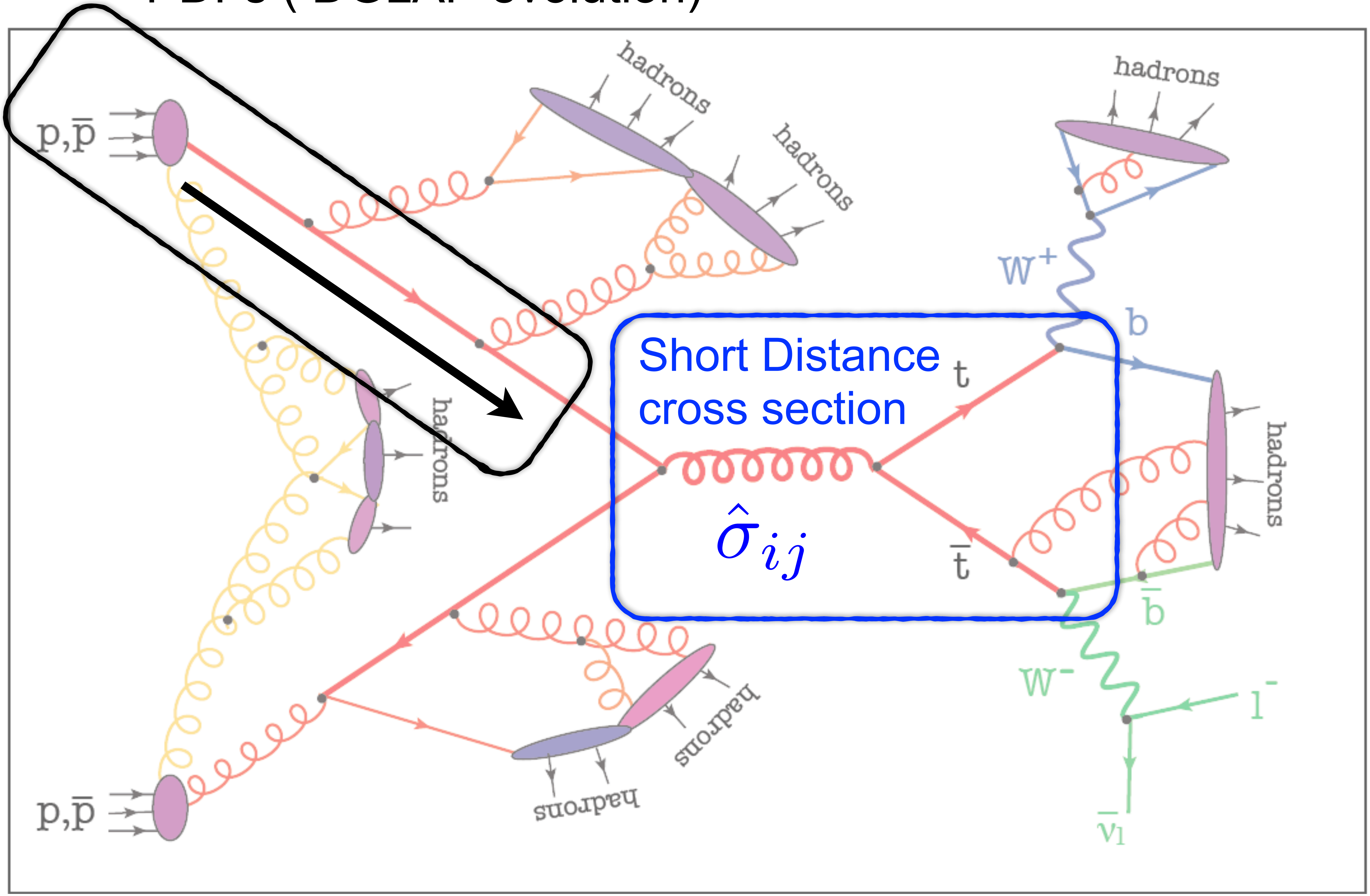

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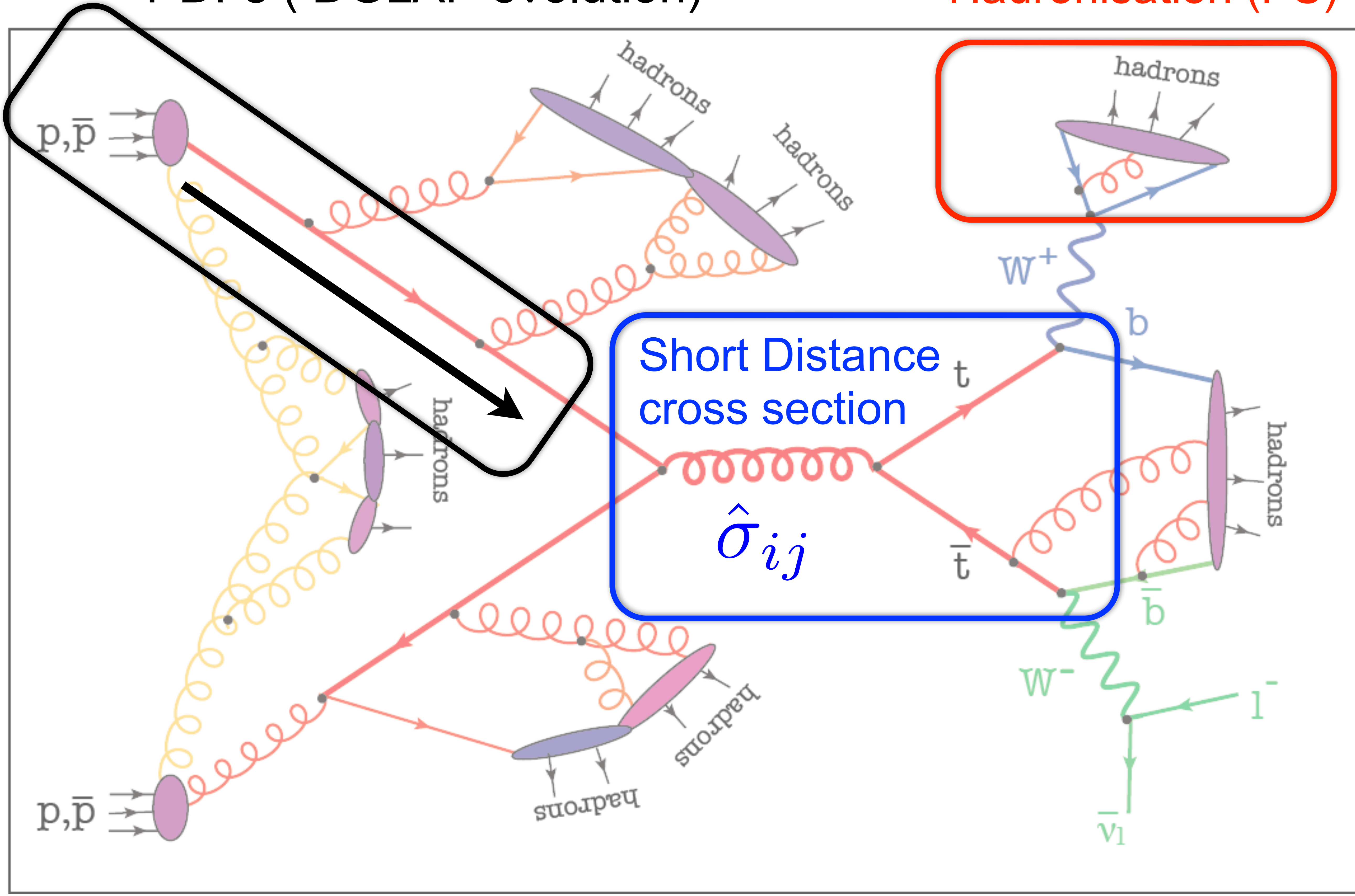
PDFs (DGLAP evolution)

Hadronisation (PS)



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How to compare with LHC data

$$\sigma_{P_A P_B \to Q\bar{Q}X} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) d\hat{\sigma}_{ab \to Q\bar{Q}X} \left(\hat{s}, \mu_F^2, \mu_R^2, \alpha_s(\mu_R^2)\right)$$

$$+ \mathcal{O}\left(\frac{Q^2}{\Lambda_{\mathrm{QCD}}^2}\right)$$

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Process **dependent** short-distance cross-section

NLO inclusive P. Nason, S. Dawson, and R. K. Ellis, 1988

NLO differential: P. Nason, S. Dawson, and R. K. Ellis, 1989

NLO interfaced with PS: S. Frixione, P. Nason, and B. R. Webber/(G. Ridolfi), 2003/(2007)

NNLO inclusive: M. Czakon, P. Fiedler, and A. Mitov, 2013

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+Exhaustive list of resummation calculations
+Electroweak corrections
+NLO decay

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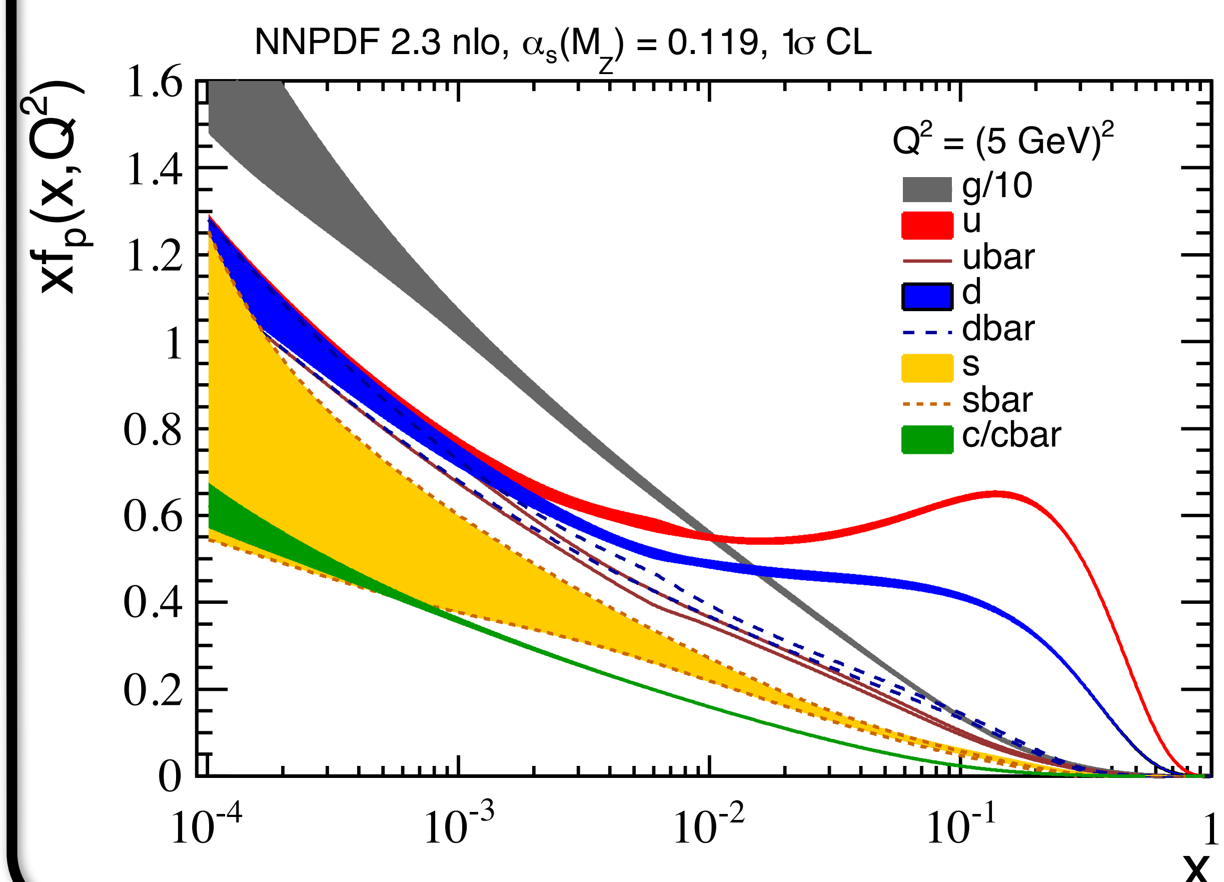
Process **independent** PDFs



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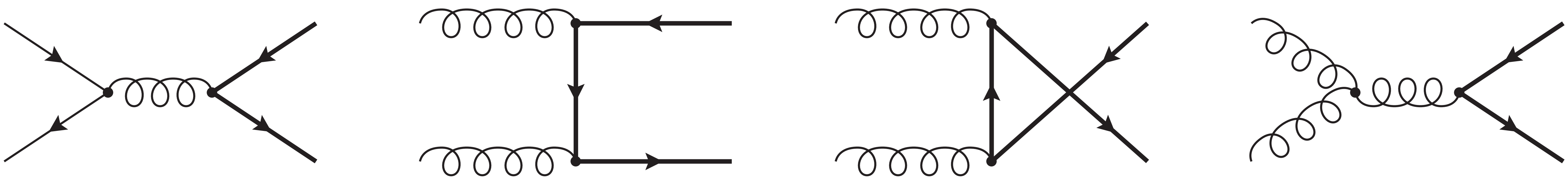
Theoretical uncertainty, $pp \to Q_3\bar{Q}_4 + X$



$$\hat{\sigma}_{ij}(\hat{s}, m_Q^2, \mu_F^2) = \frac{\alpha_s^2(\mu_R)}{m_Q^2}\left(\kappa_{ij}^{(0)} + \alpha_s(\mu_R)\kappa_{ij}^{(1)}(\mu_R) + \ldots\right)$$

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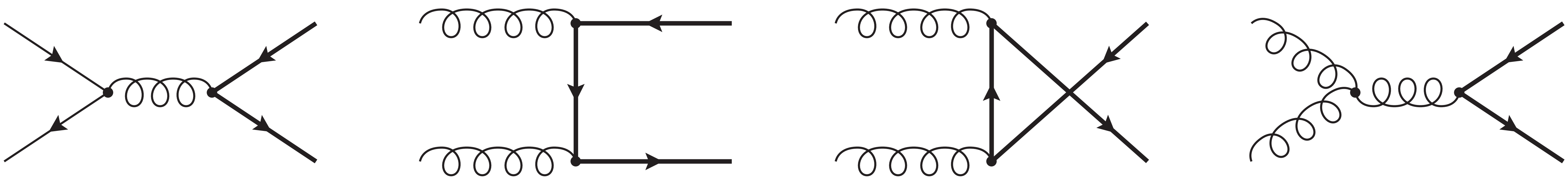

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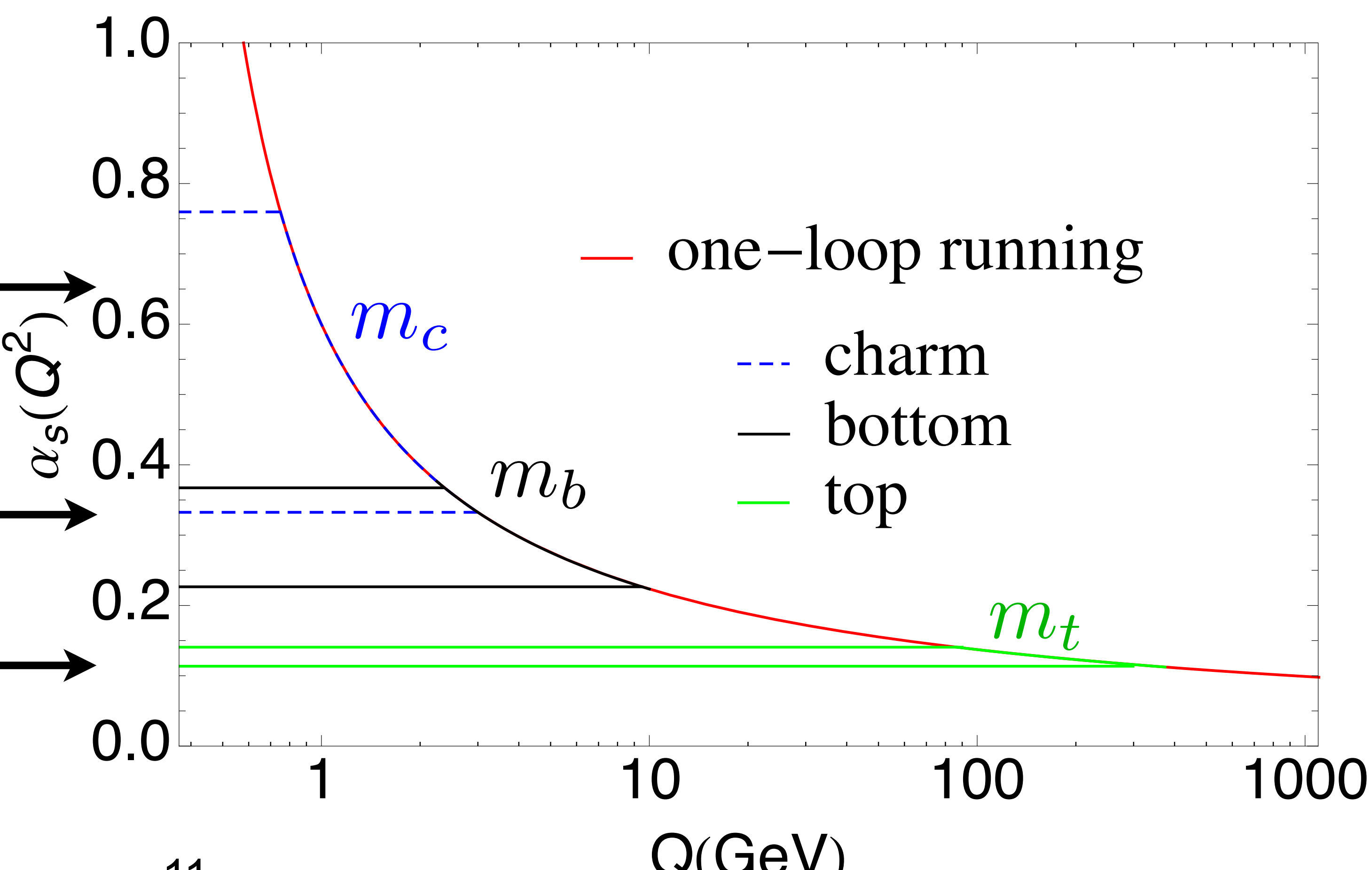
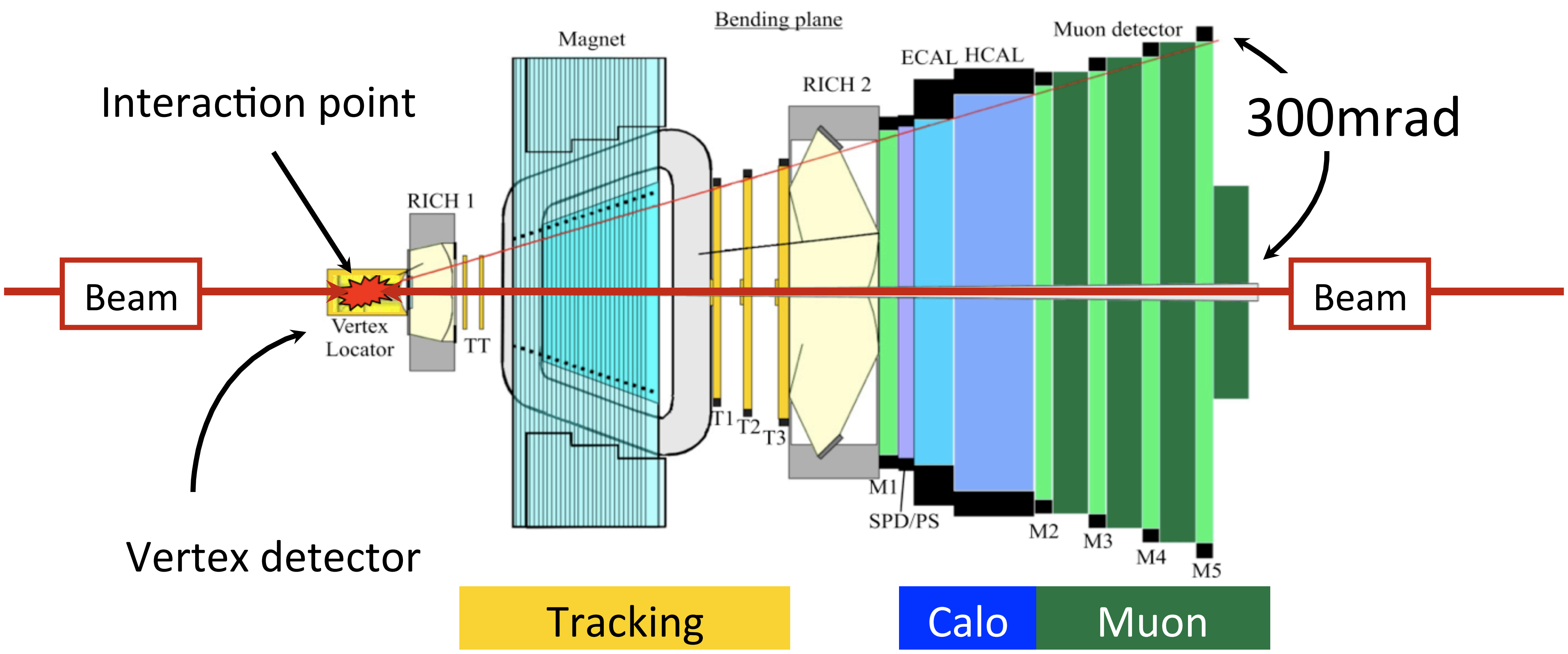
$$\delta\alpha_s(0.5\,m_c, 2\,m_c) =^{+170\%}_{-48\%}$$

$$\delta\alpha_s(0.5\,m_b, 2\,m_b) =^{+72\%}_{-34\%}$$

$$\delta\alpha_s(0.5\,m_t, 2\,m_t) =^{+25\%}_{-19\%}$$



The LHCb detector and data



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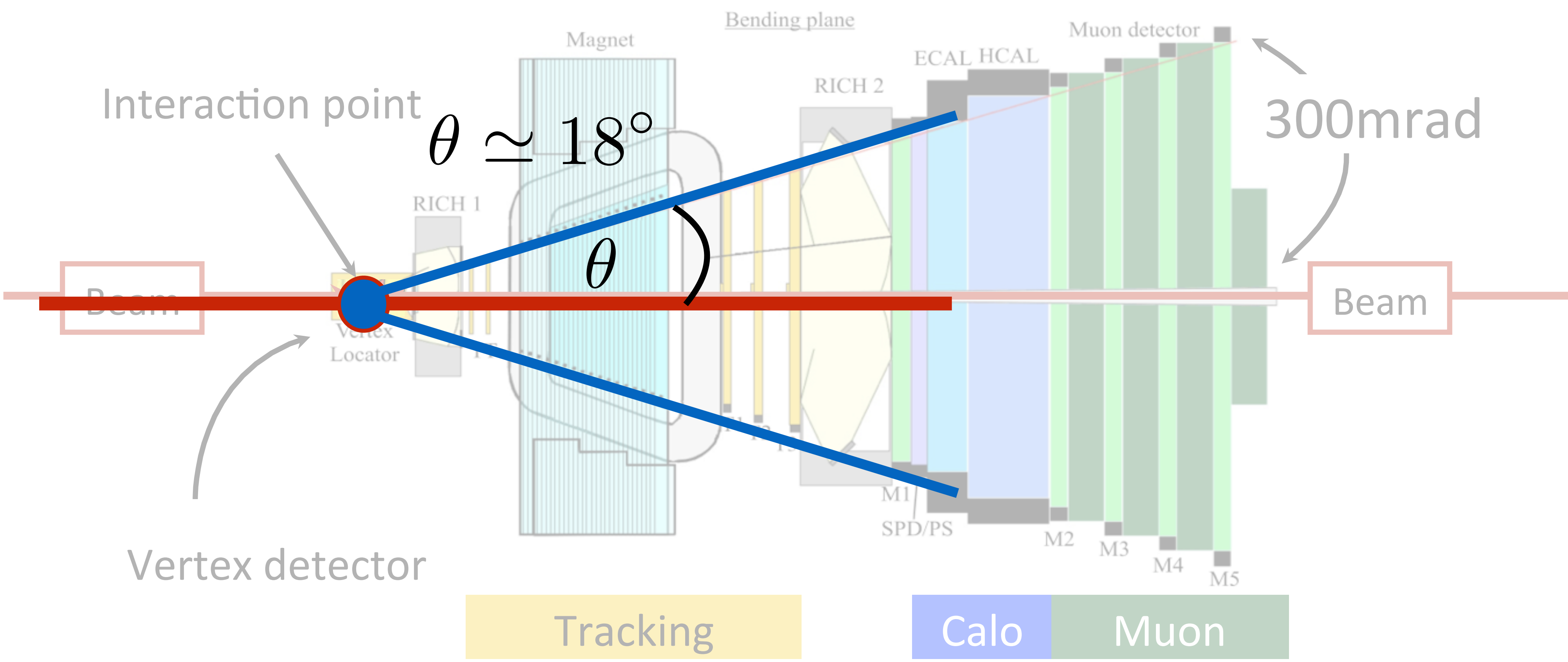
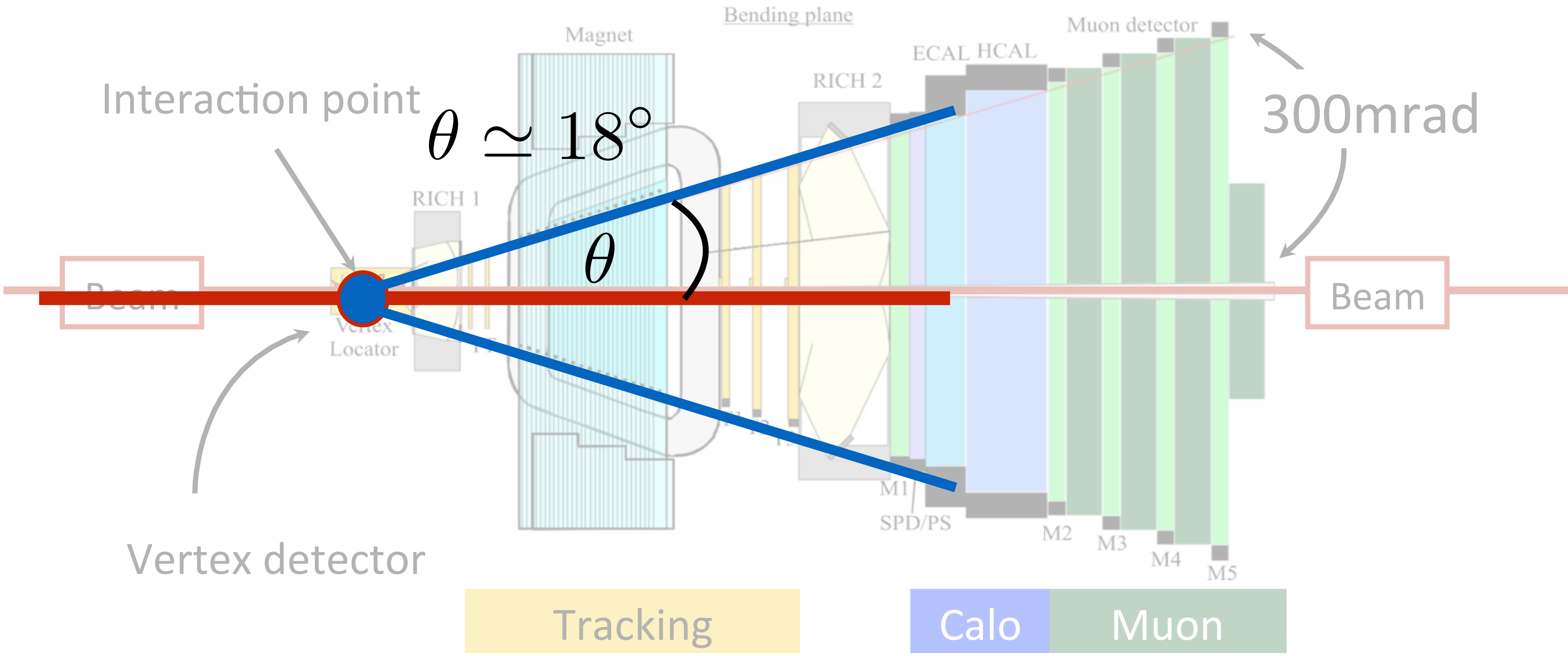


LHCb - forward acceptance: $\eta \in [2.0, 4.5]$

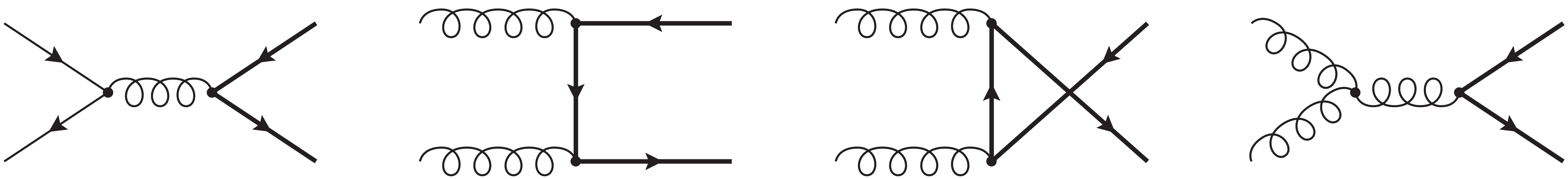
The LHCb detector and data



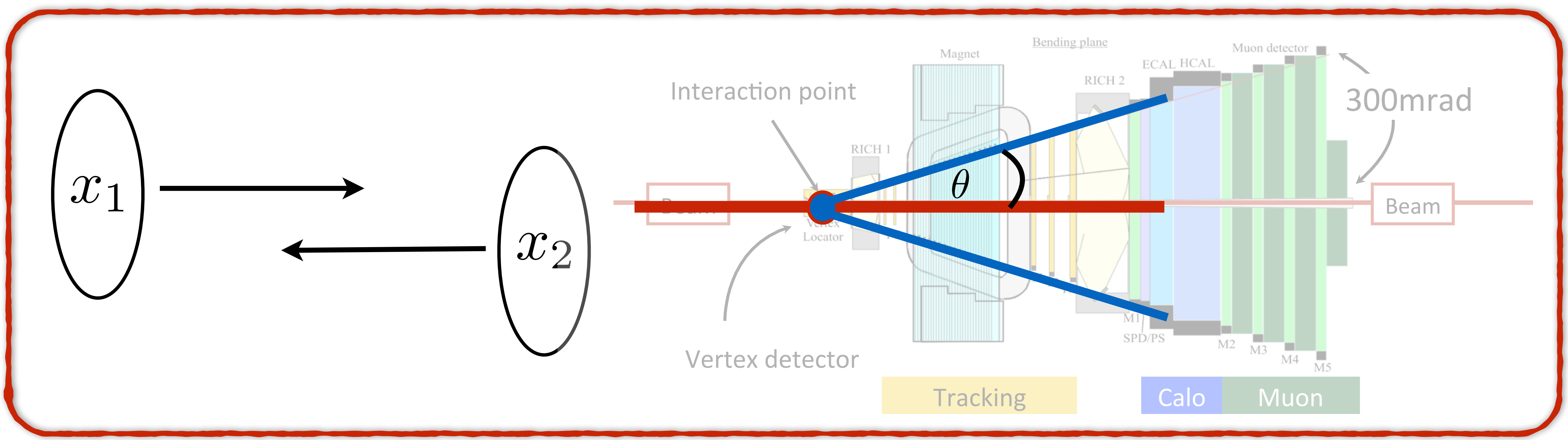
LHCb - forward acceptance: $\eta \in [2.0, 4.5]$

Data (ifb)	7 TeV	8 TeV	13 TeV	14 TeV (2030)
ATLAS/CMS	5	20	100	3000?
LHCb	**1**	**2**	**~5**	**~50**

Why study forward $pp \to Q_3\bar{Q}_4 + X$?

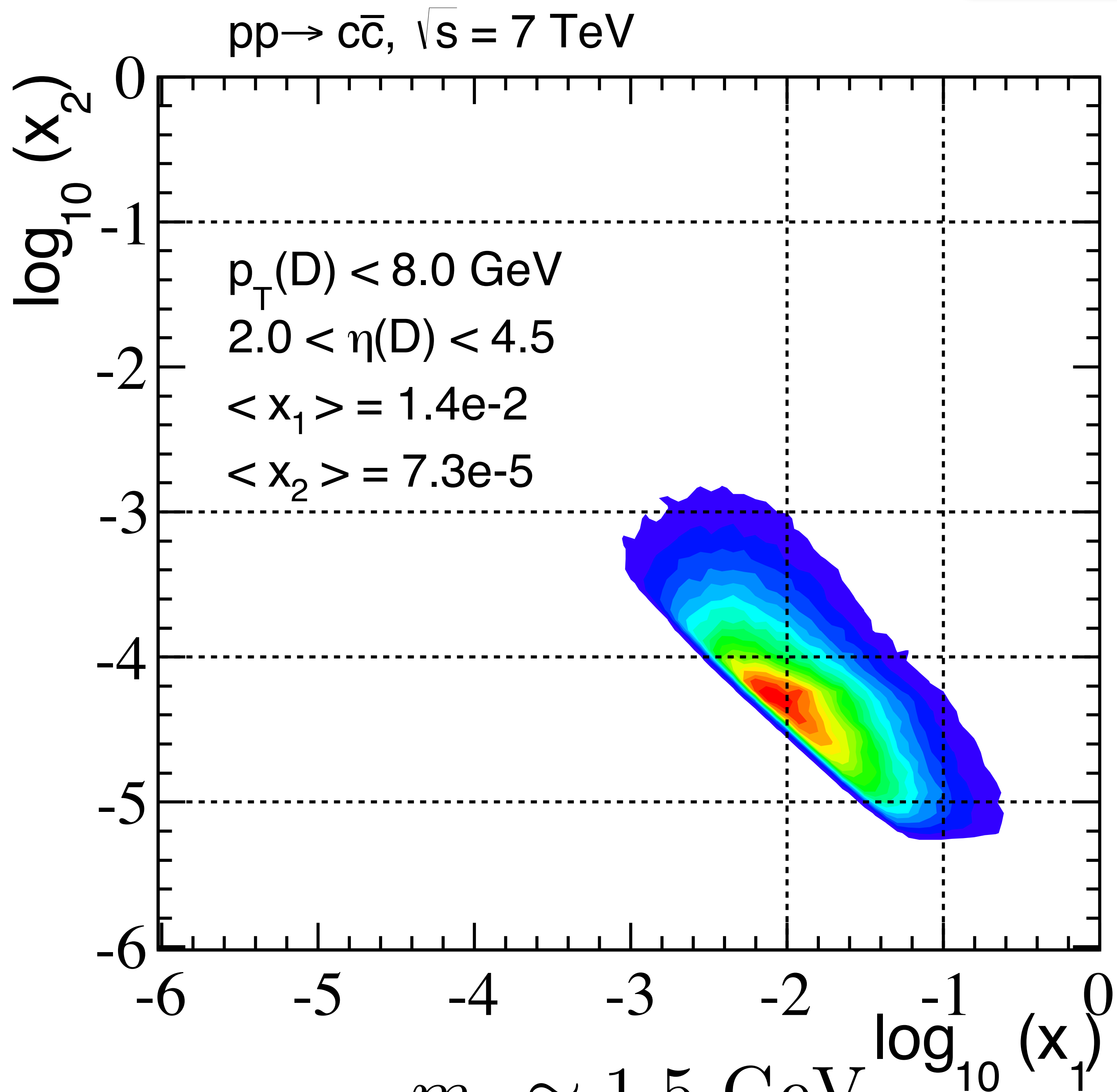


$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}\left(e^{(-)y_3} + e^{(-)y_4}\right)$$



$$pp \to c\bar{c}$$

$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}(e^{(-)y_3} + e^{(-)y_4})$$

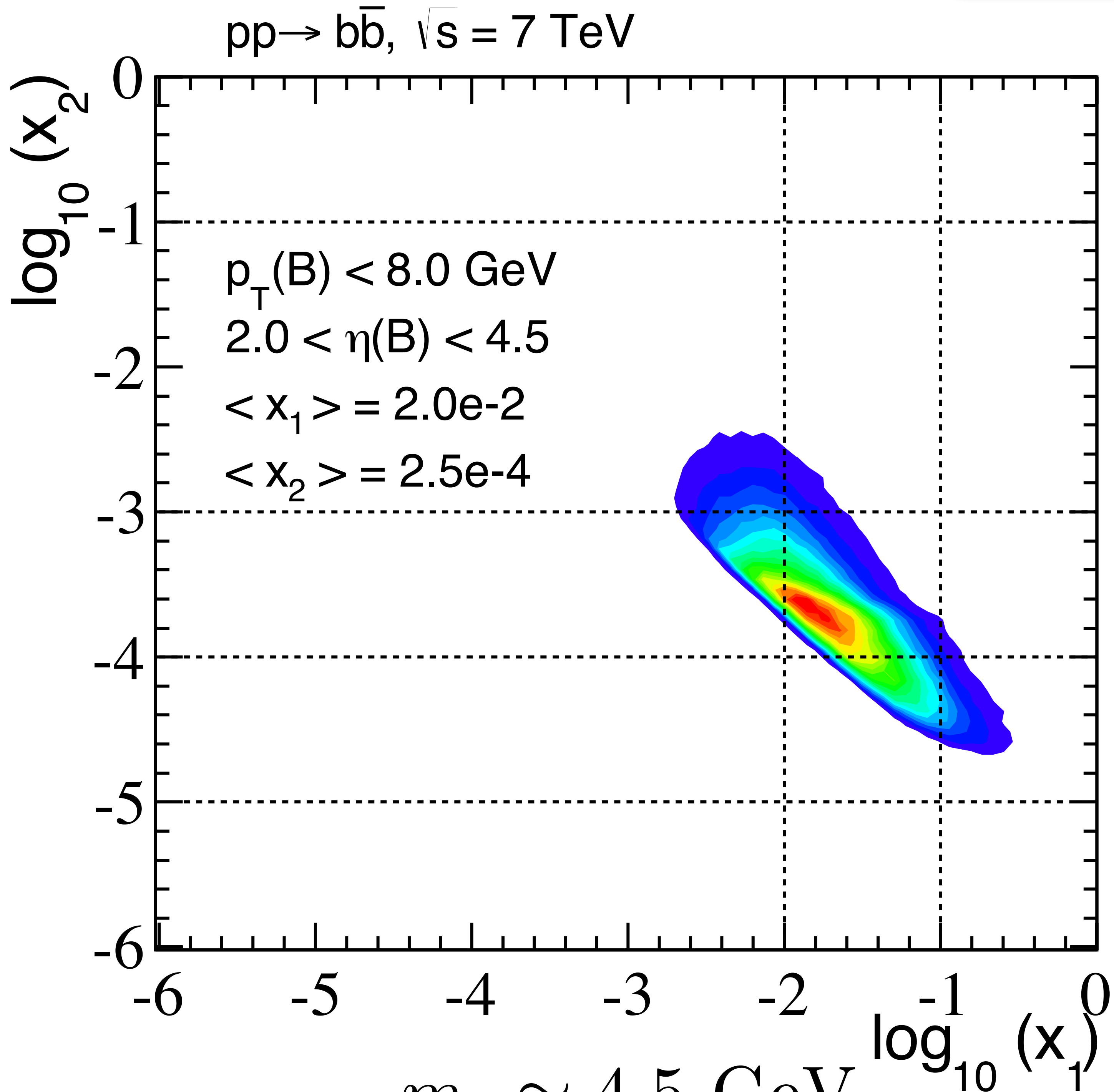


$m_c \simeq 1.5$ GeV

LHCb measurement arXiv: 1302.2864

$$pp \to b\bar{b}$$

$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}(e^{(-)y_3} + e^{(-)y_4})$$

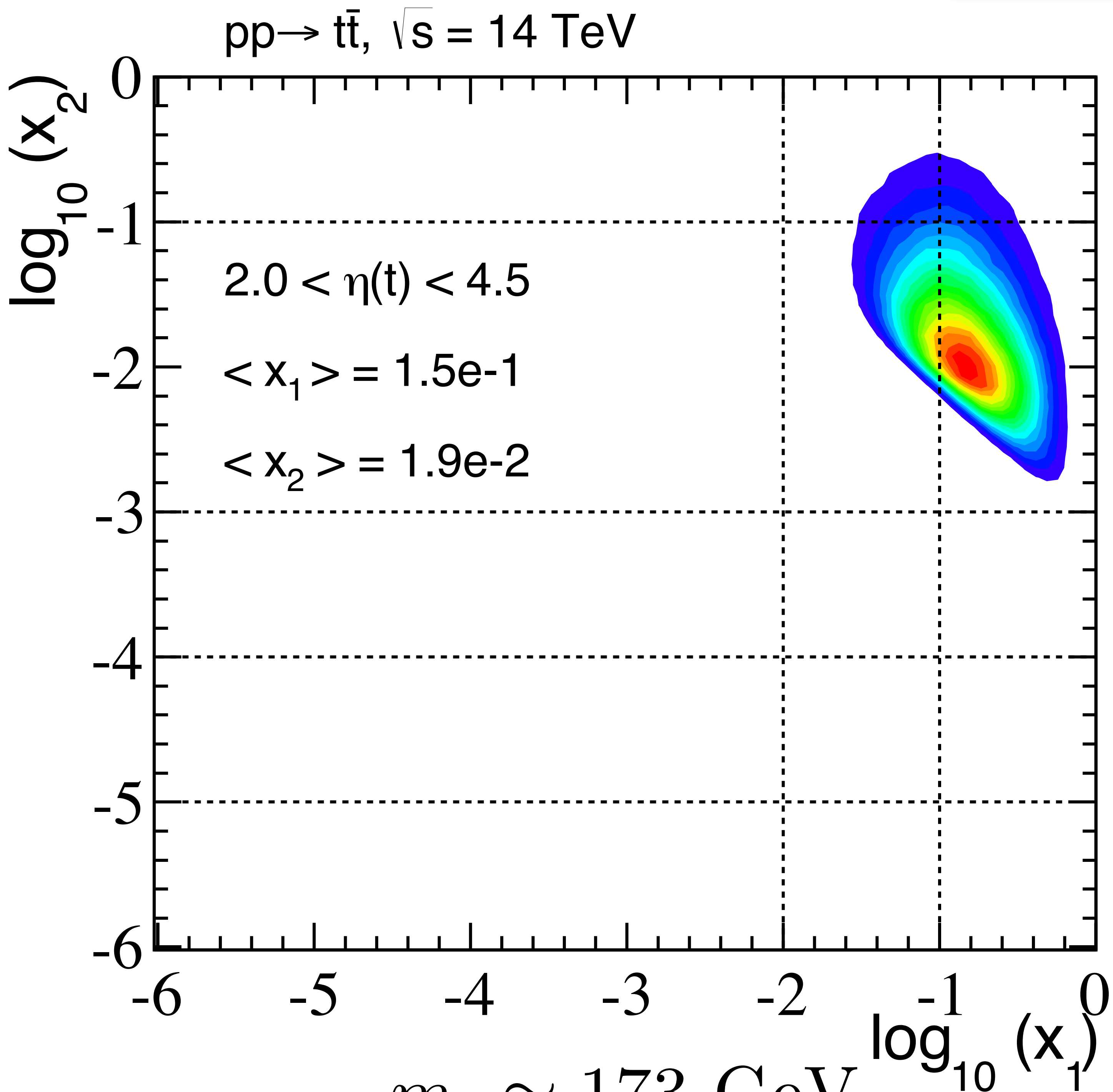


$m_b \simeq 4.5$ GeV

LHCb measurement arXiv: 1306.3663

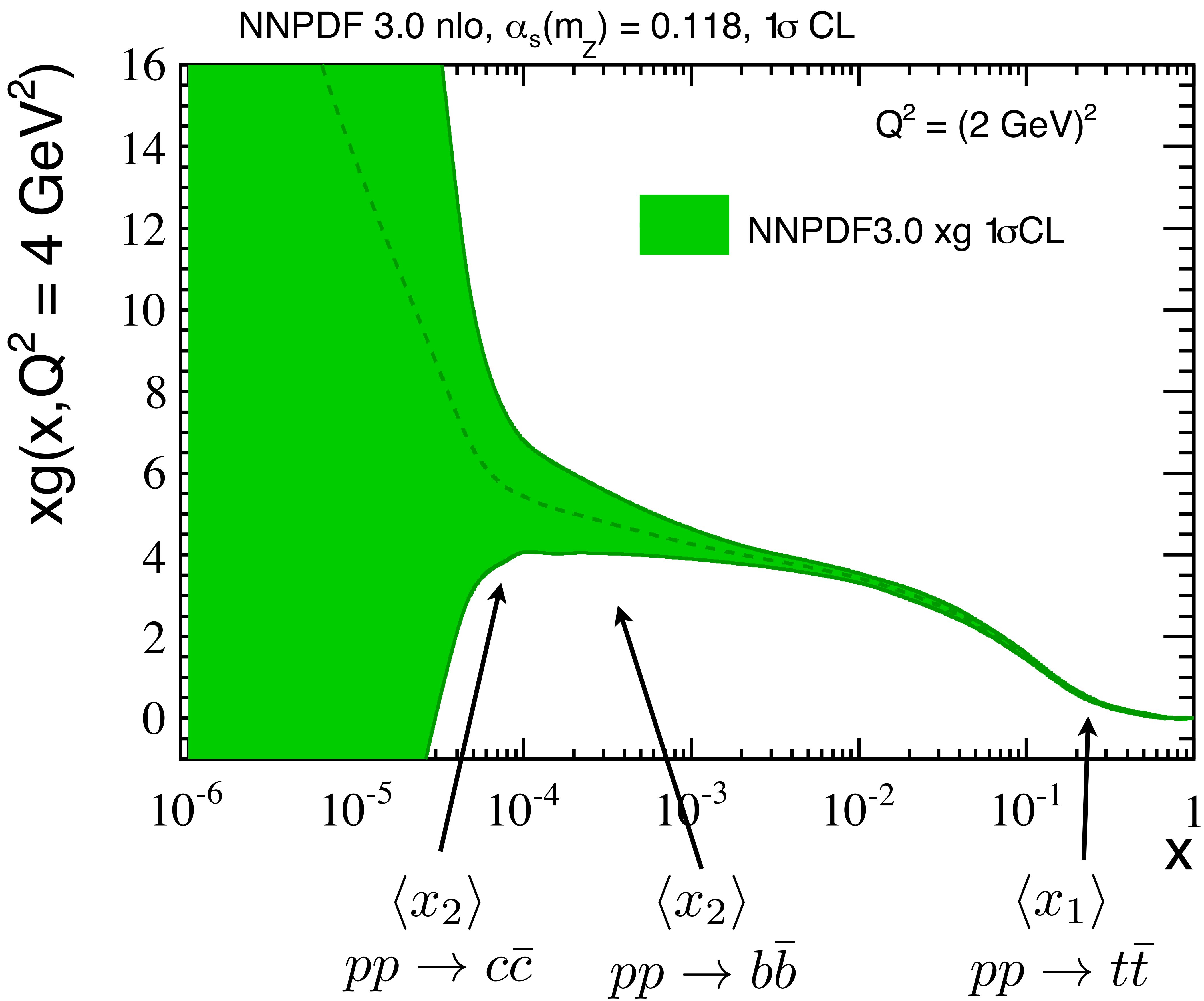
$$pp \to t\bar{t}$$

$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}(e^{(-)y_3} + e^{(-)y_4})$$

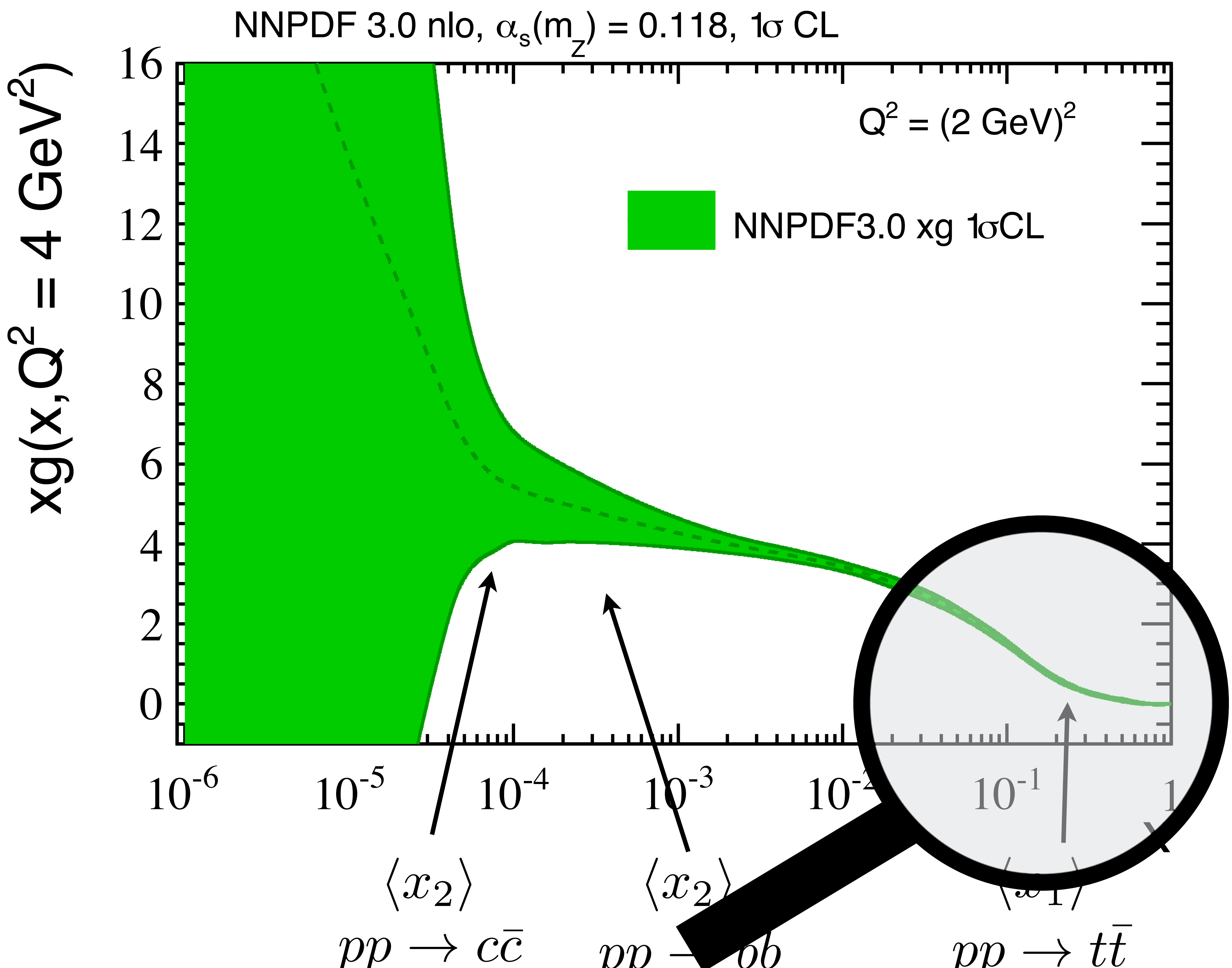


$m_t \simeq 173$ GeV

LHCb measurement arXiv: 15??.????



NNPDF 3.0 nlo, $\alpha_s(m_Z)$ = 0.118, 1σ CL
$xg(x,Q^2 = 4\ GeV^2)$
$Q^2 = (2\ GeV)^2$
NNPDF3.0 xg 1σCL
16
14
12
10
8
6
4
2
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
$\langle x_2 \rangle$
$pp \to c\bar{c}$
$\langle x_2 \rangle$
$pp \to b\bar{b}$
$\langle x_1 \rangle$
$pp \to t\bar{t}$



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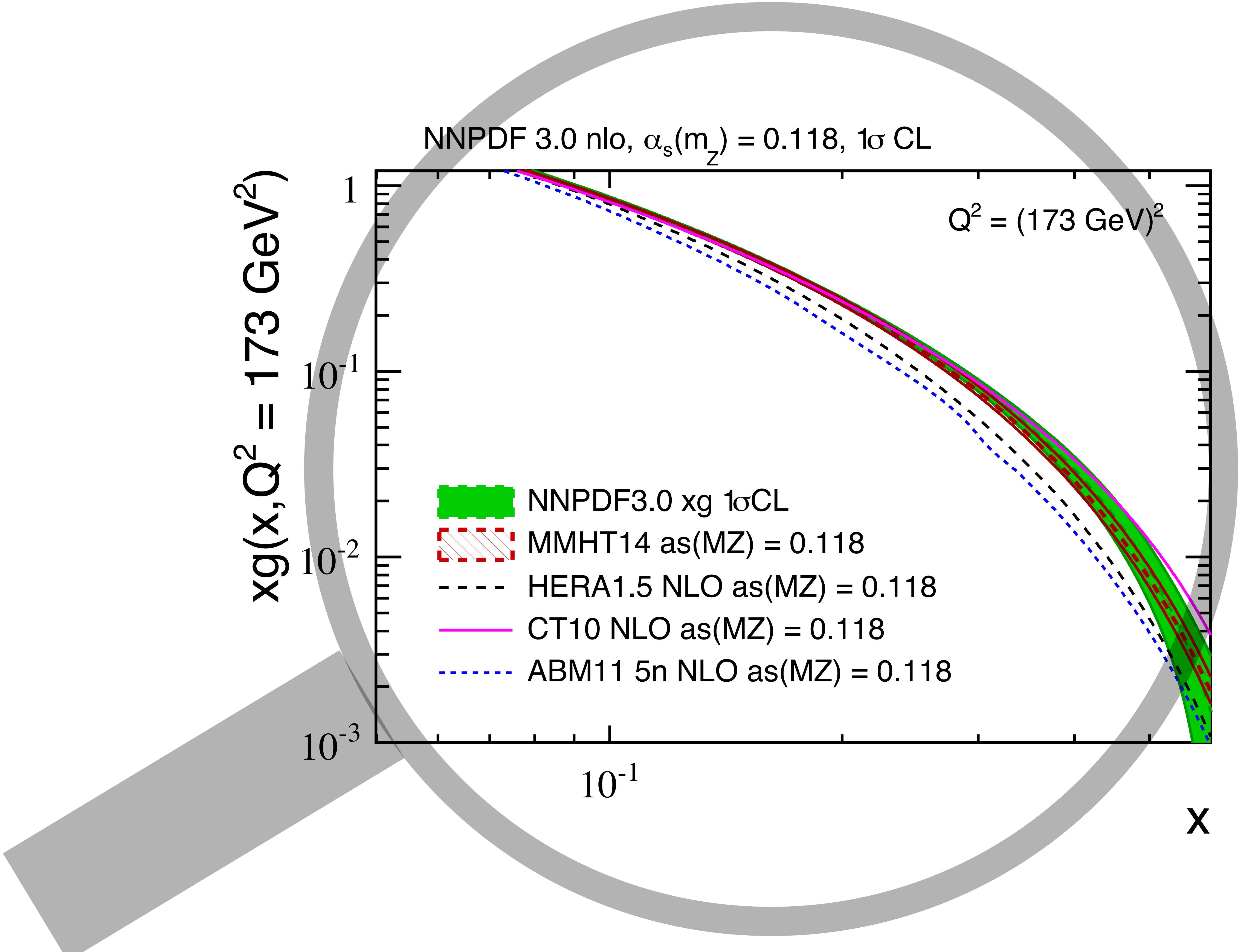
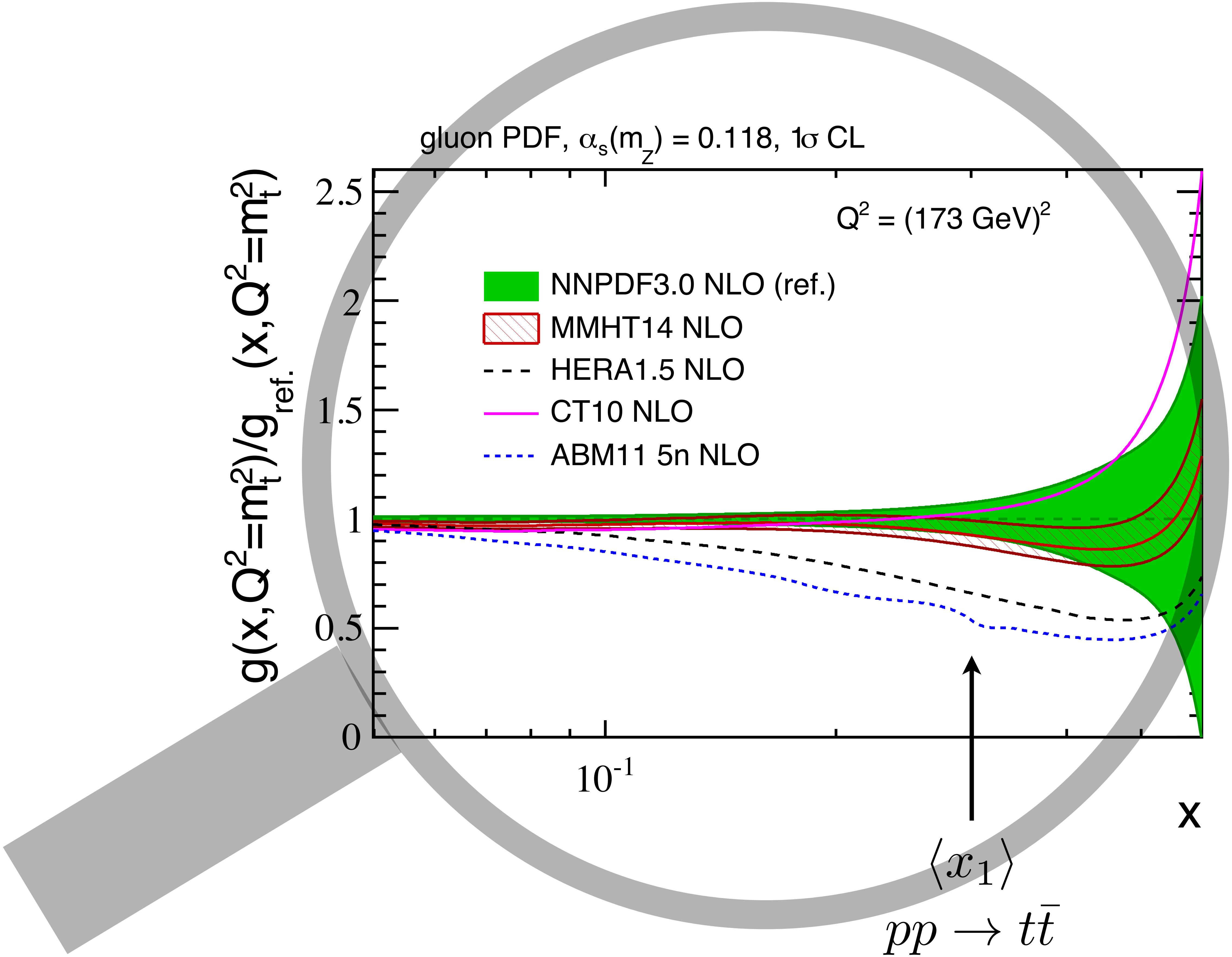
16
14
12
10
8
6
4
2
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-1}
1
$\langle x_2 \rangle$
$pp \to c\bar{c}$
$\langle x_2 \rangle$
$pp \to t\bar{t}$



NNPDF 3.0 nlo, $\alpha_s(m_Z)$ = 0.118, 1σ CL
$xg(x,Q^2 = 173\ GeV^2)$
$Q^2 = (173\ GeV)^2$
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
x
NNPDF3.0 xg 1σCL
MMHT14 as(MZ) = 0.118
HERA1.5 NLO as(MZ) = 0.118
CT10 NLO as(MZ) = 0.118
ABM11 5n NLO as(MZ) = 0.118

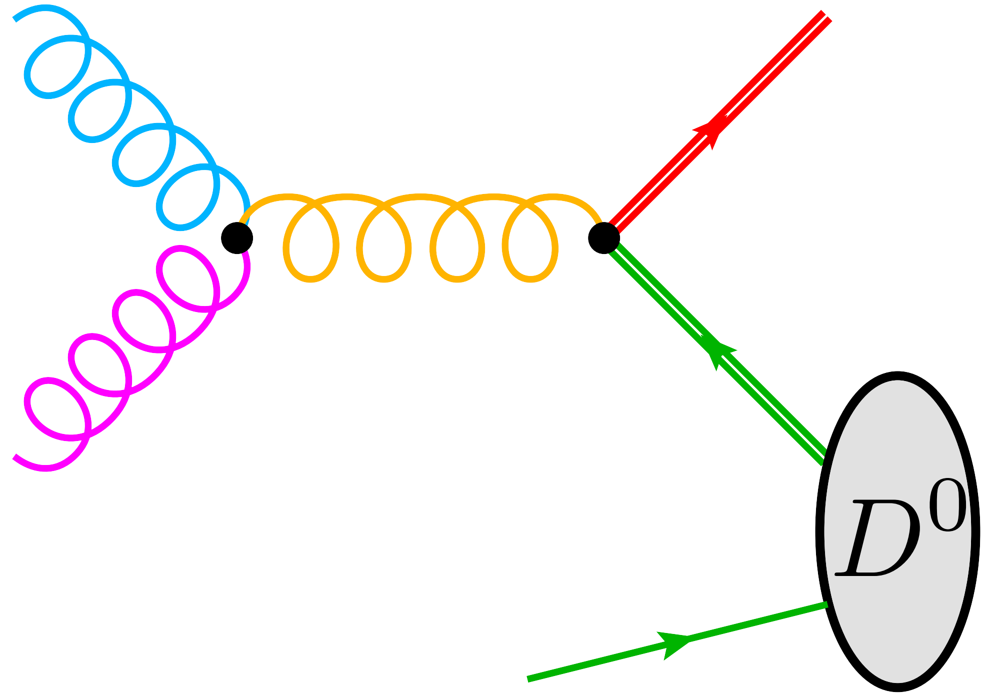


gluon PDF, $\alpha_s(m_Z)$ = 0.118, 1σ CL
$Q^2 = (173\ \mathrm{GeV})^2$
NNPDF3.0 NLO (ref.)
MMHT14 NLO
HERA1.5 NLO
CT10 NLO
ABM11 5n NLO
$g(x,Q^2=m_t^2)/g_{ref.}(x,Q^2=m_t^2)$
2.5
2
1.5
1
0.5
0
10^{-1}
x
$\langle x_1 \rangle$
$pp \to t\bar{t}$

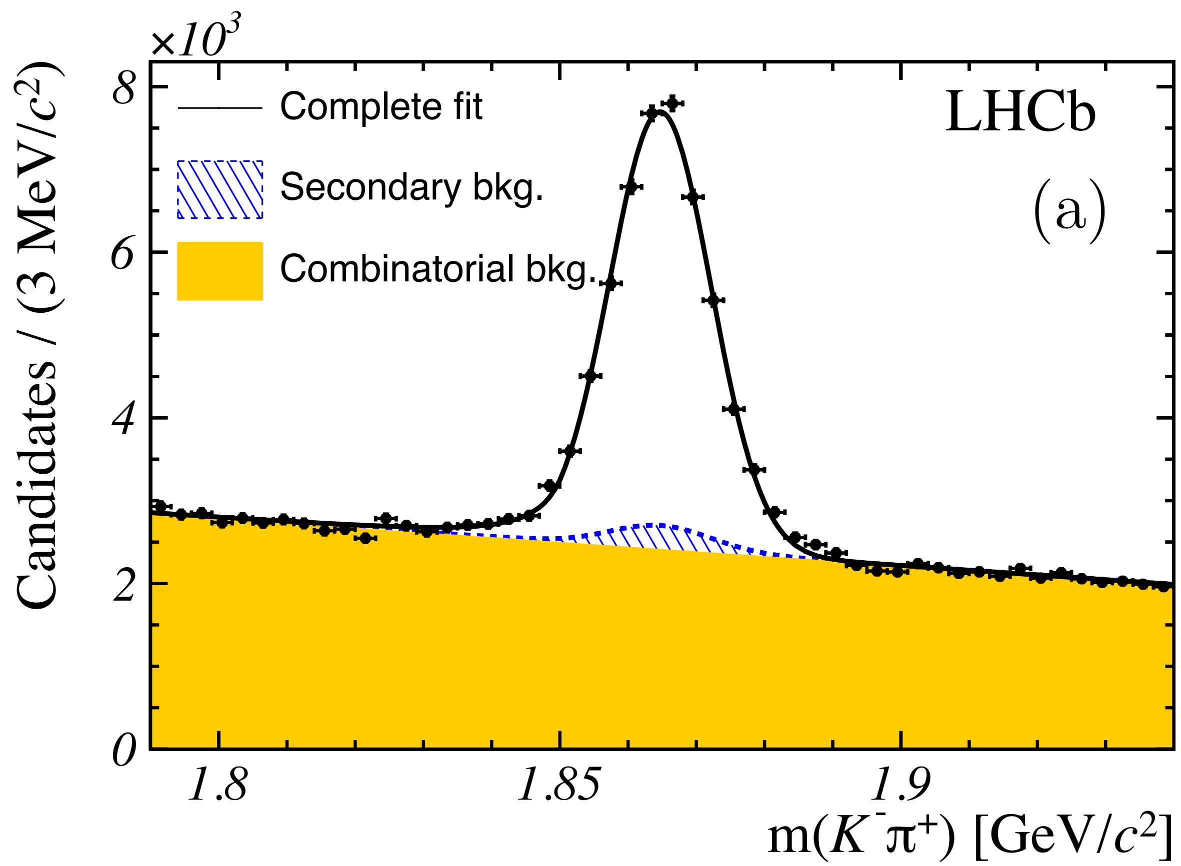
Cross-section measurements

D measurement (arXiv: 1302.2864)

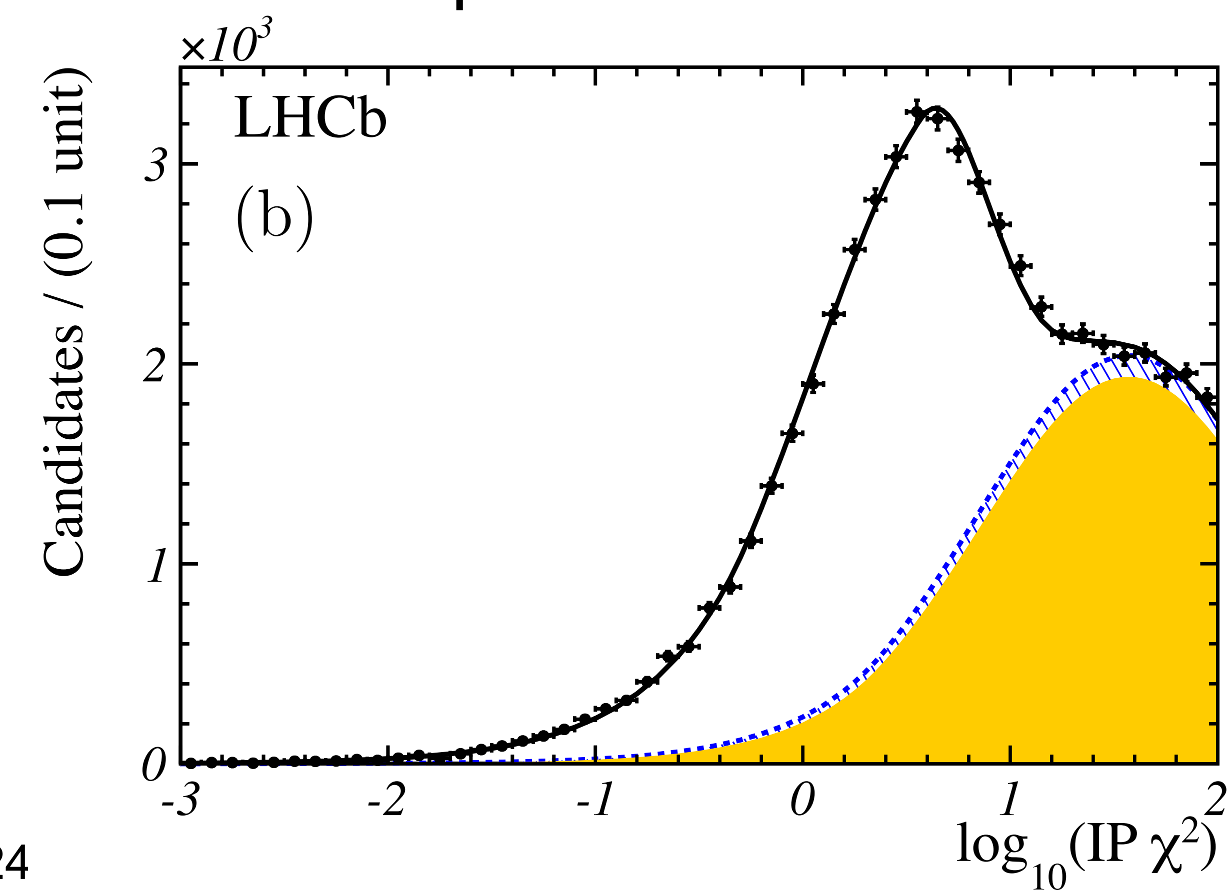
$$pp \to D + X$$
$$2.0 < y_D < 4.5$$
$$Dp_T < 8.0GeV$$



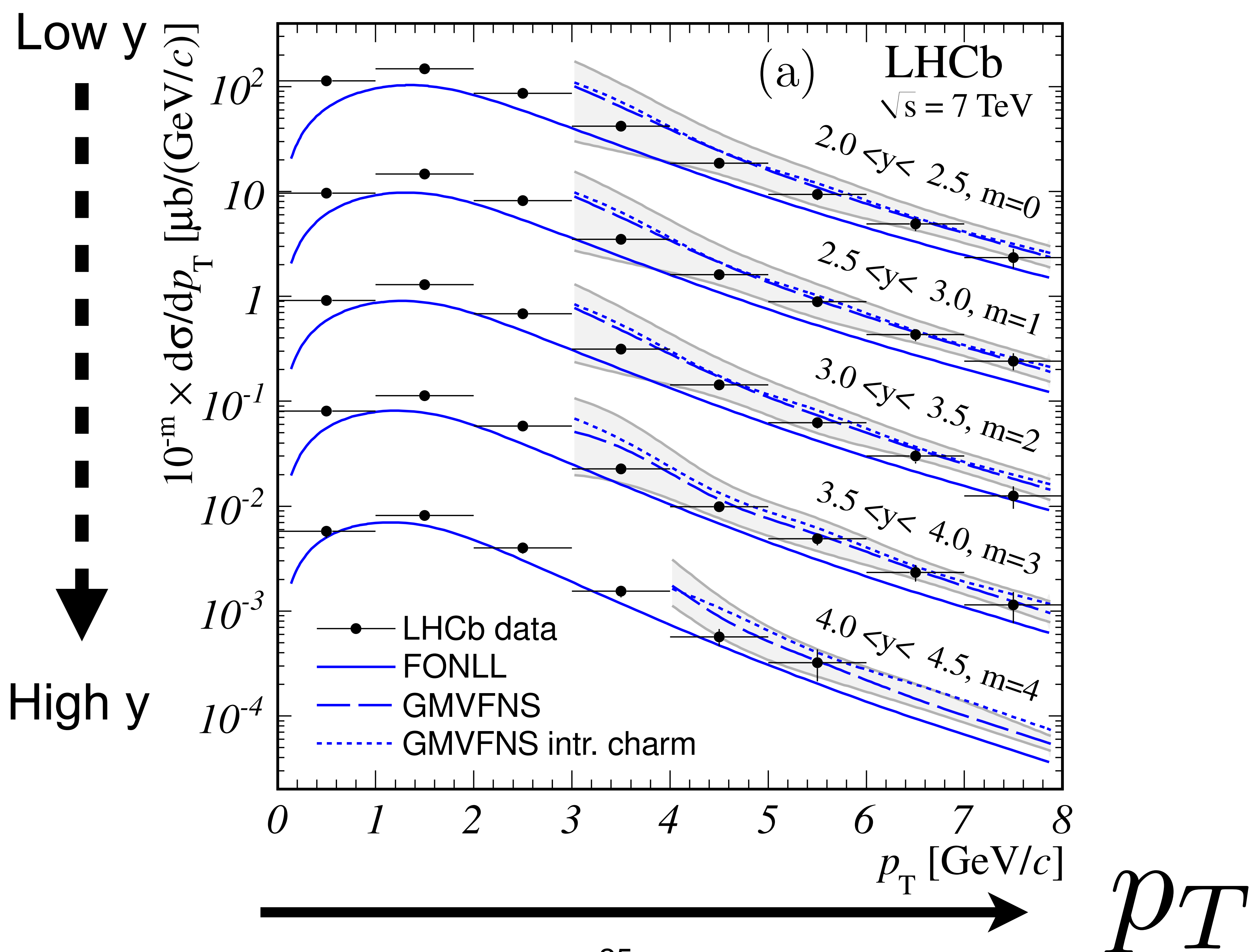
Mass requirement



Displaced vertex



D measurement (arXiv: 1302.2864)

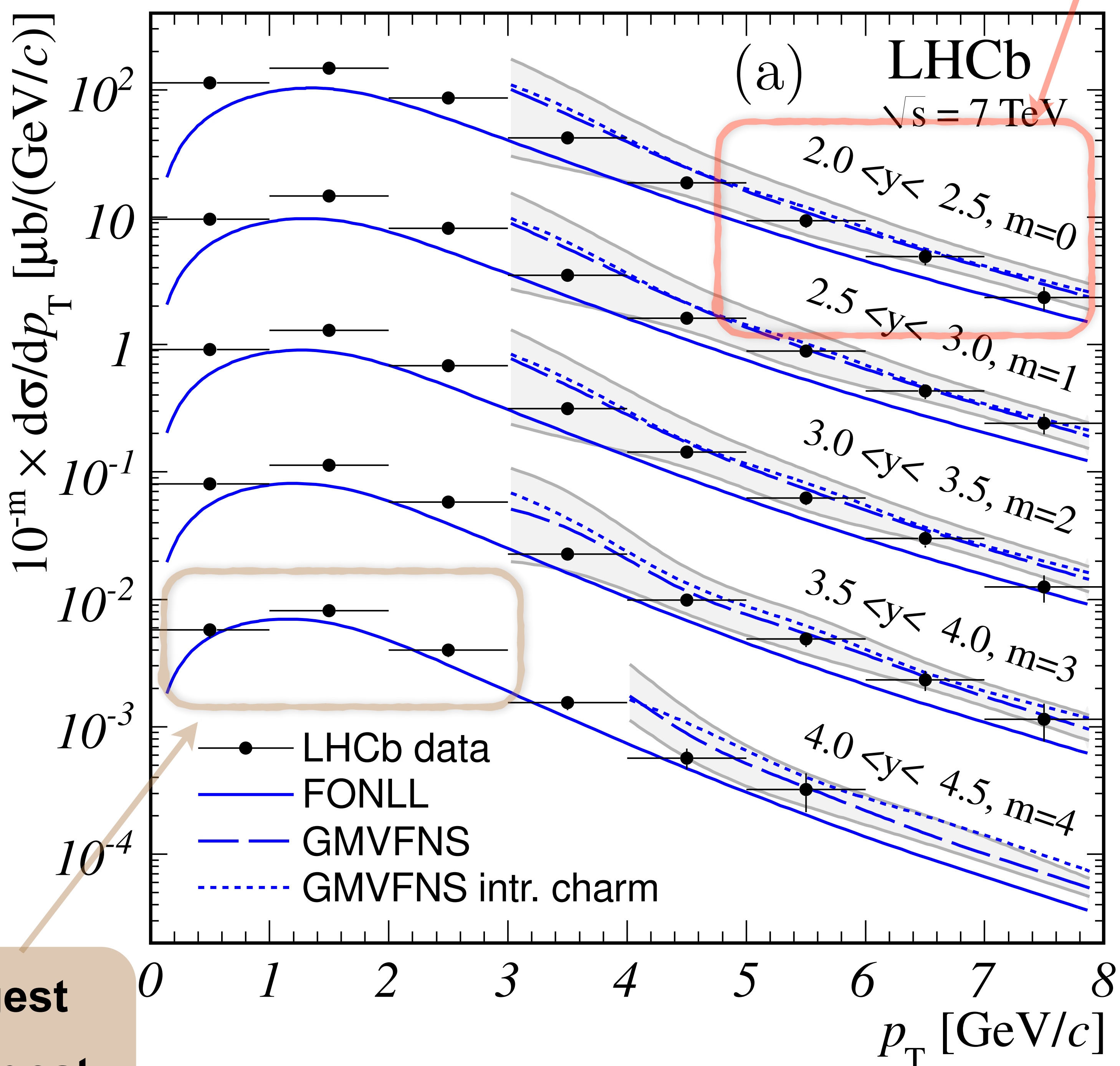


D measurement (arXiv: 1302.2864)

PDF Uncertainties **smallest**

Scale Uncertainties **smallest**

Low y



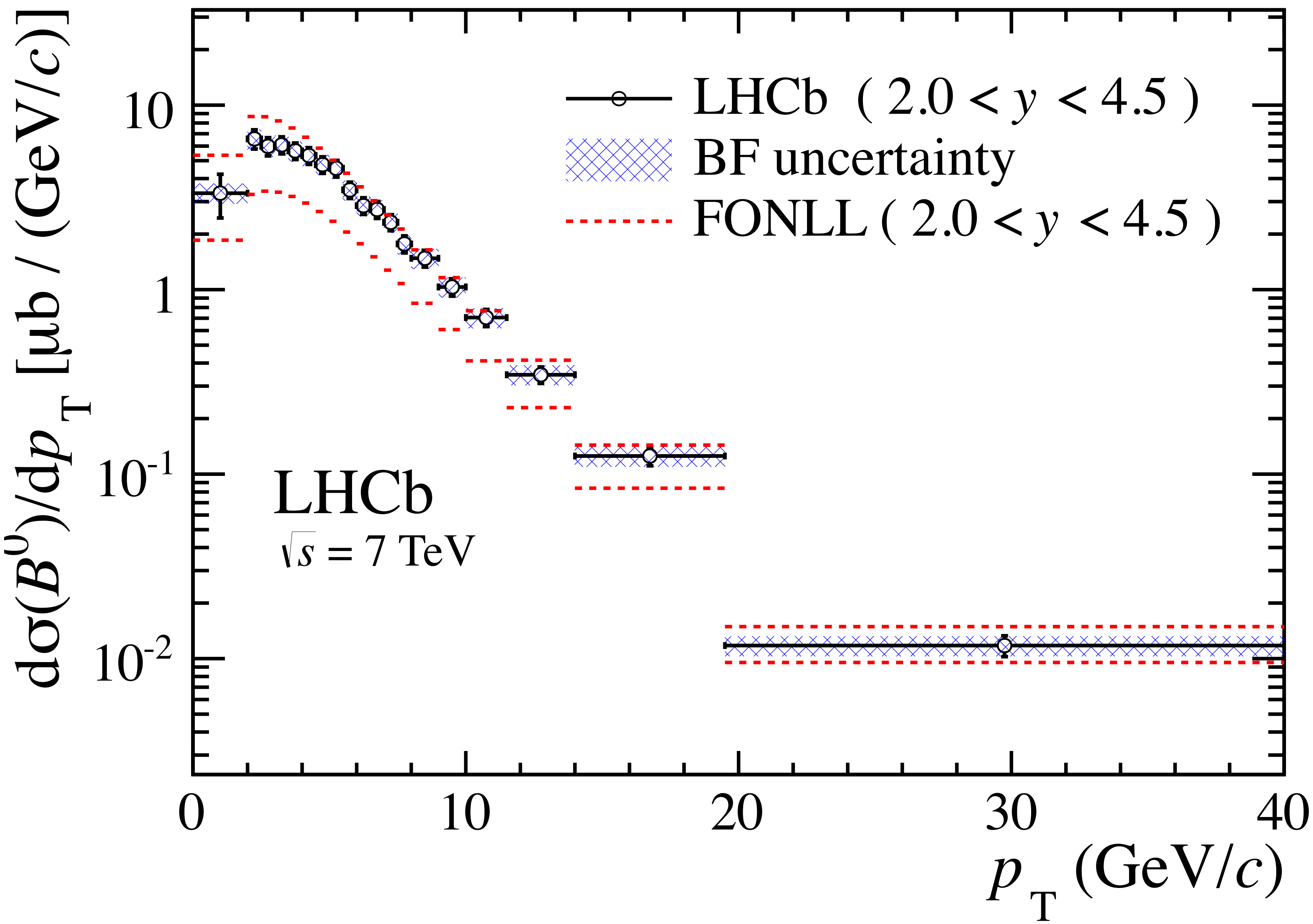
High y

PDF Uncertainties **largest**

Scale Uncertainties **largest**

p_T

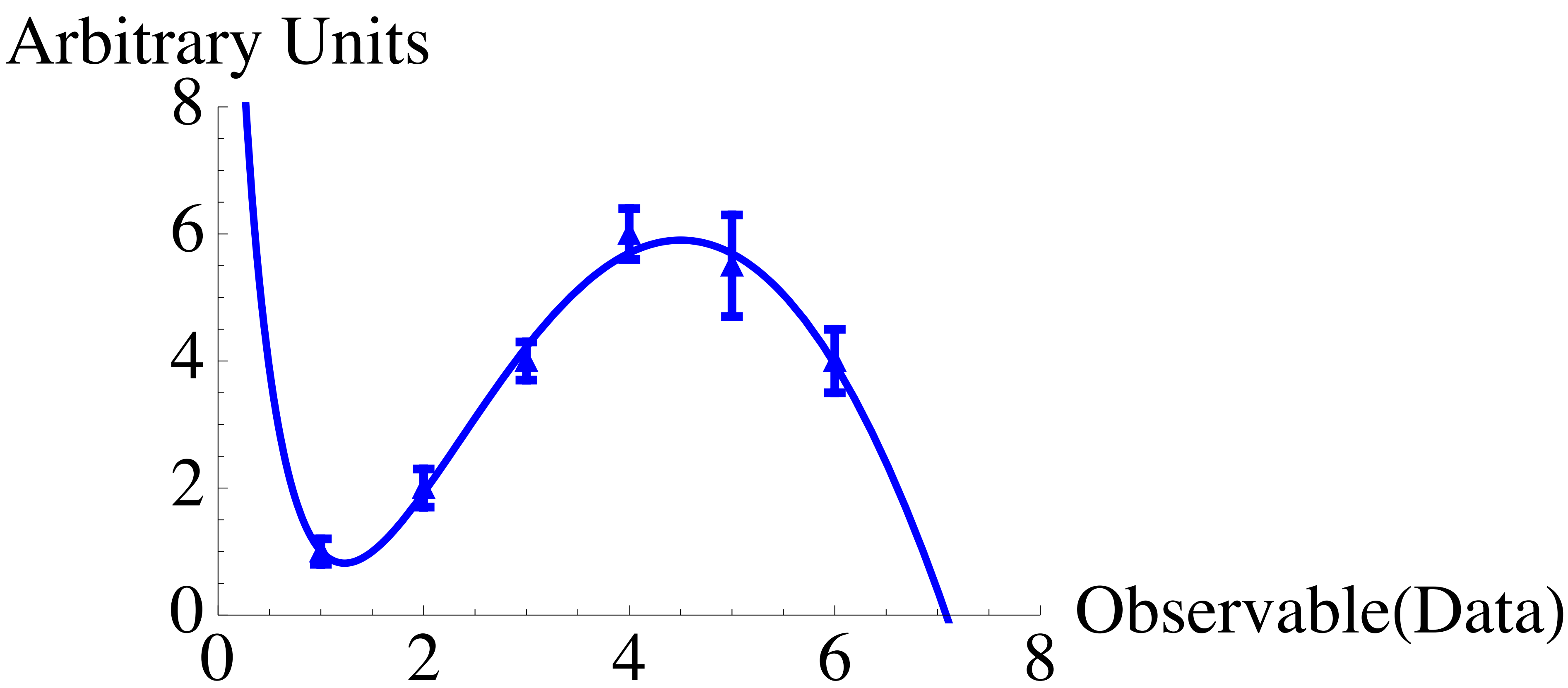
B measurement (arXiv: 1306.3663)



Theory + Data in agreement - within large theoretical uncertainties (scale)

Wish to determine the impact of the data

Use a reweighting technique of PDF replicas
see - arXiv:1012.0836, NNPDF collaboration
(this is very qualitative)



1. NNPDF provide central member (from global fit)

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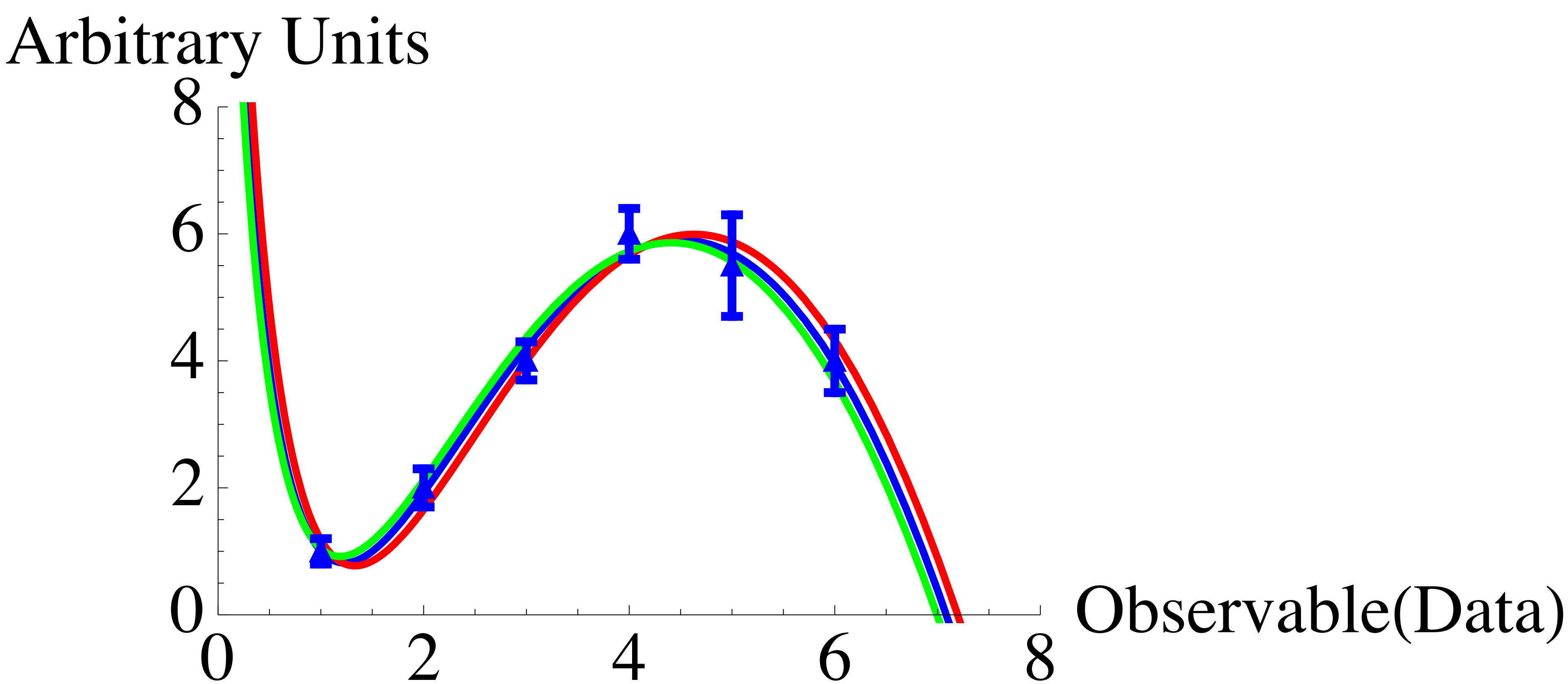

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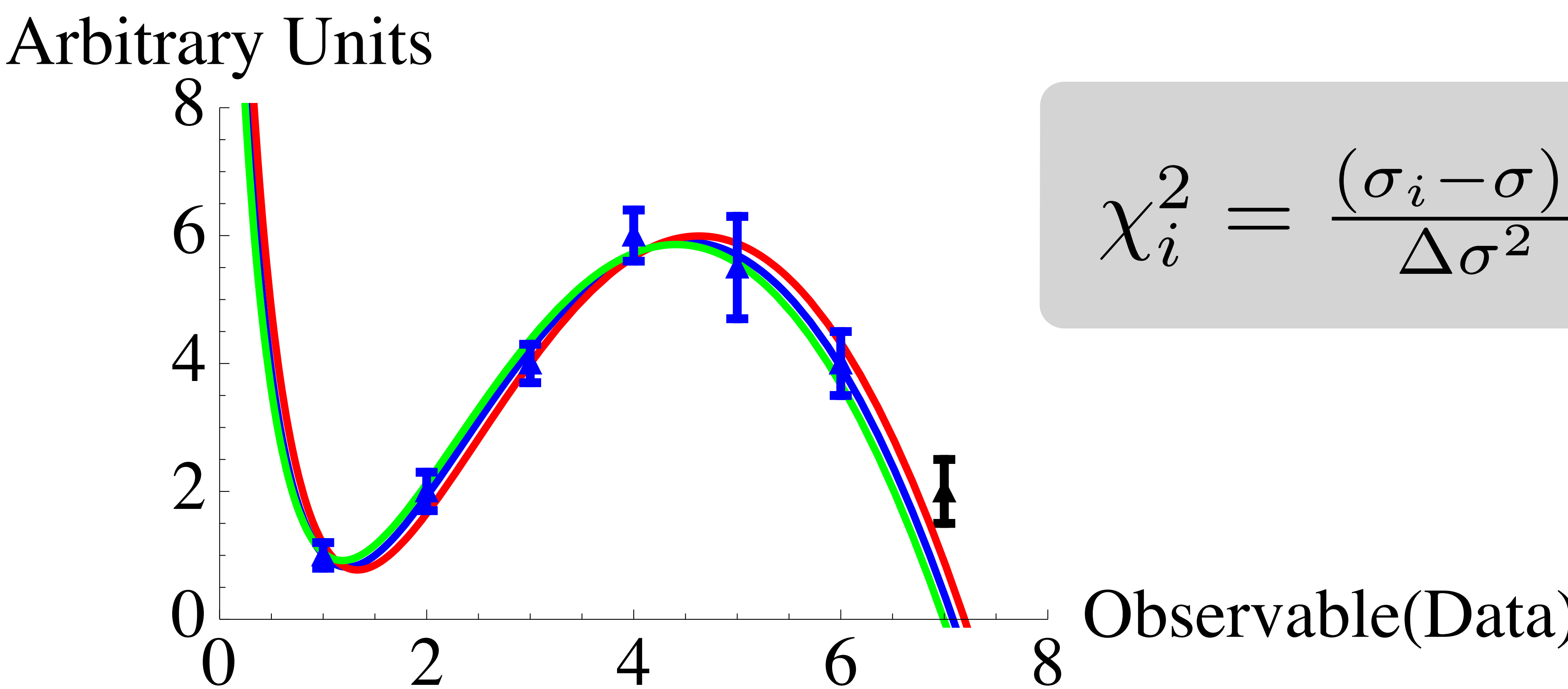


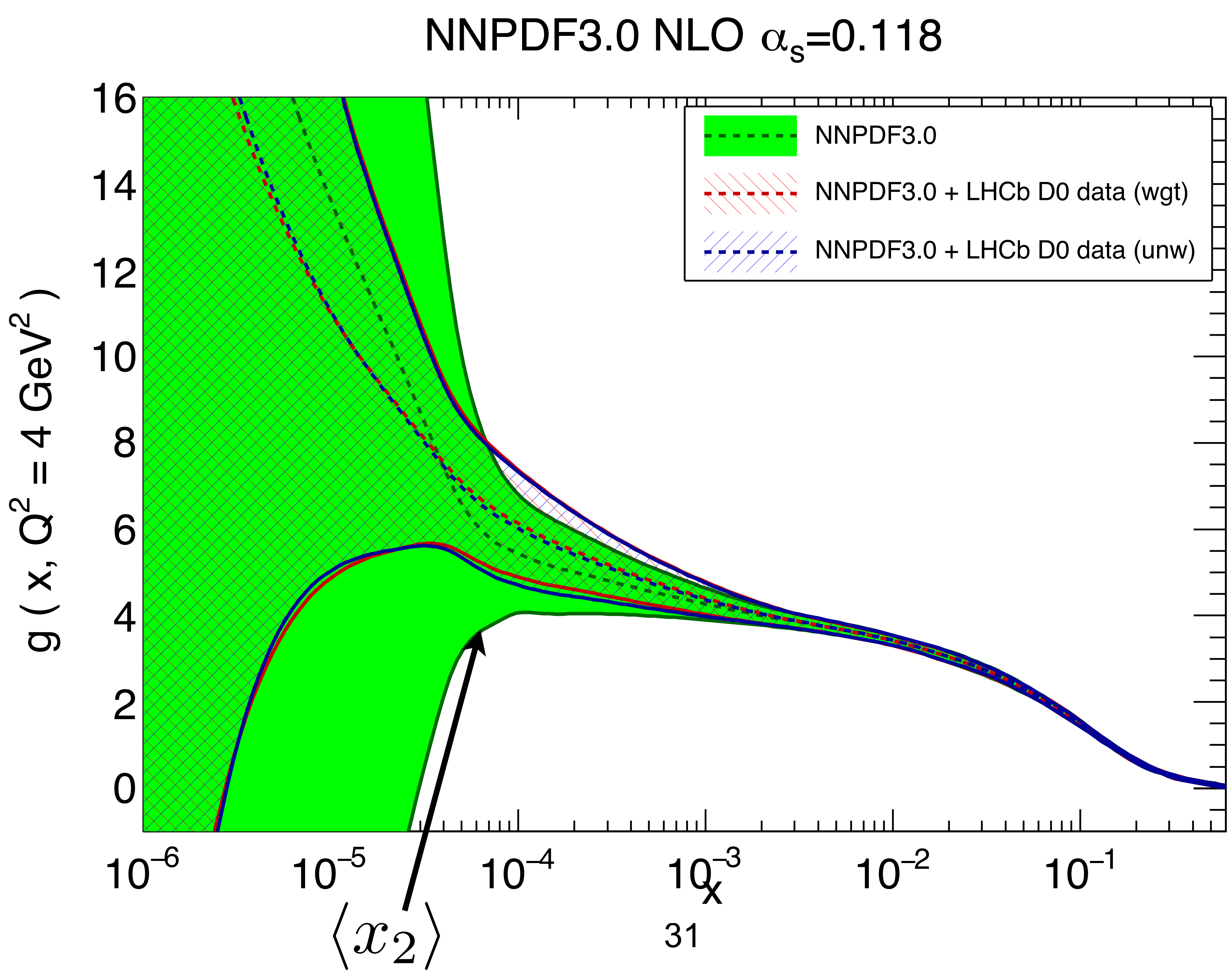
$$\chi_i^2 = \frac{(\sigma_i - \sigma)^2}{\Delta\sigma^2}$$

1. NNPDF provide central member (from global fit)
2. NNPDF provide 100 replica members (gives uncertainty)
3. Look at the impact of a new measurement (cross section)

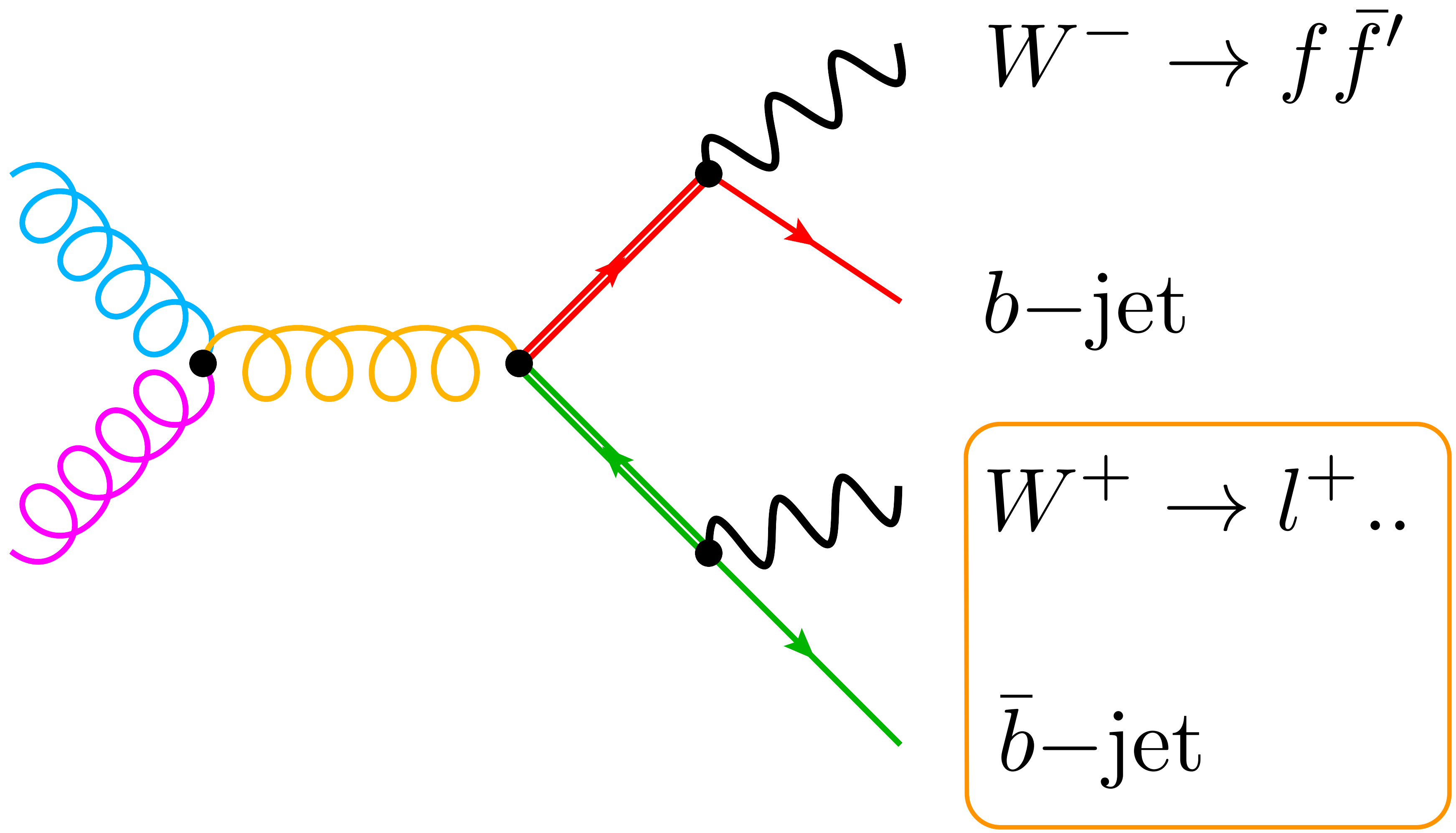
Preliminary results, reweighting NNPDF3.0

Work in progress with J. Rojo, L. Rottoli, S. Sarkar, J. Talbert

1) Normalise LHCb differential charm data to **high-pt**, **low-y** bin
2) Reweight the 100 replicas based on compatibility with LHCb data (here we use the FONLL predictions obtained from public web interface)



LHCb̸t (arXiv: 15xx.xxxx?)



Original proposal (in context of ttbar asymmetry):
Kagan, Kamenik, Perez, Stone arXiv: 1103.3747

Follow-up papers:
RG arXiv: 1311.1810 (cross section and PDF constraints)

RG arXiv: 1409.8631 (SM asymmetry predictions)

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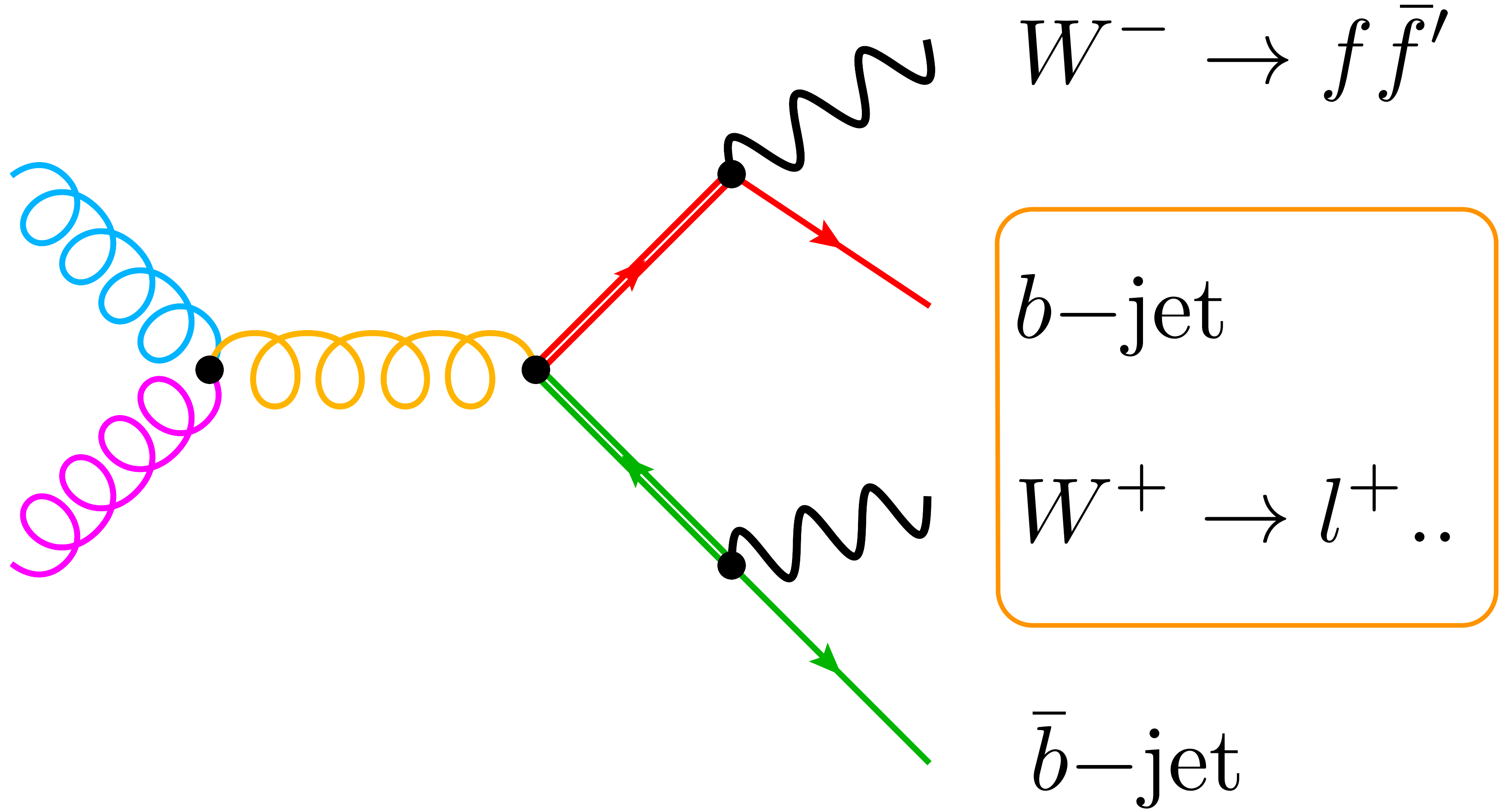

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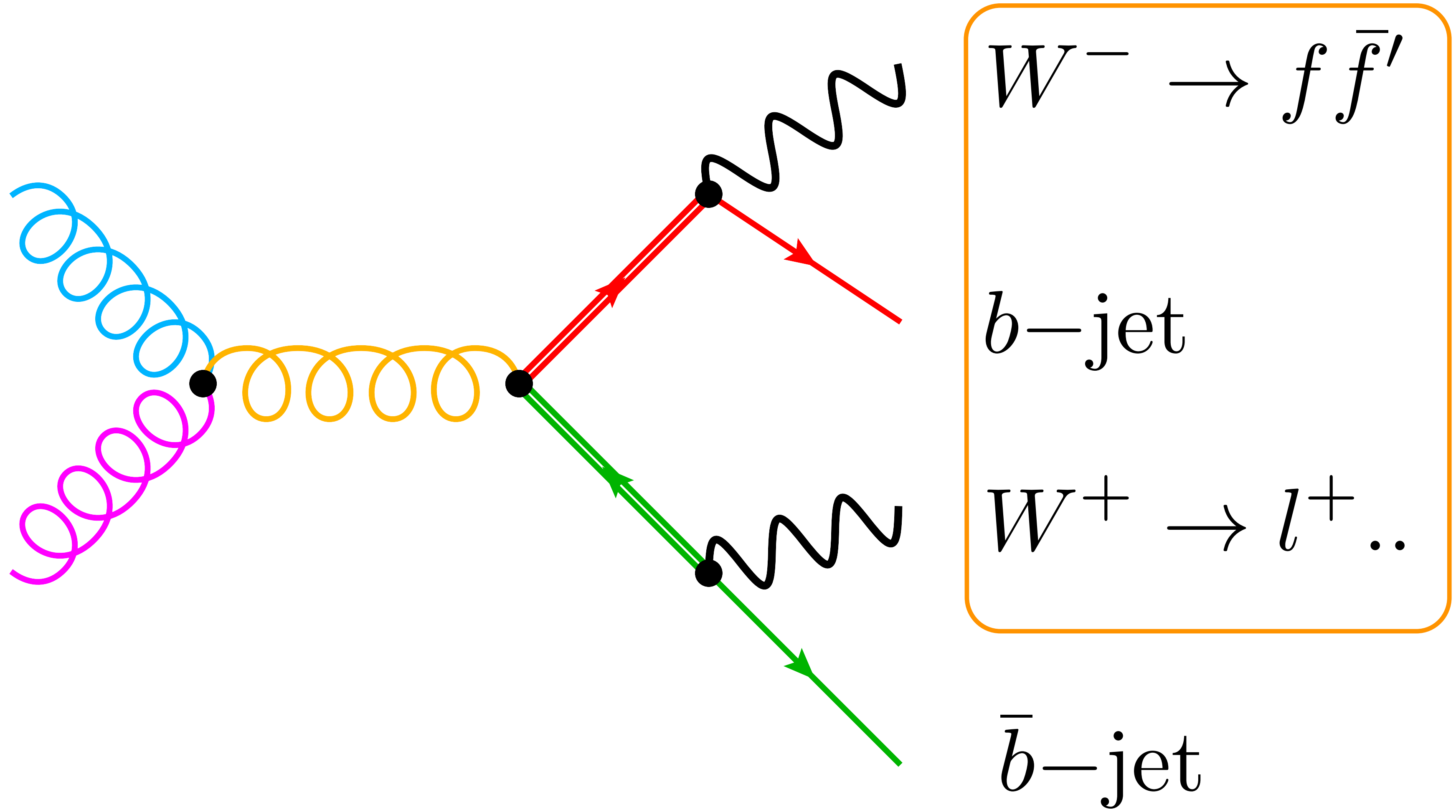

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Statistical feasibility of top measurements

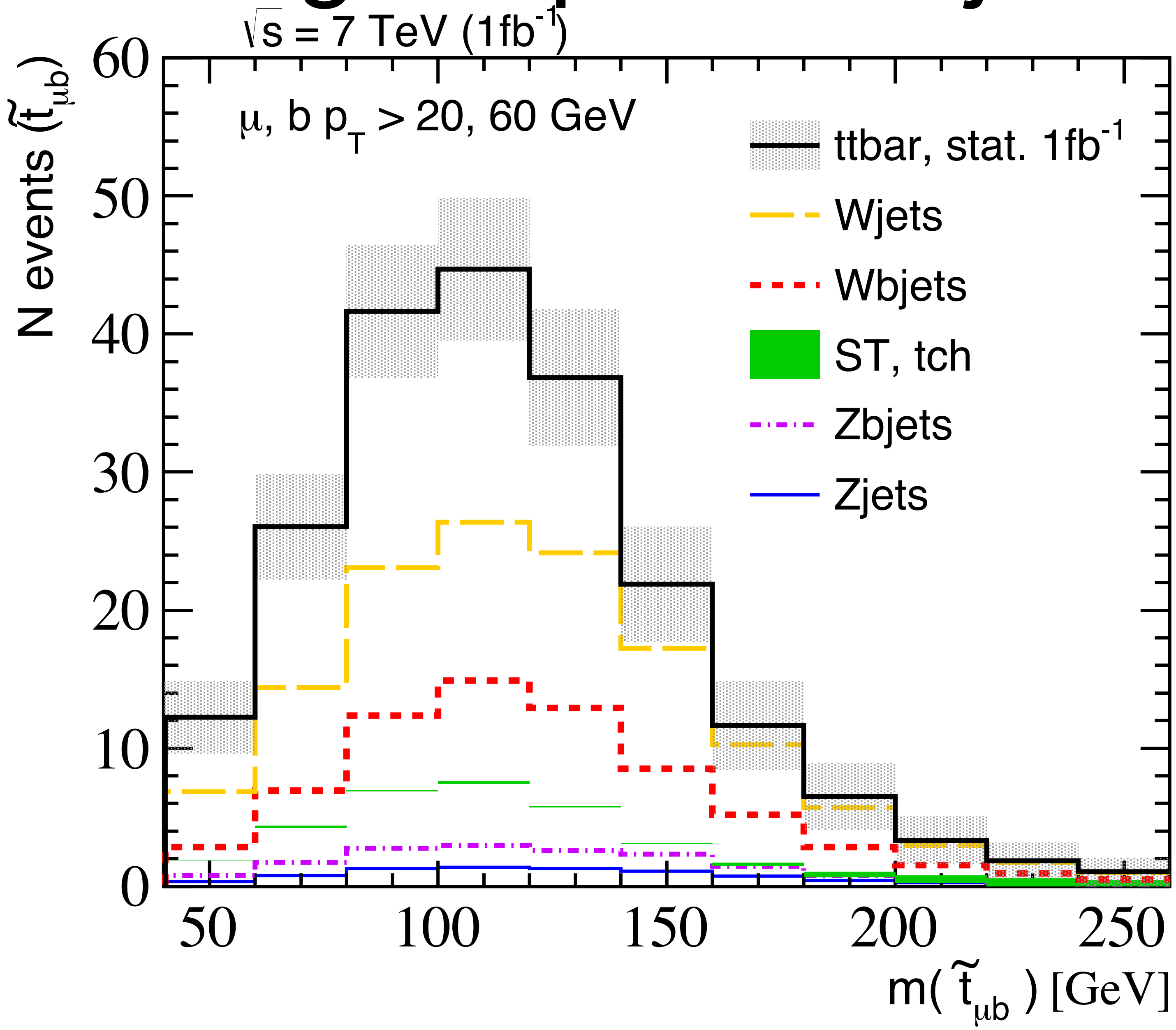
Set-up

- Signal and background generated with NLO (**POWHEG**) interfaced to PS (**P8**)
- Cluster jets with anti-kt algorithm using R = 0.5 distance parameter
- Truth match parton level b-quarks to jets within dR < 0.5 (b)
- Apply experimental trigger efficiencies (0.75 for high pT muons arxiv: 1204.1620)
- b-tagging assumptions:
    - mis-tag rate 1% (accidentaly think a light-jet is a b-jet)
    - efficiency 70% (how often you correctly tag a b-jet)

$$t\bar{t} \to XYZ$$

Acceptance
Kinematics
Isolation

Single lepton + b-jet



$$t\bar{t} \rightarrow l^{\pm} b X$$

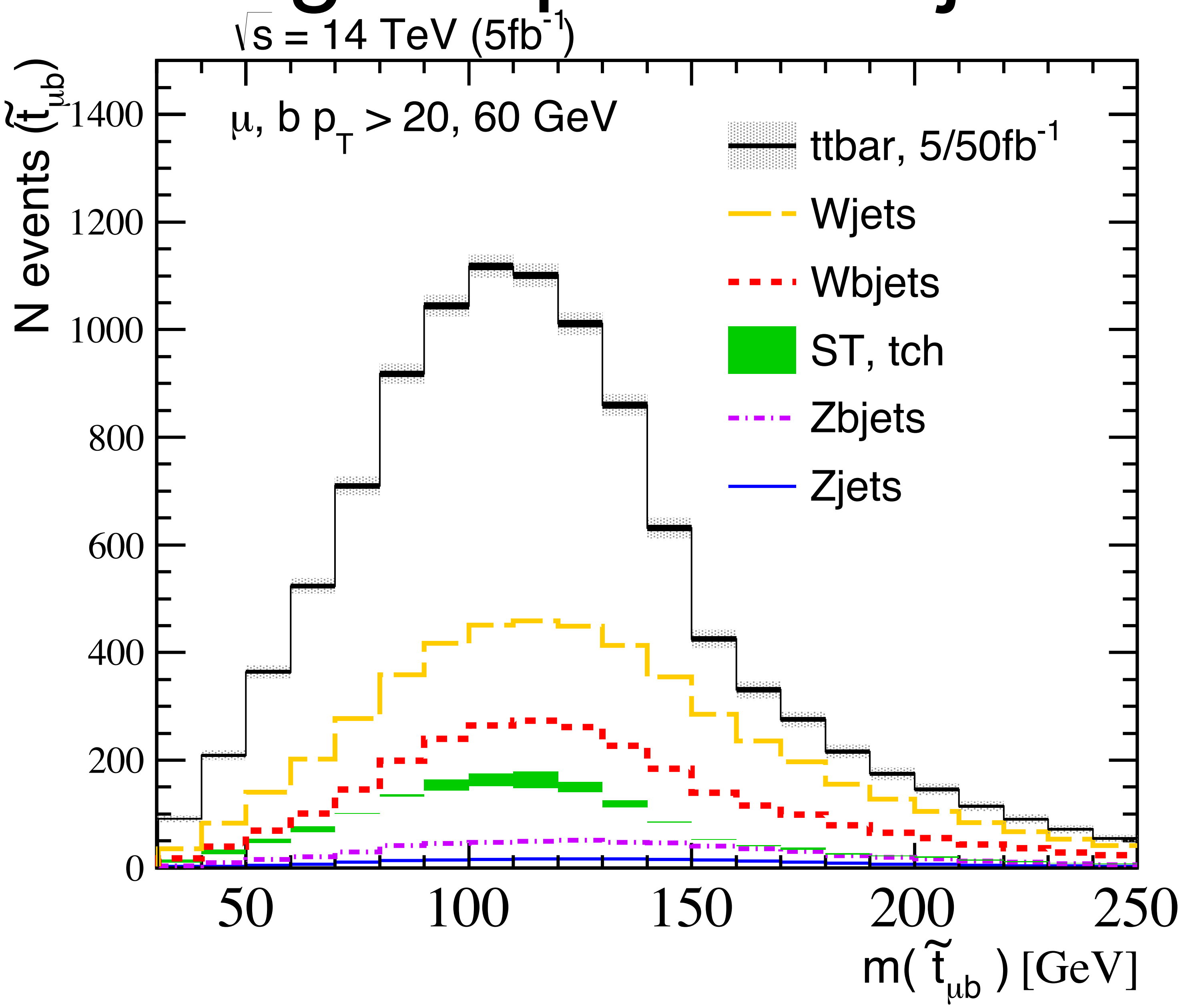
7 TeV

$$2.0 < \eta(l, b) < 4.5$$

$$p_T(l/b) > 20/60 \text{ GeV}$$

$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

Single lepton + b-jet



$$t\bar{t} \to l^{\pm} b X$$

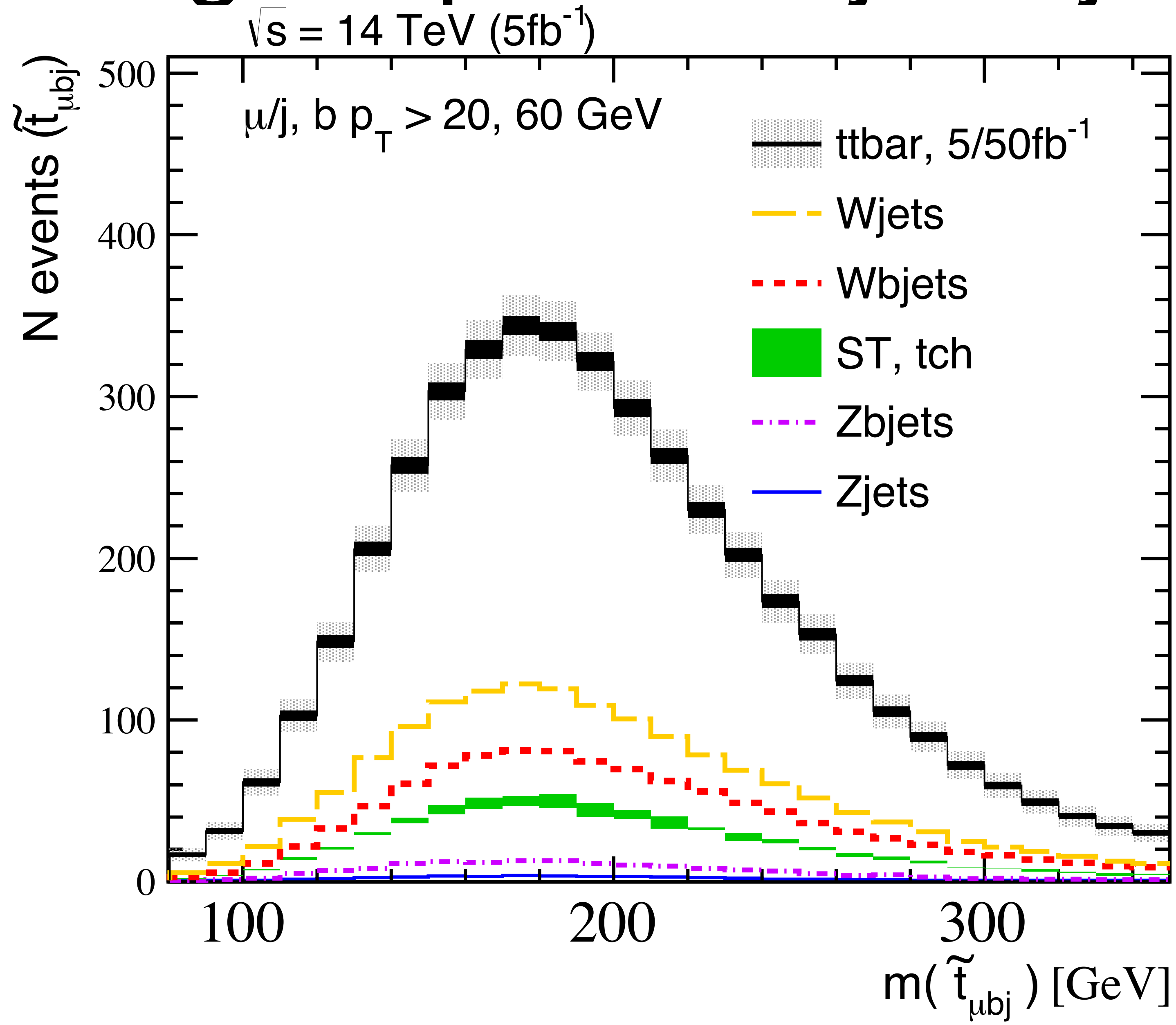
14 TeV

$$2.0 < \eta(l, b) < 4.5$$

$$p_T(l/b) > 20/60 \text{ GeV}$$

$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

Single lepton + b-jet + jet



$$t\bar{t} \rightarrow l^{\pm} b j X$$

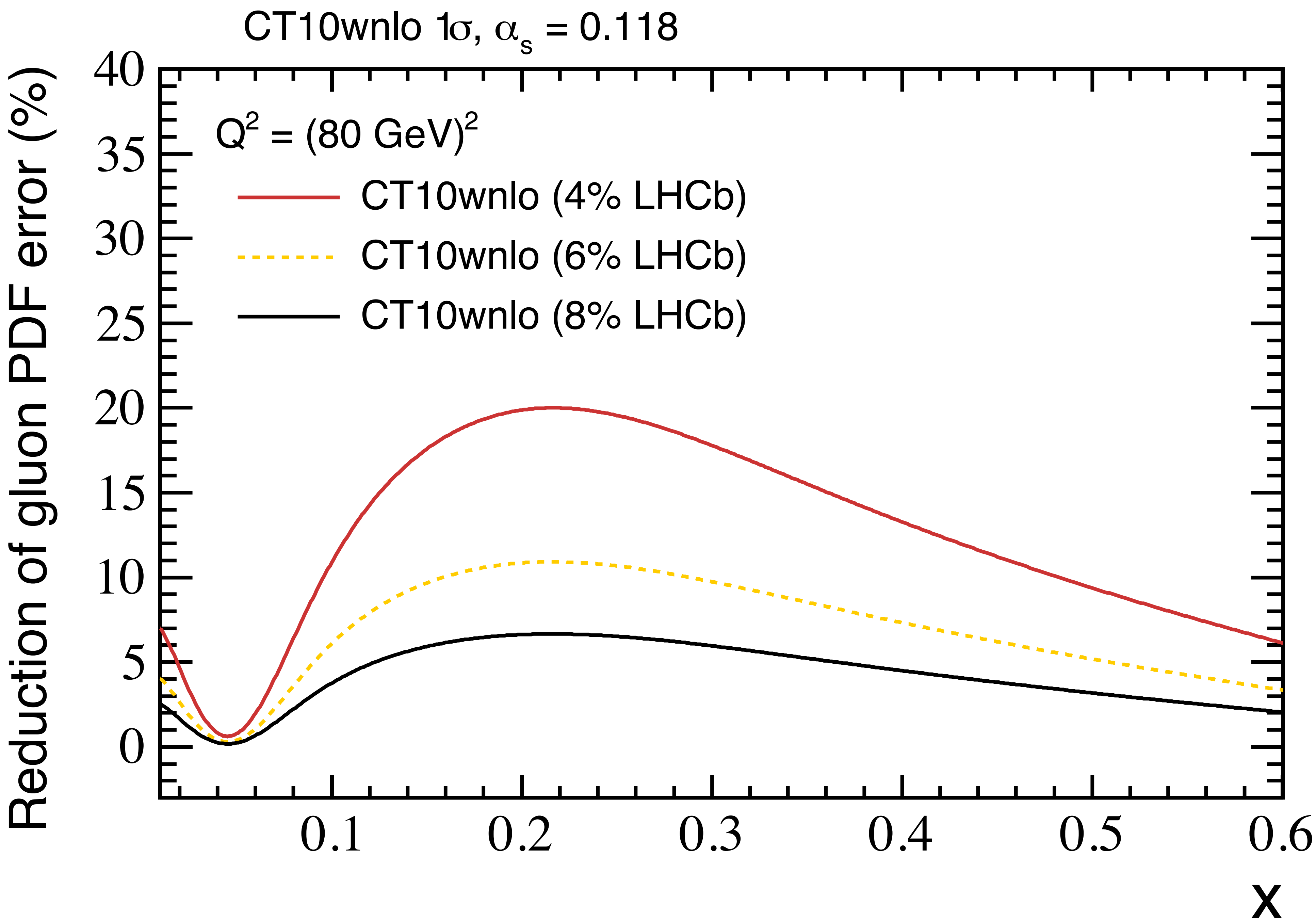
14 TeV

$$2.0 < \eta(l, b) < 4.5$$

$$p_T(l, j/b) > 20/60 \text{ GeV}$$

$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

As a constraint on the gluon PDF

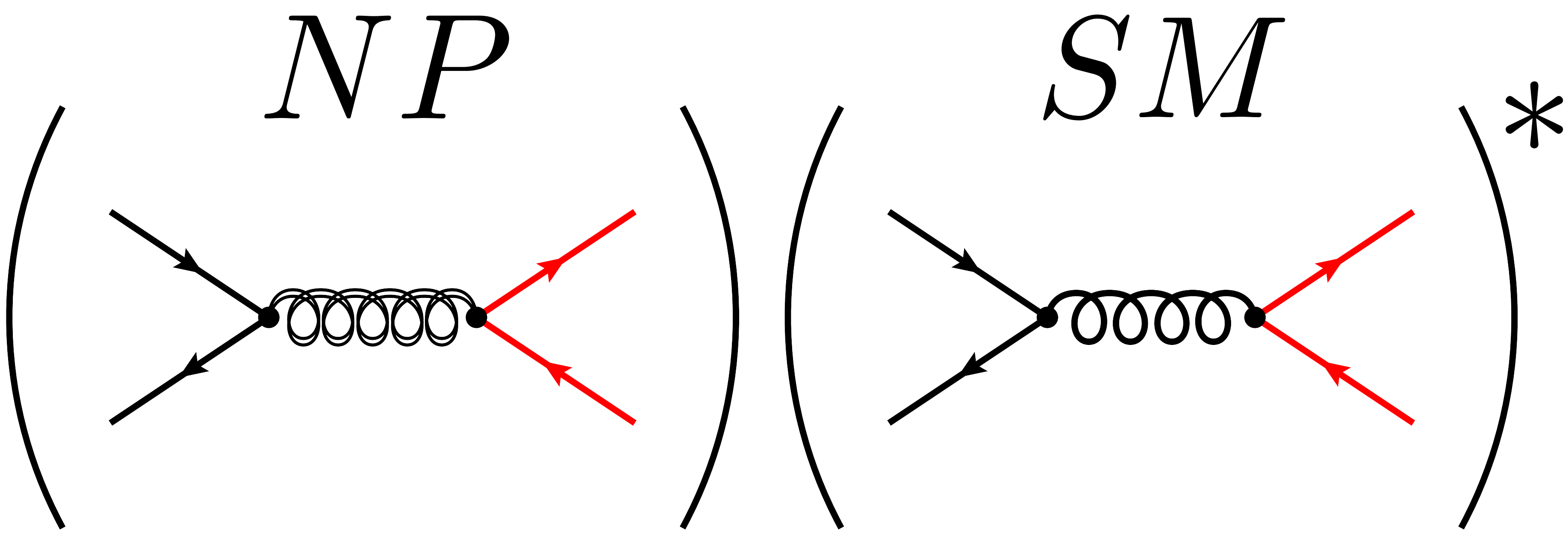


Estimated improvement in gluon PDF with LHCb data

Very **conservative** (doesn't include kinematic cuts)

Production asymmetry measurements

Motivations



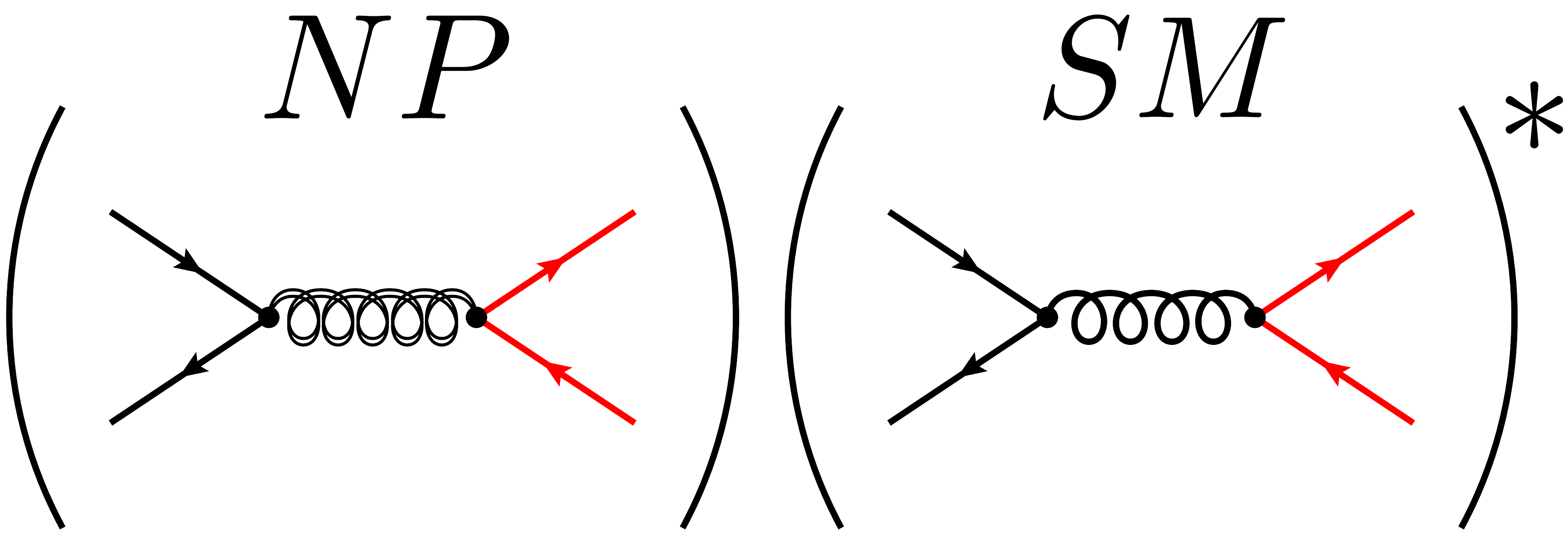
1. Can see (N)ew (P)hysics effects through interference
2. A tree-level interference effect can be large!

$$A_{fb} = \frac{(N_f - N_b)^{\mathrm{SM}} + (N_f - N_b)^{\mathrm{NP}}}{(N_f + N_b)^{Total}}$$

$$N_f^{\mathrm{NP}} \gg N_b^{\mathrm{NP}}, \qquad (N_f + N_b)^{\mathrm{NP}} \ll (N_f + N_b)^{\mathrm{SM}}$$

See for example arXiv:1107.5257, J. Kamenik, J. Shu, J, Zupan

Motivations



1. Can see (N)ew (P)hysics effects through interference
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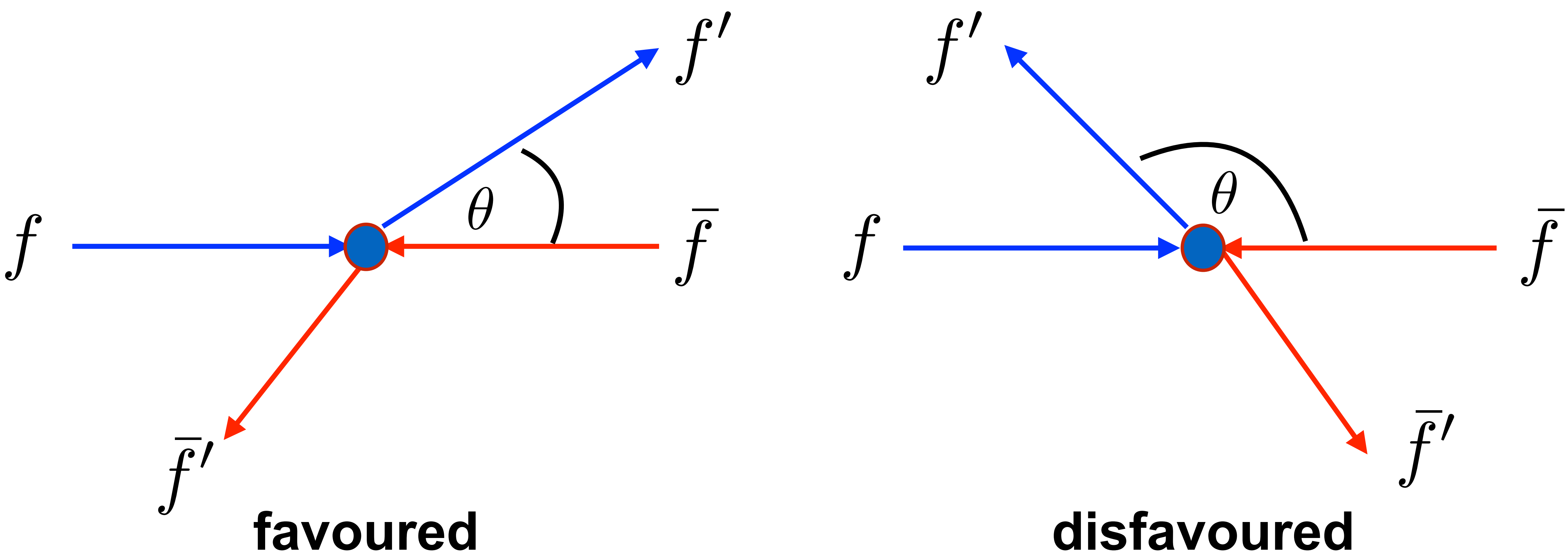
0 at LO in SM for QCD

$$A_{fb} = \frac{\cancel{(N_f - N_b)^{\mathrm{SM}}} + (N_f - N_b)^{\mathrm{NP}}}{(N_f + N_b)^{Total}}$$

$$N_f^{\mathrm{NP}} \gg N_b^{\mathrm{NP}}, \qquad (N_f + N_b)^{\mathrm{NP}} \ll (N_f + N_b)^{\mathrm{SM}}$$

Angular asymmetry in $f\bar{f} \to f'\bar{f}'$

Known for a long time in QCD and QED……



Nucl. Phys. B57 (1973) 381, F. A. Berends, K. Gaemer, and R. Gastmans,

Acta Phys. Polon. B14 (1983) 413, F. A. Berends, R. Kleiss, S. Jadach, and Z. Was,

Phys. Lett. B195(1987) 74 F. Halzen, P. Hoyer, and C. Kim

Nucl. Phys. B327 (1989) 49 P. Nason, S. Dawson, and R. K. Ellis

arXiv:hep-ph/9802268, arXiv:hep-ph/9807420 J.H.Kuhn, G. Rodrigo…. many more

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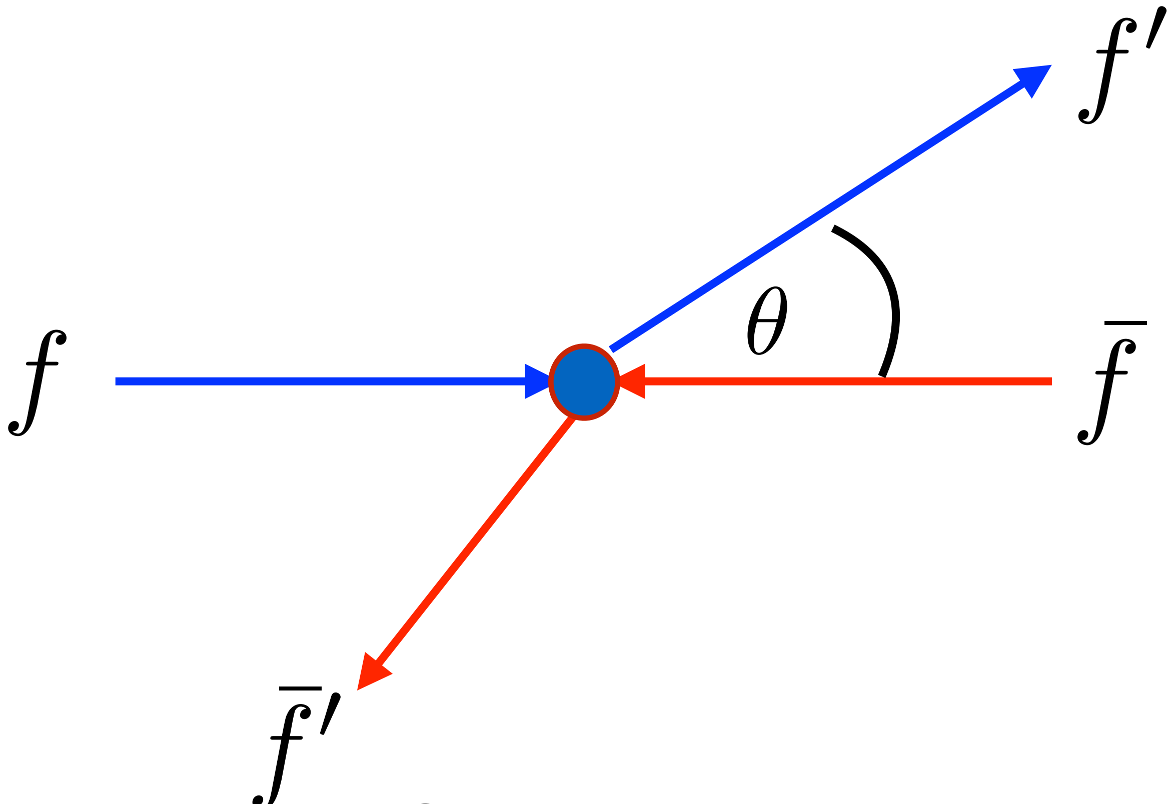
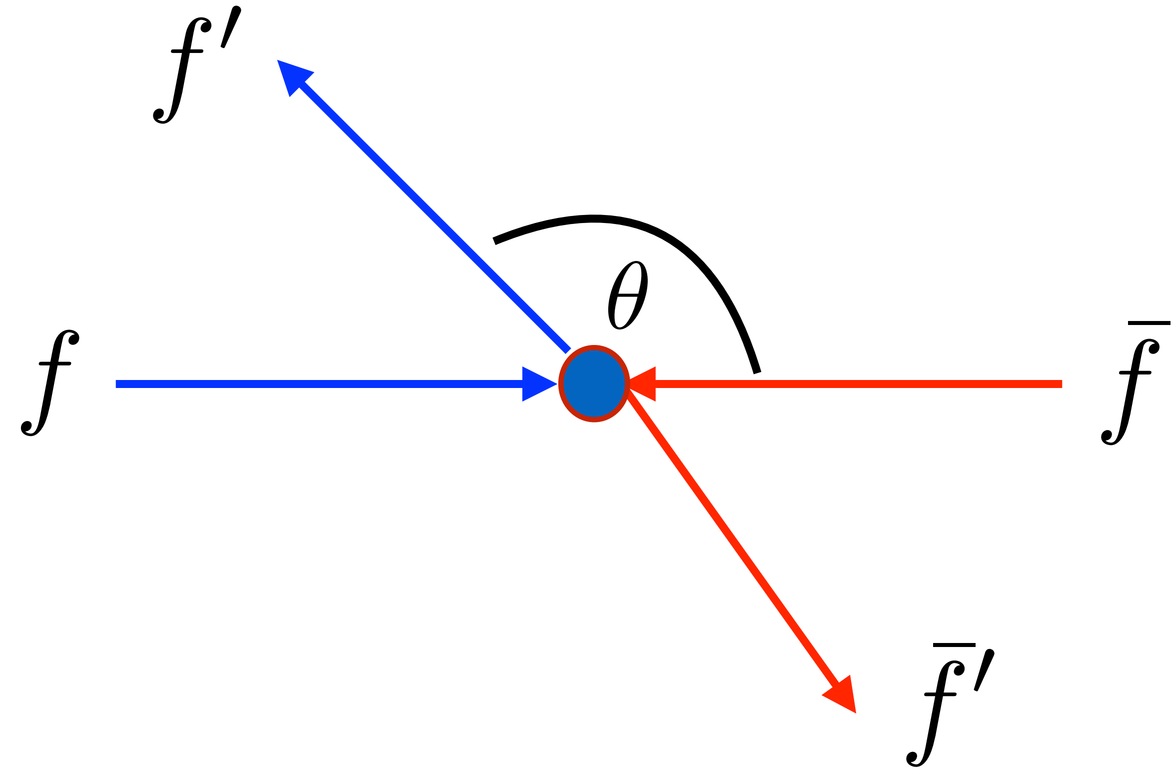


favoured



disfavoured

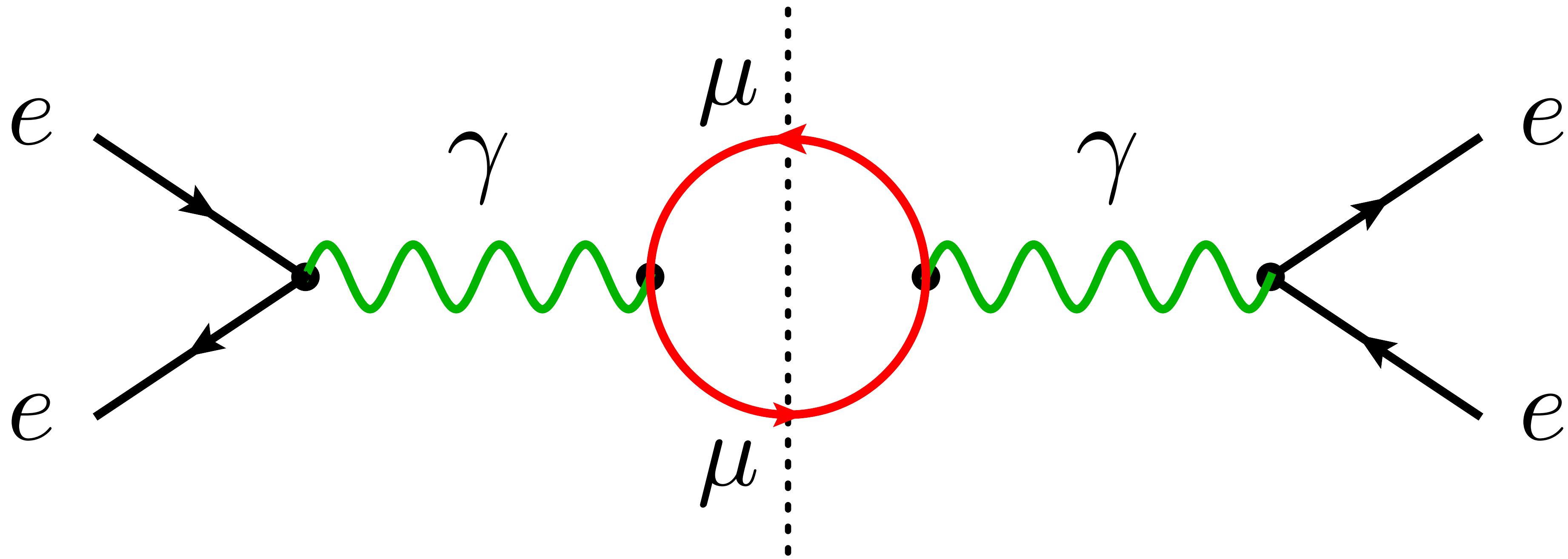
$$\hat{s} = (p_f + p_{\bar{f}})^2$$

$$\beta^2 = 1 - \frac{4m_{f'}}{\hat{s}}$$

$$t_H = -\frac{\hat{s}}{2}(1 - \beta\cos\theta)$$

$$u_H = -\frac{\hat{s}}{2}(1 + \beta\cos\theta)$$

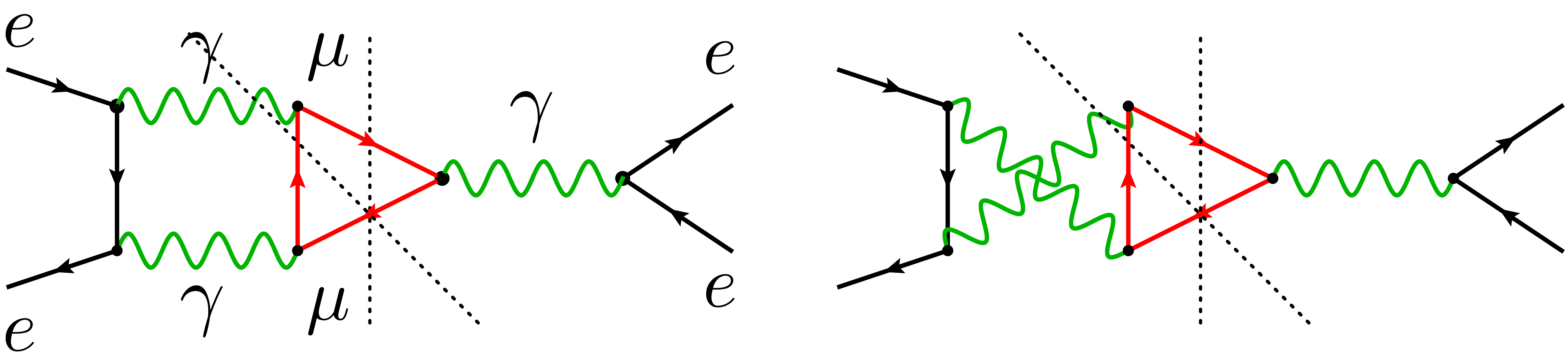
Qualitative example $e^+e^- \to \mu^+\mu^-$



$$\mathcal{M}_{\rm LO} \cdot \mathcal{M}_{\rm LO}^*$$

$$d\sigma_{\rm asym} = \frac{1}{2}\left(d\sigma(t_H, u_H) - d\sigma(u_H, t_H)\right) = 0$$

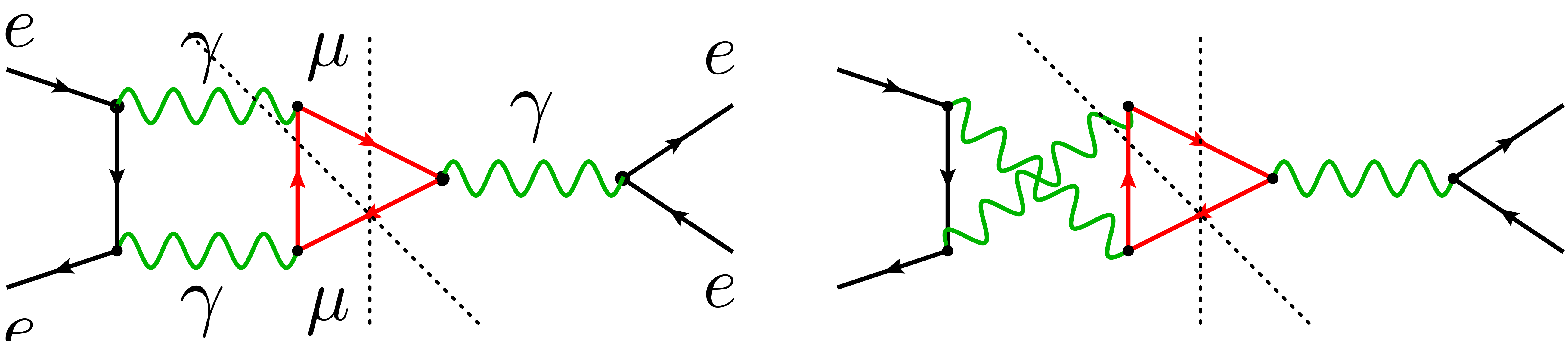
Qualitative example $e^+e^- \to \mu^+\mu^-$



$\mathcal{M}_{\rm A} \cdot \mathcal{M}^*_{\rm LO}$ $\mathcal{M}_{\rm B} \cdot \mathcal{M}^*_{\rm LO}$

$$d\sigma_{\rm asym} = \frac{1}{2}\left(d\sigma(t_H, u_H) - d\sigma(u_H, t_H)\right) \neq 0$$

Qualitative example $e^+e^- \to \mu^+\mu^-$



$\mathcal{M}_{\rm A}\cdot\mathcal{M}^*_{\rm LO}$ $\mathcal{M}_{\rm B}\cdot\mathcal{M}^*_{\rm LO}$

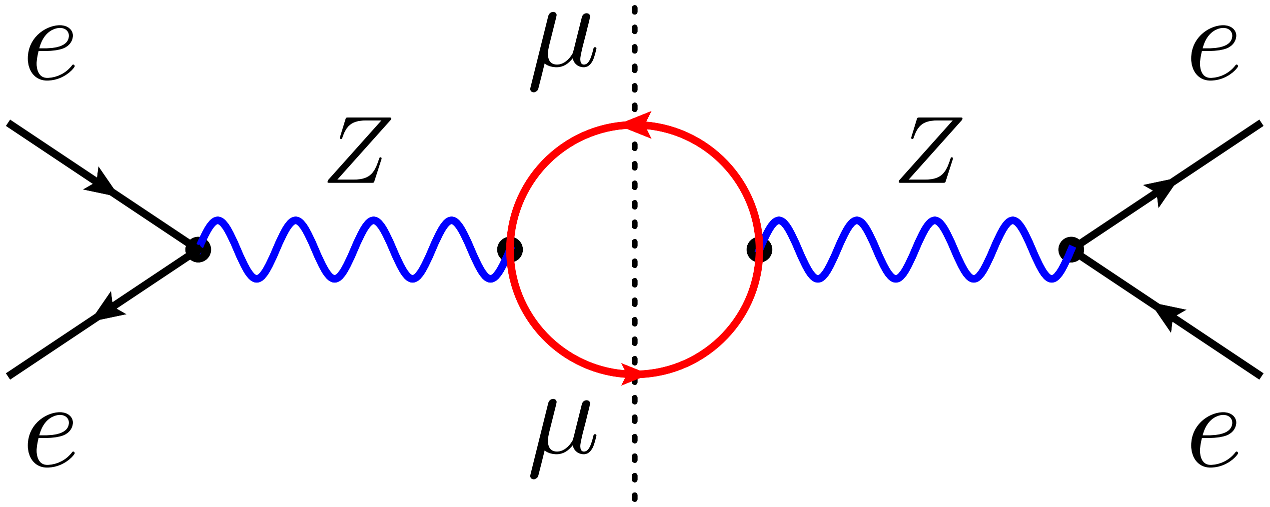
$$d\sigma_{\rm asym} = \frac{1}{2}\left(d\sigma(t_H, u_H) - d\sigma(u_H, t_H)\right) \neq 0$$

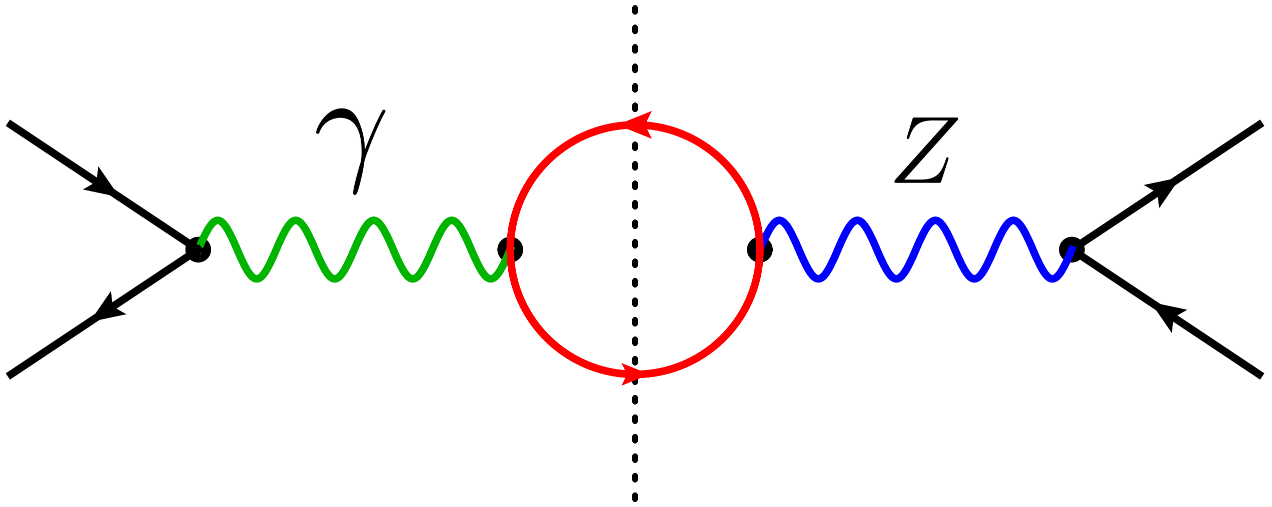
$$\boxed{d\sigma_{\rm A}\left(t_H, u_H\right) = -d\sigma_{\rm B}\left(u_H, t_H\right)}$$

← Feature of box amplitude

$$d\sigma_{\rm asym} \propto d\sigma_{\rm A}\left(t_H, u_H\right) + d\sigma_{\rm B}\left(t_H, u_H\right)$$

Qualitative example $e^+e^- \to \mu^+\mu^-$



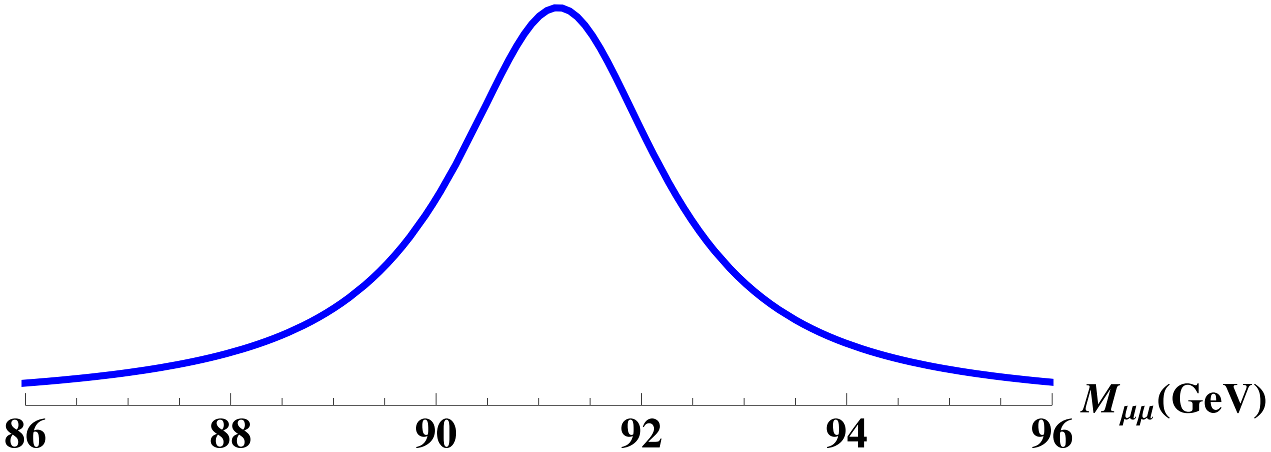


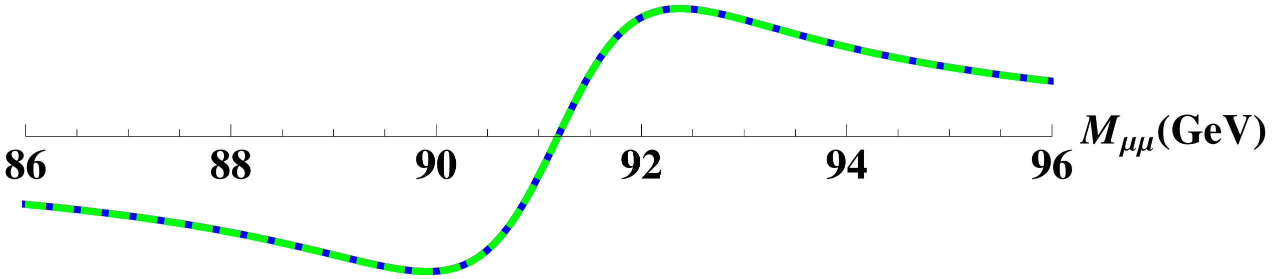
$$\mathcal{M}_Z \cdot \mathcal{M}_Z^*$$

$$\mathcal{M}_\gamma \cdot \mathcal{M}_Z^*$$

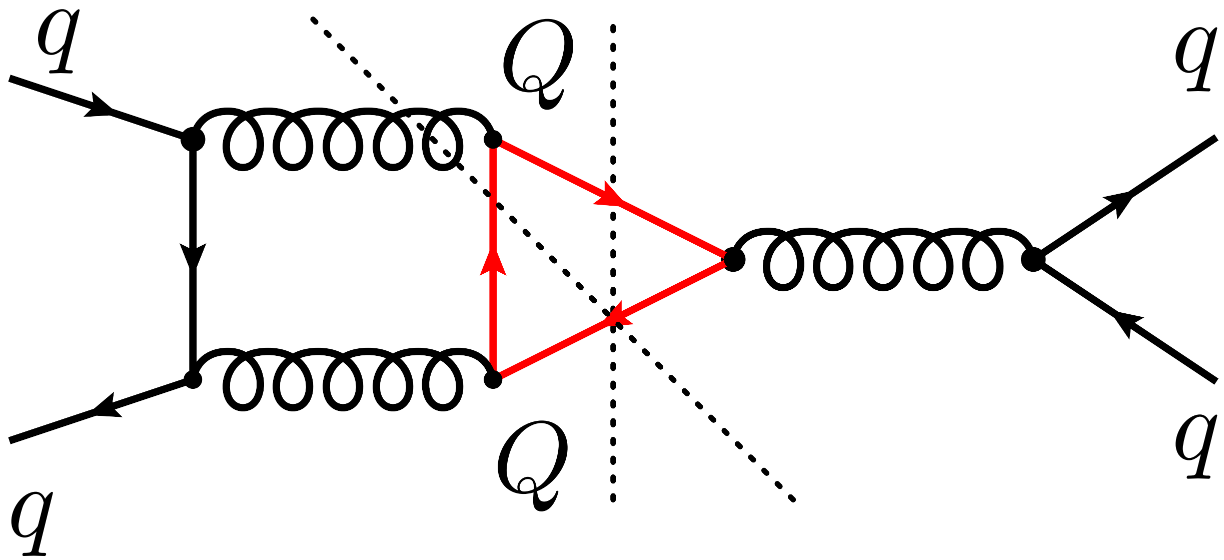
$$d\sigma_{\rm asym}^{\gamma/Z} \propto \frac{\alpha\, g_A^e g_A^\mu g_V^e g_V^\mu \beta^2 \kappa^2\, \hat{s} \cos\theta}{(\hat{s} - M_Z^2)^2}$$

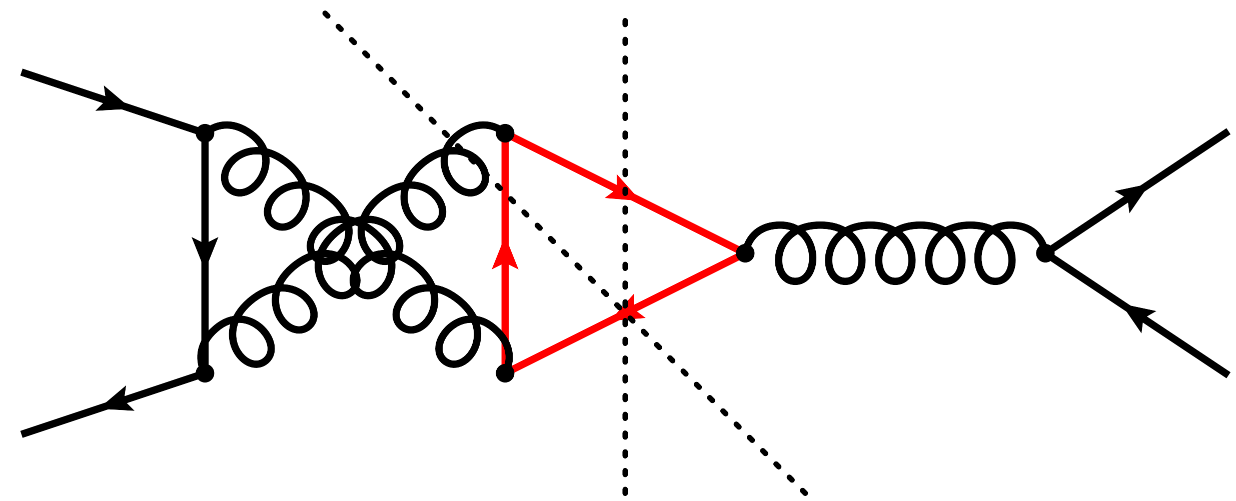
$$d\sigma_{\rm asym}^{\gamma/Z} \propto \frac{\alpha\, g_A^e g_A^\mu Q^e Q^\mu \beta^2 \kappa \cos\theta}{\hat{s} - M_Z^2}$$



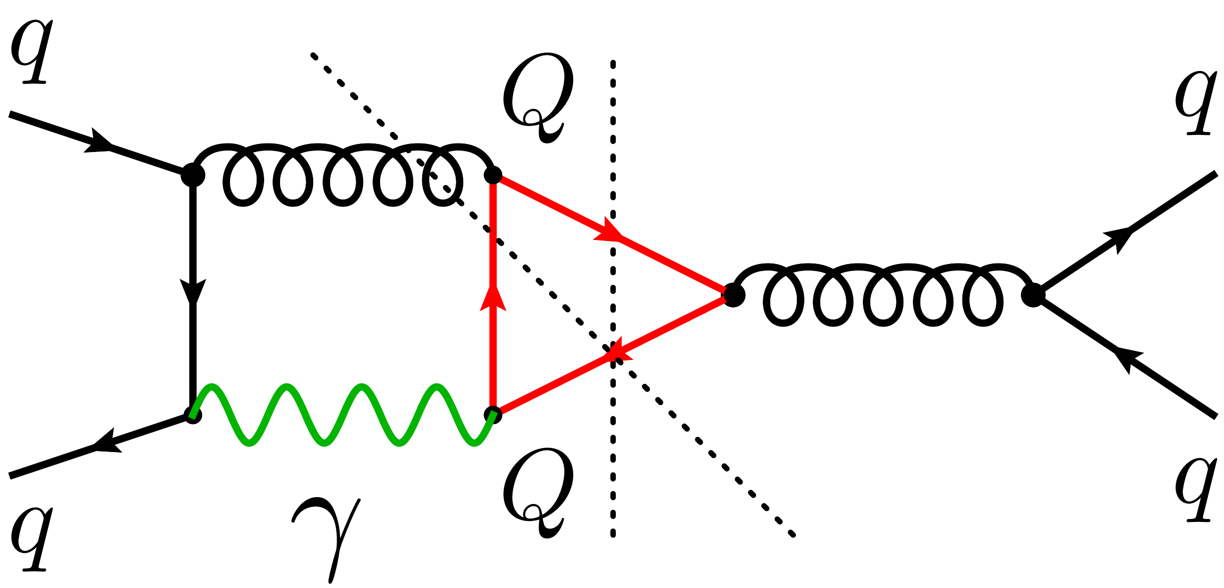


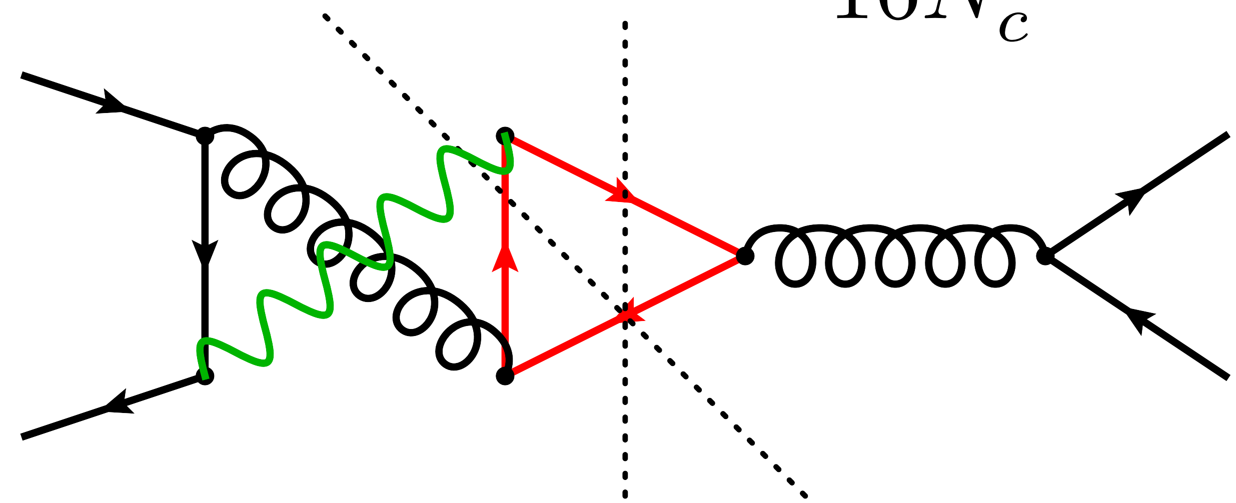
$Q\bar{Q}$ final state at hadron colliders





Can obtain QCD from QED result: $\alpha^3 Q_f^3 Q_{f'}^3 \to \alpha_s^3 \frac{d_{\mathrm{ABC}}^2}{16 N_c^2}$



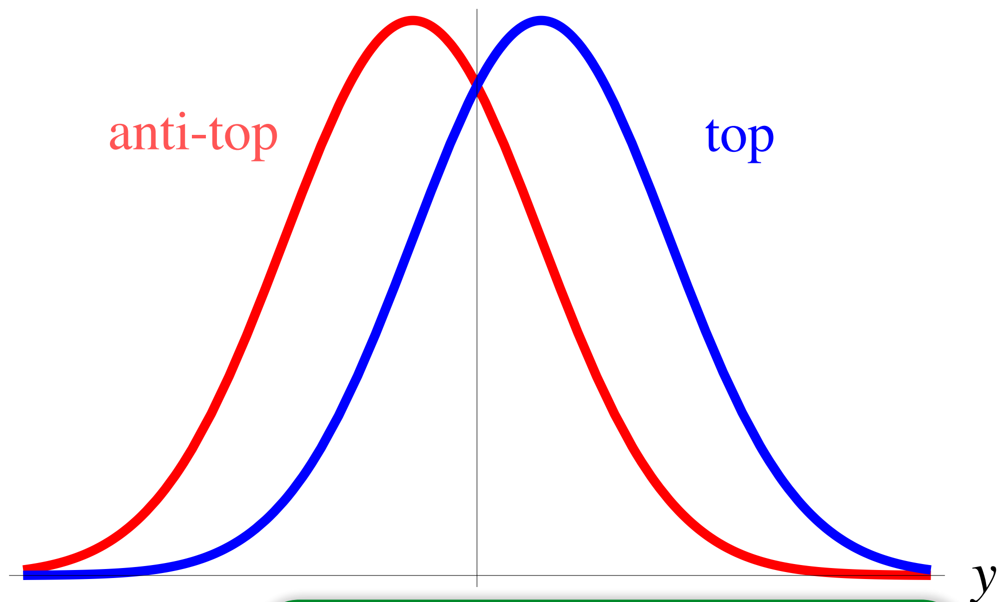


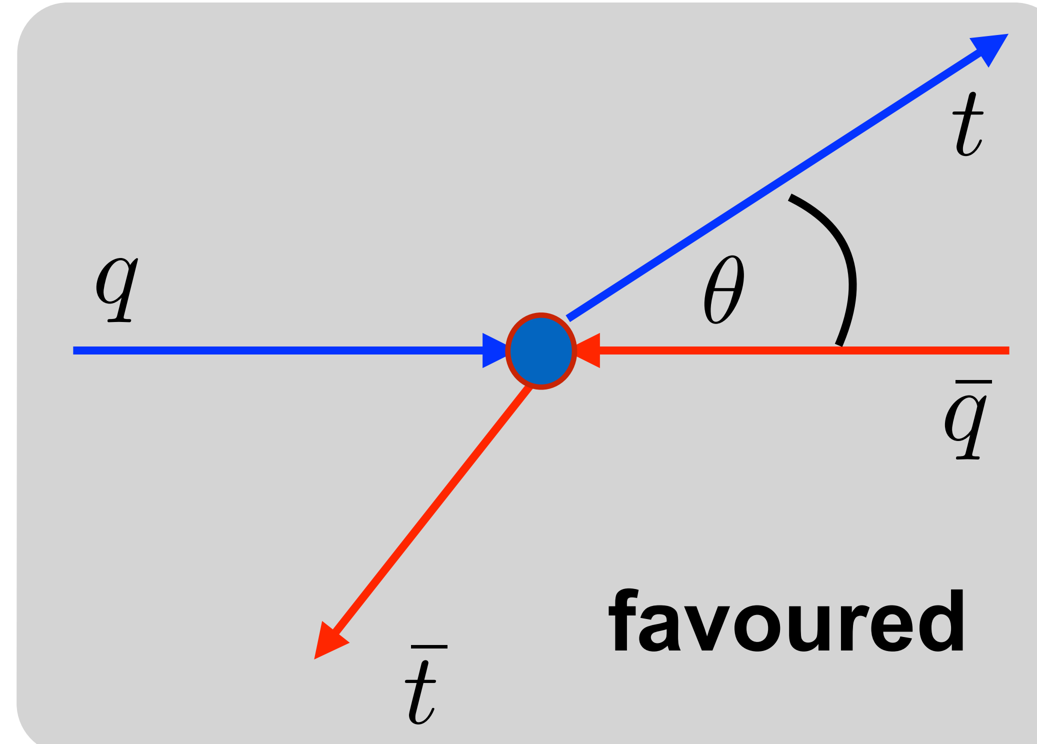
Can obtain QED-QCD from QED result: $\alpha^3 Q_f^3 Q_{f'}^3 \to 3 \left(\alpha Q_f Q_{f'} \alpha_s^2 \frac{C_F}{2N_c} \right)$

COMMENT: Since $q\bar{q} \to Q\bar{Q}X$, $X = \gamma\,, g\,, Z\,, W^{\pm}$ contribute to asym.
By crossing symmetry, so do $qX \to Q\bar{Q}q$, $\bar{q}X \to Q\bar{Q}\bar{q}$

Results from the Tevatron

Tevatron $\quad p\bar{p} \to Q\bar{Q}$





nnlo QCD + nlo ewk
Czakon,Fielder,Mitov

Inclusive results with **all data**

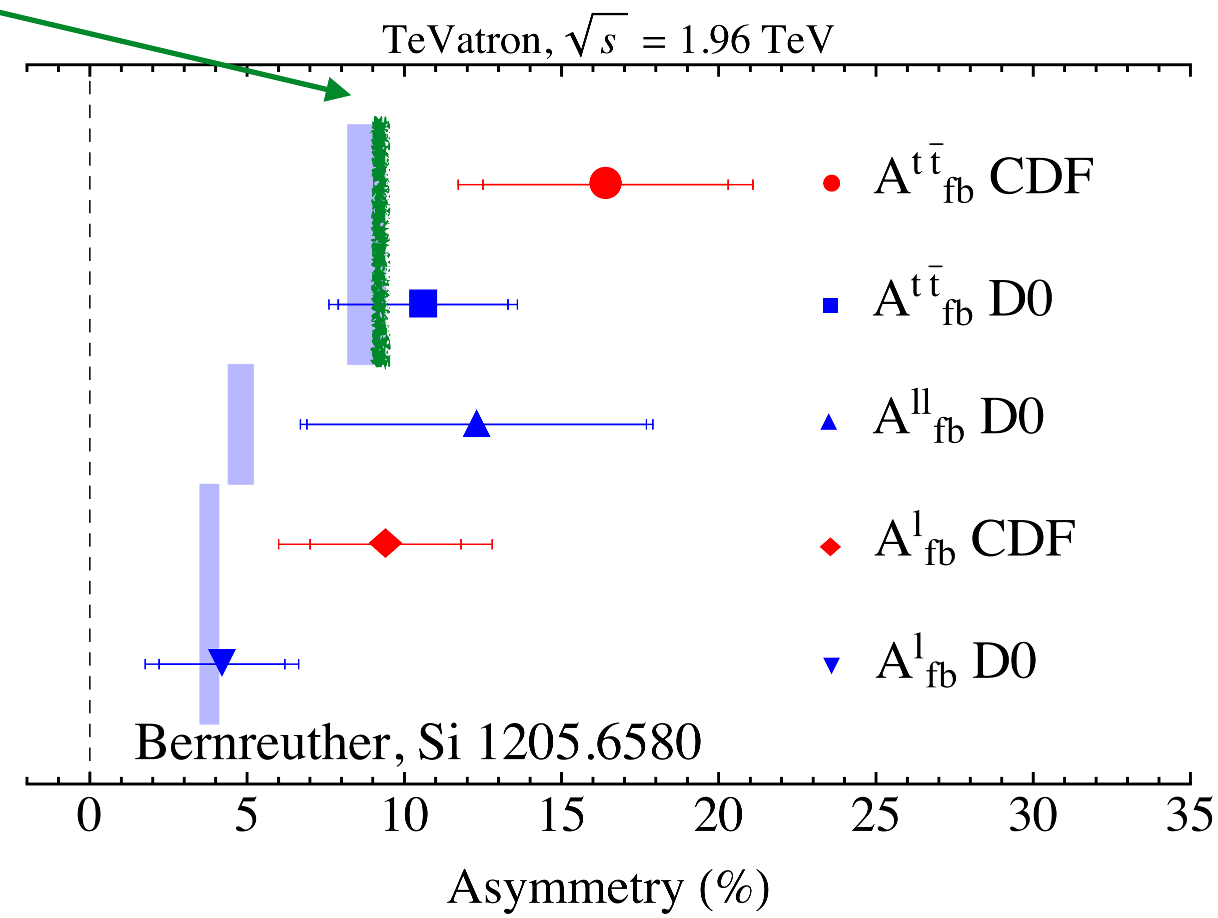
CDF Collaboration, arXiv:1211.1003.

D0 Collaboration, arXiv:1405.0421.

D0 Collaboration, 1308.6690.

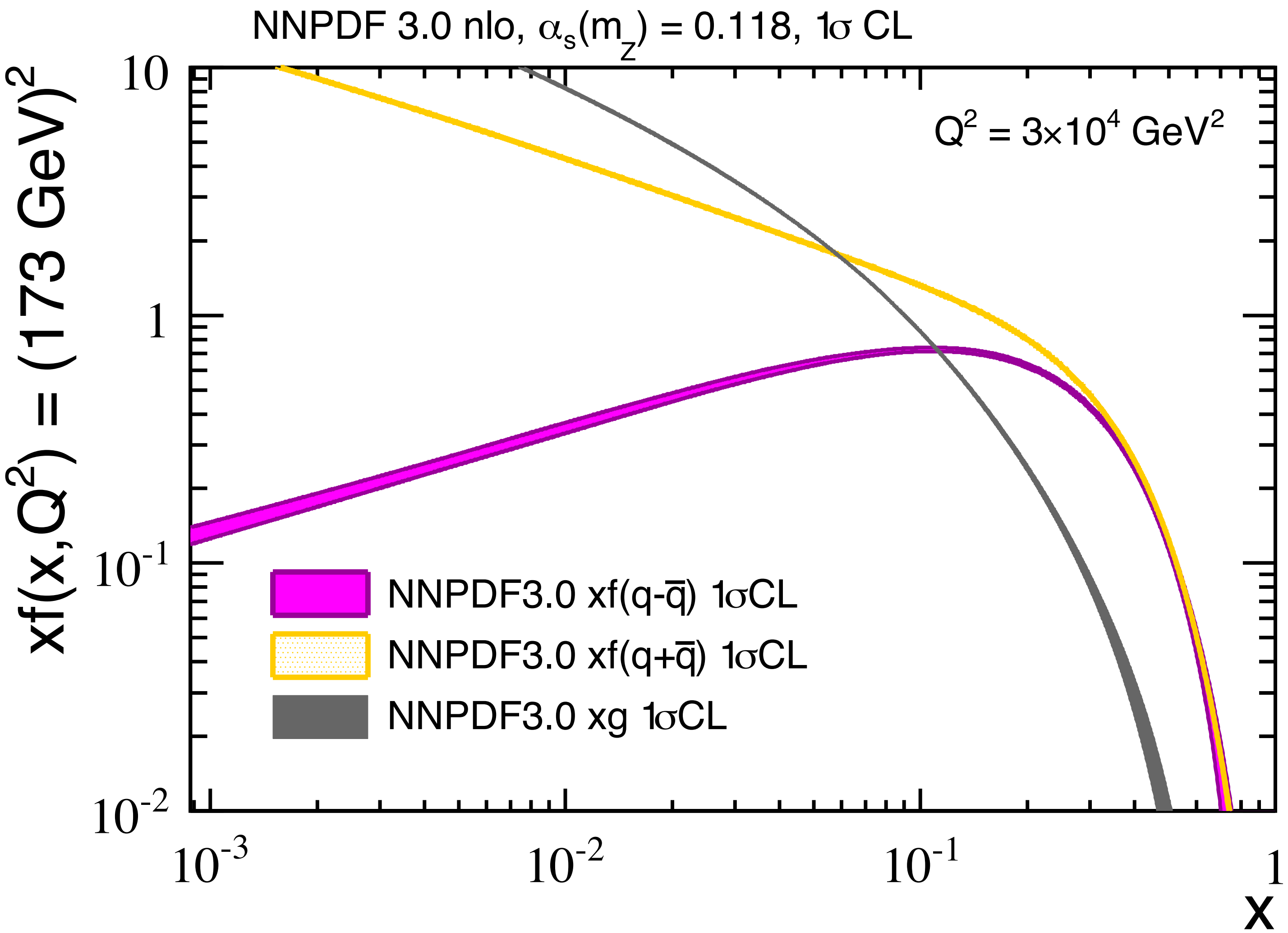
CDF Collaboration, arXiv:1308.1120.

D0 Collaboration, arXiv:1403.1294.

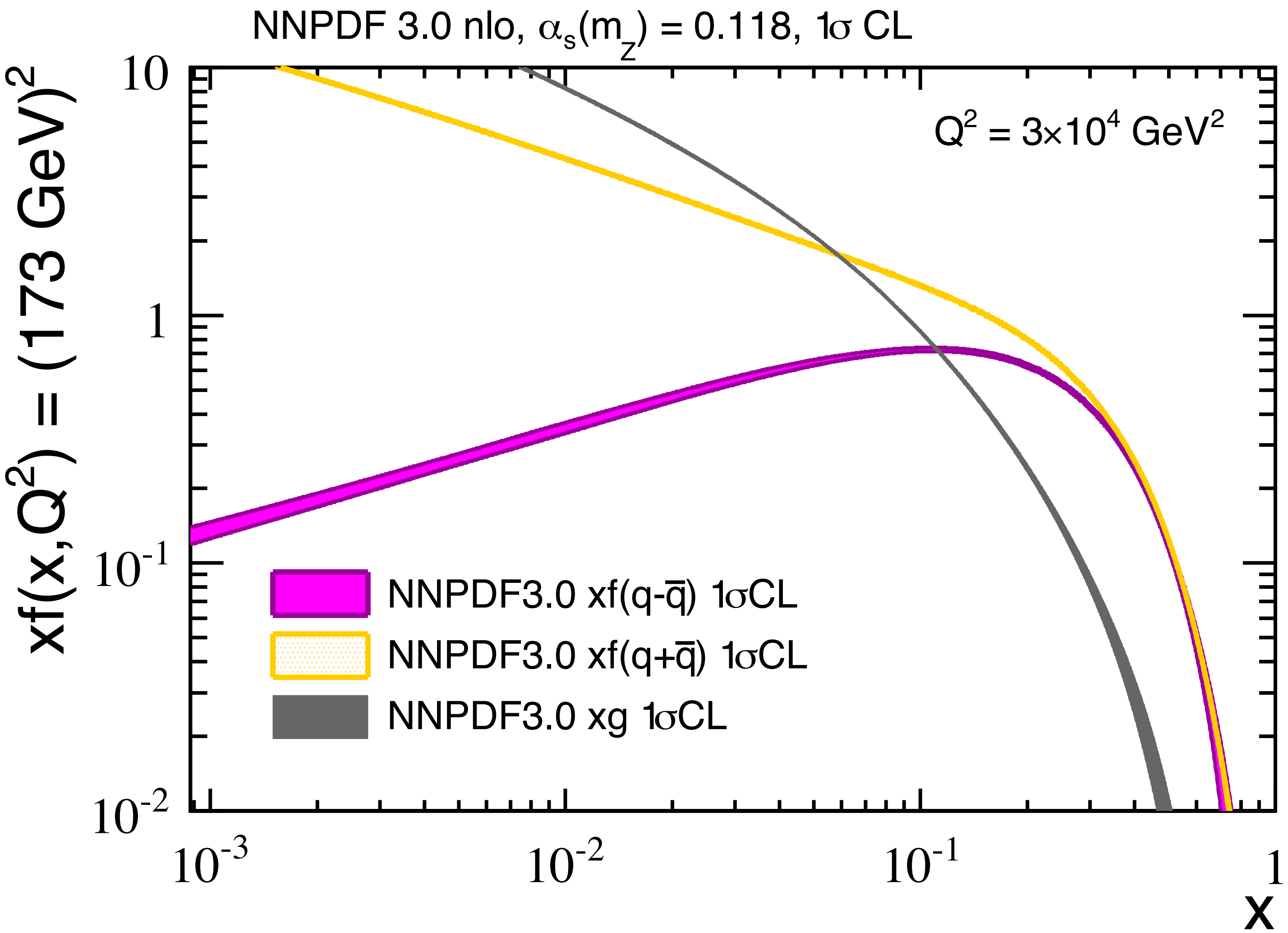


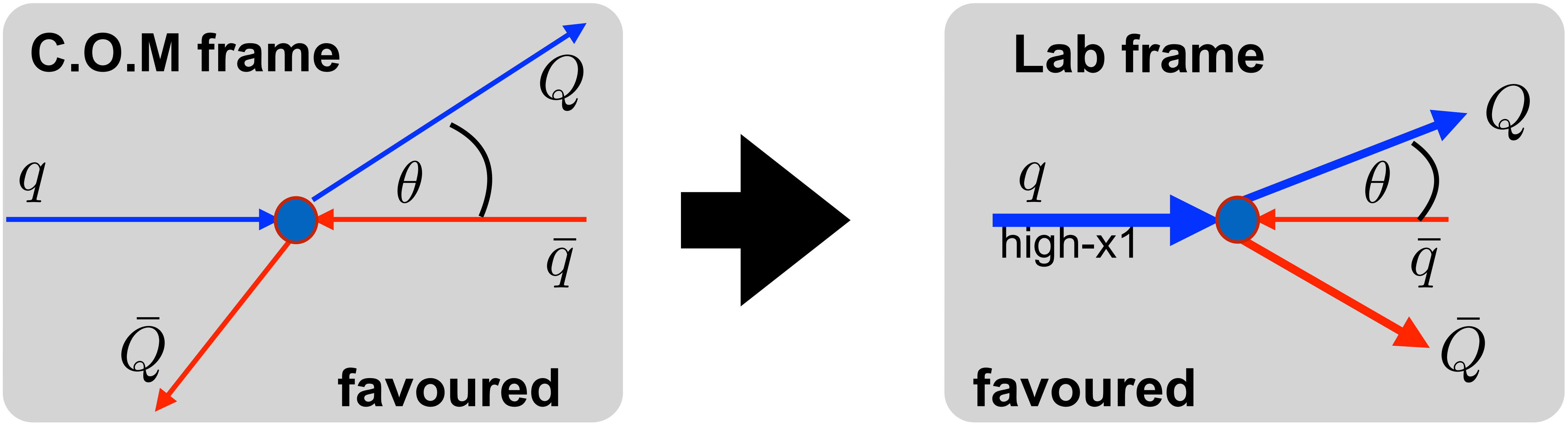
$$\chi^2/N_{\rm d.o.f.} \simeq 7.1/5 \simeq 1.3\sigma$$

What about the LHC?



What about the LHC?





arXiv:1406.4789v2 [hep-ex] 13 Sep 2014

First measurement of the charge asymmetry in beauty-quark pair production at a hadron collider

The LHCb collaboration†

Abstract

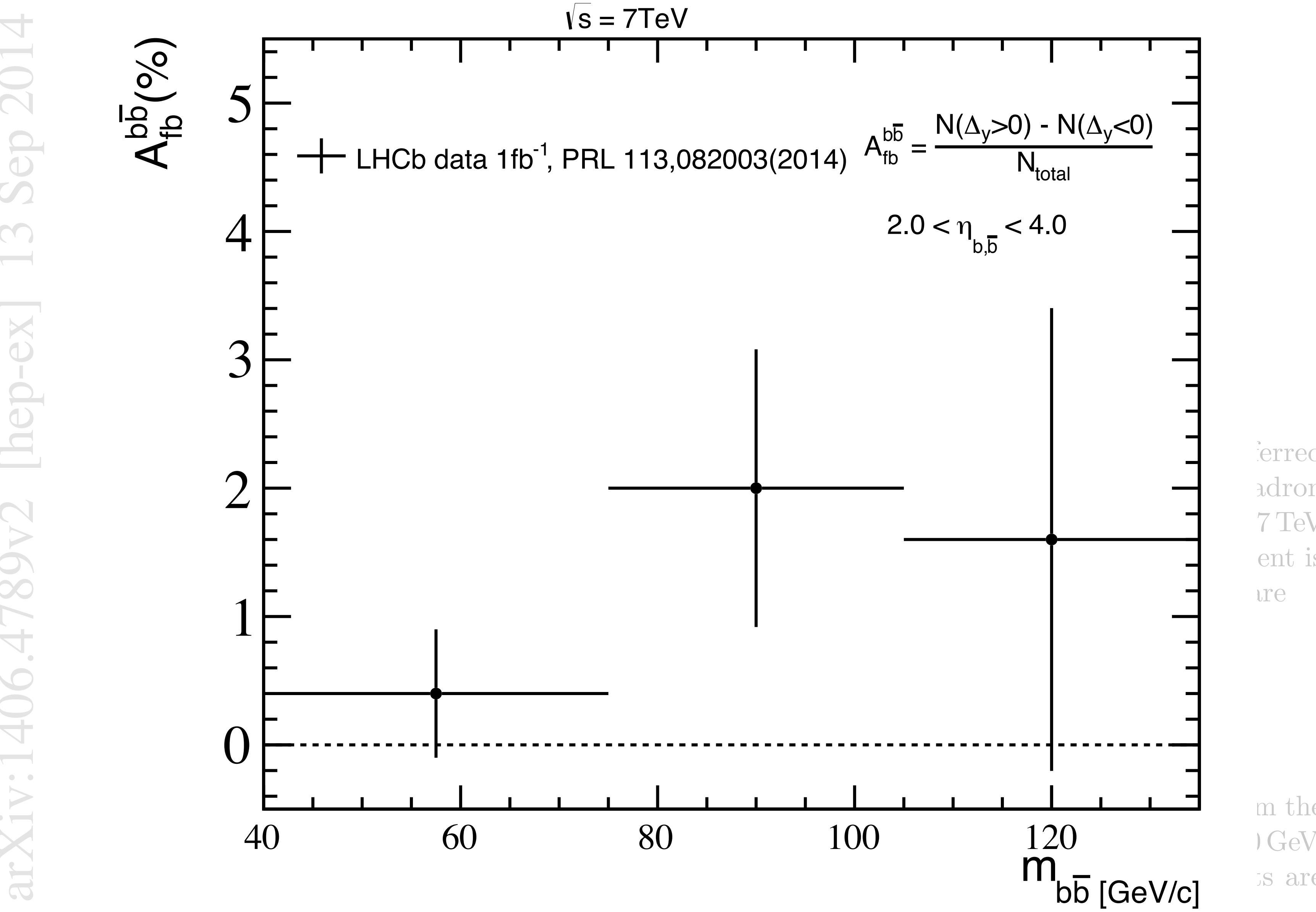
The difference in the angular distributions between beauty quarks and antiquarks, referred to as the charge asymmetry, is measured for the first time in $b\bar{b}$ pair production at a hadron collider. The data used correspond to an integrated luminosity of $1.0\,\mathrm{fb}^{-1}$ collected at 7 TeV center-of-mass energy in proton-proton collisions with the LHCb detector. The measurement is performed in three regions of the invariant mass of the $b\bar{b}$ system. The results obtained are

$$\begin{aligned} A_{\mathrm{C}}^{b\bar{b}}(40 < M_{b\bar{b}} < 75\,\mathrm{GeV}/c^2) &= 0.4 \pm 0.4\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})\%, \\ A_{\mathrm{C}}^{b\bar{b}}(75 < M_{b\bar{b}} < 105\,\mathrm{GeV}/c^2) &= 2.0 \pm 0.9\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})\%, \\ A_{\mathrm{C}}^{b\bar{b}}(M_{b\bar{b}} > 105\,\mathrm{GeV}/c^2) &= 1.6 \pm 1.7\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})\%, \end{aligned}$$

where $A_{\mathrm{C}}^{b\bar{b}}$ is defined as the asymmetry in the difference in rapidity between jets formed from the beauty quark and antiquark. The beauty jets are required to satisfy $2 < \eta < 4$, $E_{\mathrm{T}} > 20\,\mathrm{GeV}$, and have an opening angle in the transverse plane $\Delta\phi > 2.6\,\mathrm{rad}$. These measurements are consistent with the predictions of the Standard Model.

- Measure forward-backward asymmetry of b-jets using 7TeV data
- Charge tag b-jets using semi-leptonic B-decays
- Measurement performed in bins of Mbb

$$2.0 < \eta < 4.0\,, \quad E_T > 20\mathrm{GeV}\,, \quad \Delta\phi > 2.6\,\mathrm{rad}$$



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SM prediction (RG, U. Haisch, B. Pecjak, E. Re)

$$A_{\rm FC}^{Q\bar{Q}} = \frac{\sigma\left(\Delta y > 0\right) - \sigma\left(\Delta y < 0\right)}{\sigma\left(\Delta y > 0\right) + \sigma\left(\Delta y < 0\right)} \qquad \Delta y = y_b - y_{\bar{b}}$$

$$A_{\rm FC}^{Q\bar{Q}} = \frac{\alpha_s^3 \sigma_a^{s(0)} + \alpha_s^2 \alpha\, \sigma_a^{se(0)} + \alpha^2 \left(\sigma_a^{e(0)} + \alpha_s \sigma_a^{e(1)}\right)}{\alpha_s^2 \left(\sigma_s^{s(0)} + \alpha_s \sigma_s^{s(1)}\right) + \alpha^2 \left(\sigma_s^{e(0)} + \alpha_s \sigma_s^{e(1)}\right)}\,.$$

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Symmetric NLO QCD
P. Nason, S. Dawson, R. K. Ellis,
Nucl. Phys. B 303 607 (1988)
Implemented in POWHEG-BOX

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Phys. Rev. D 59, 054017 (1999)
Use analytic formula

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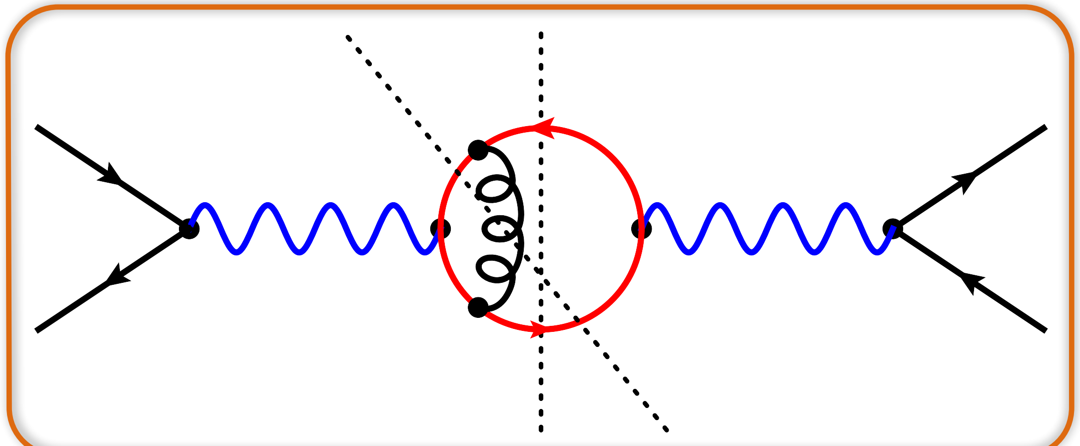

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QCD correction to Drell-Yan
S. Alioli, P. Nason, C. Oleari, E. Re,
JHEP 0807, 060 (2008)
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Asymmetric NLO QCD
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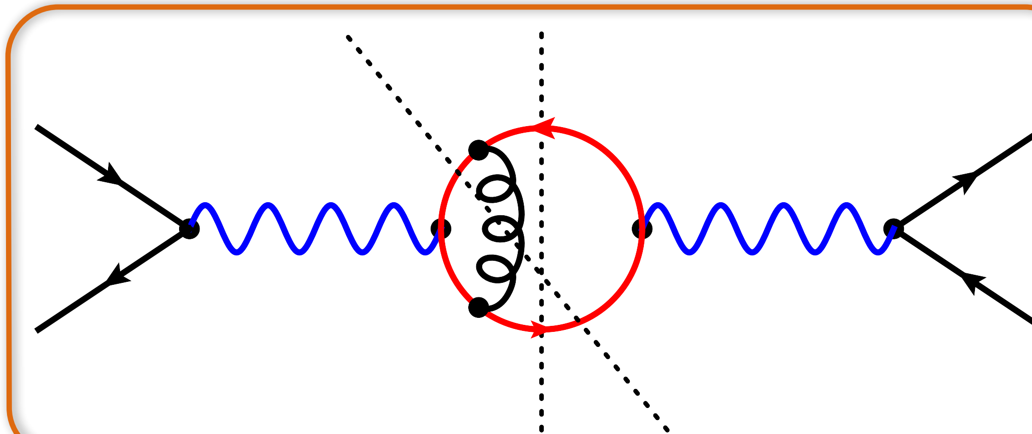
'tricky' part



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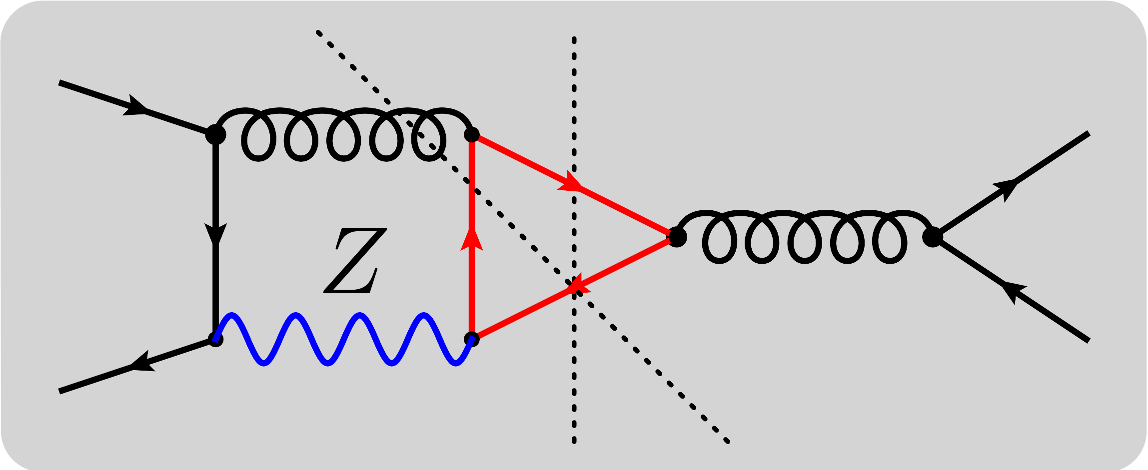
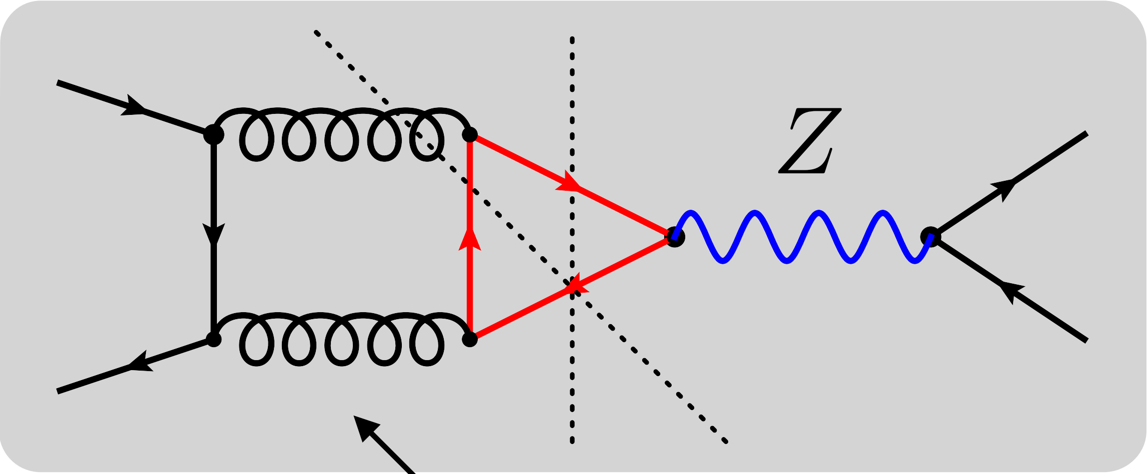
Resonant contributions



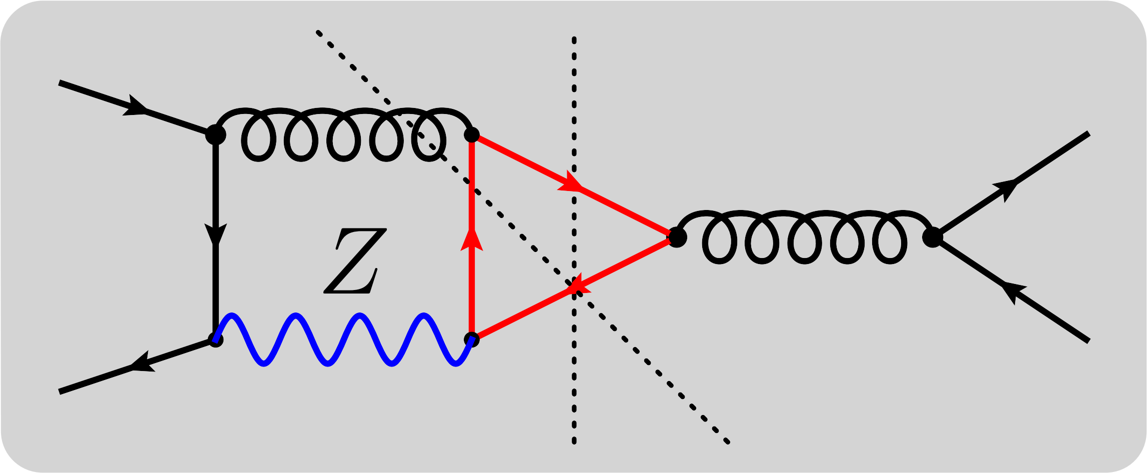


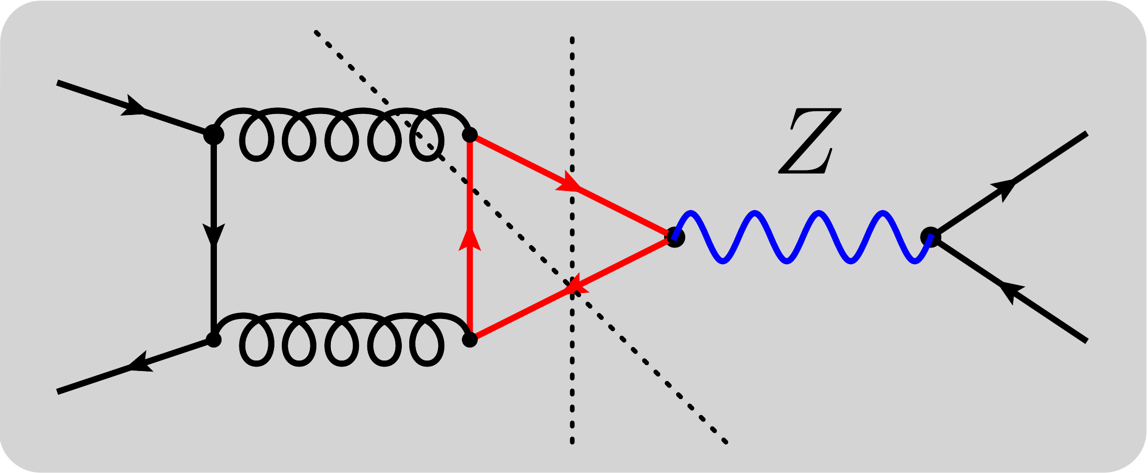
$$(\mathfrak{Im}\,\mathcal{M}_A)\cdot\mathcal{M}^*_{\mathrm{LO}}$$

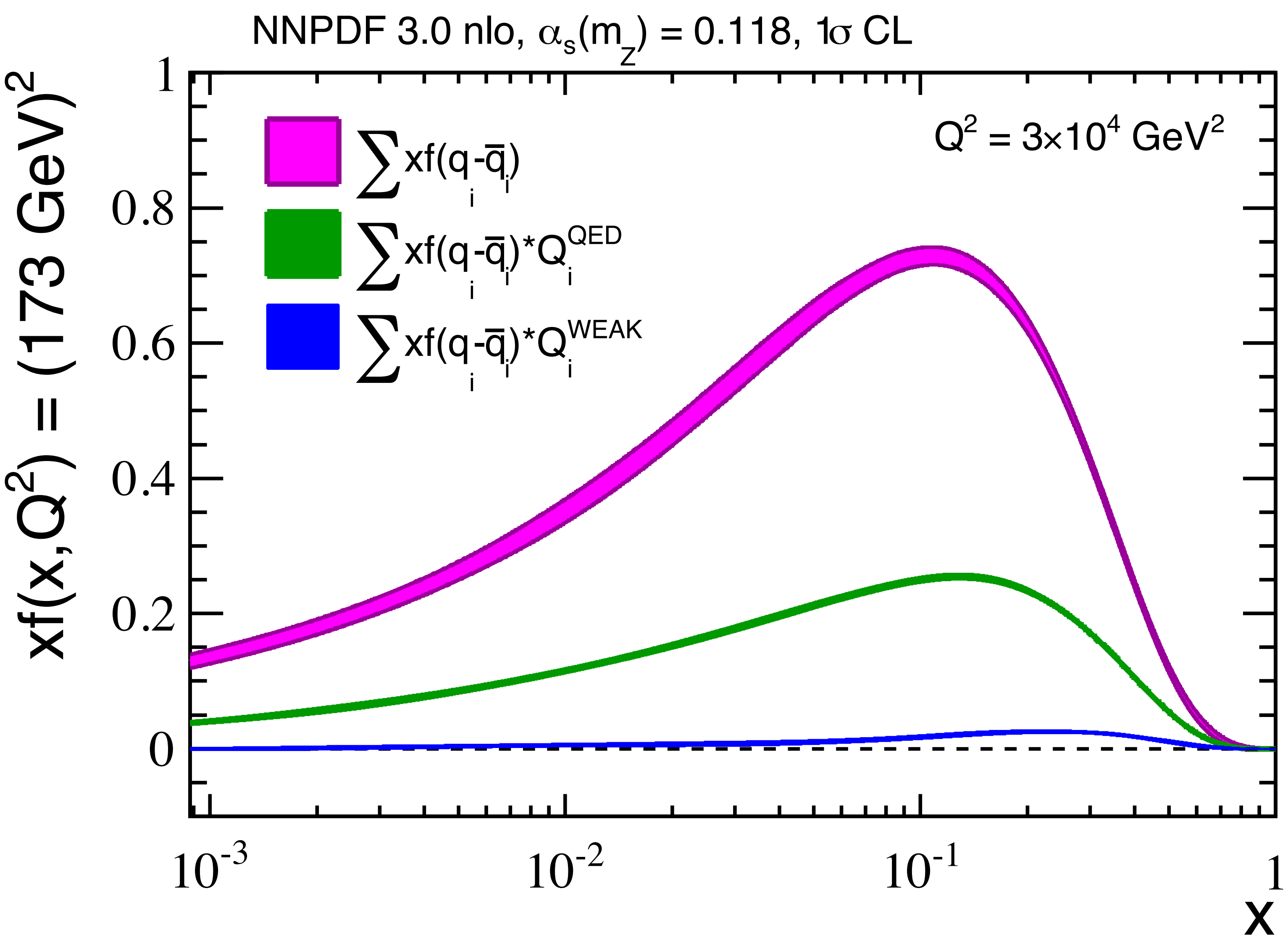
- Compute squared matrix elements (use FeynArts and FormCalc)
- Evaluate virtual (using OneLOops package - dim reg)
- Compute soft function (integrate gluon PS in d-dim to Ecut)
- Combine virtual+soft and real emission into Integrand
- Link to LHAPDF and do integration with VEGAS (CUBA library)

$$\mu_W^2 = M_W^2 - iM_W\Gamma_W\,, \quad \mu_Z^2 = M_Z^2 - iM_Z\Gamma_Z$$
$$c_w^2 = 1 - s_w^2 = \mu_W^2/\mu_Z^2$$

Resonant contributions

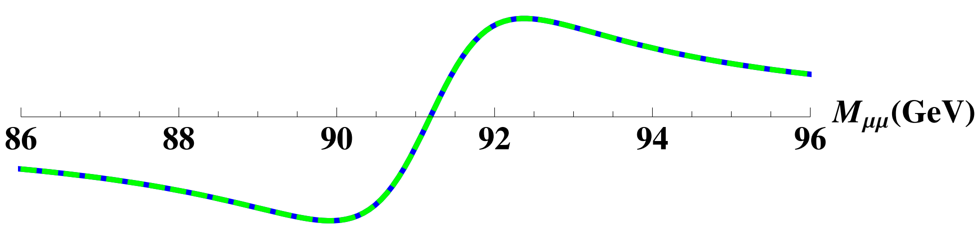






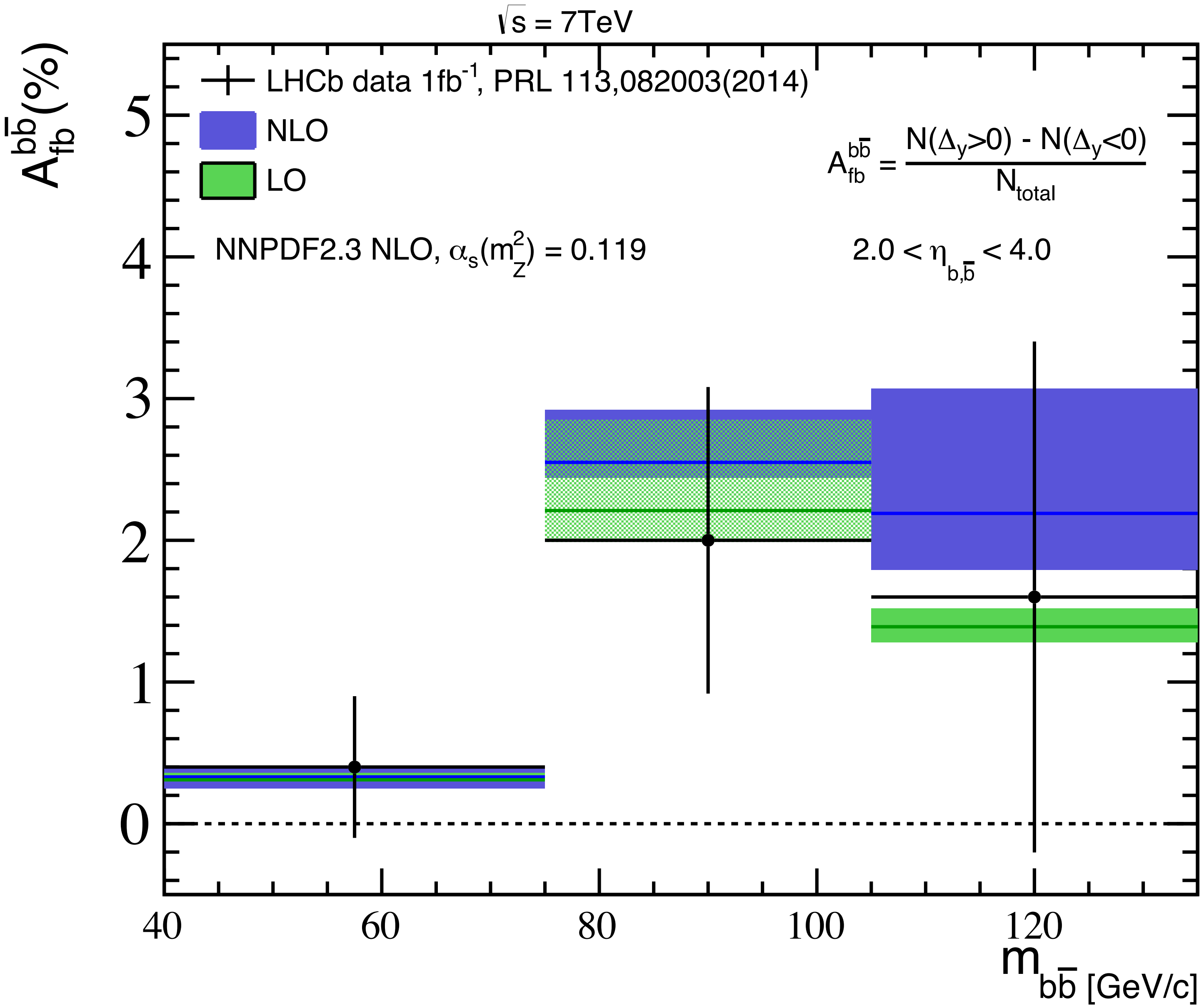
$$Q_u^{\text{WEAK}} = \frac{1}{2} - \frac{4}{3} s_w^2$$

$$Q_d^{\text{WEAK}} = -\frac{1}{2} + \frac{2}{3} s_w^2$$



PDF cancellation (2up 1down)
Cancellation integrating over res.

Preliminary Result



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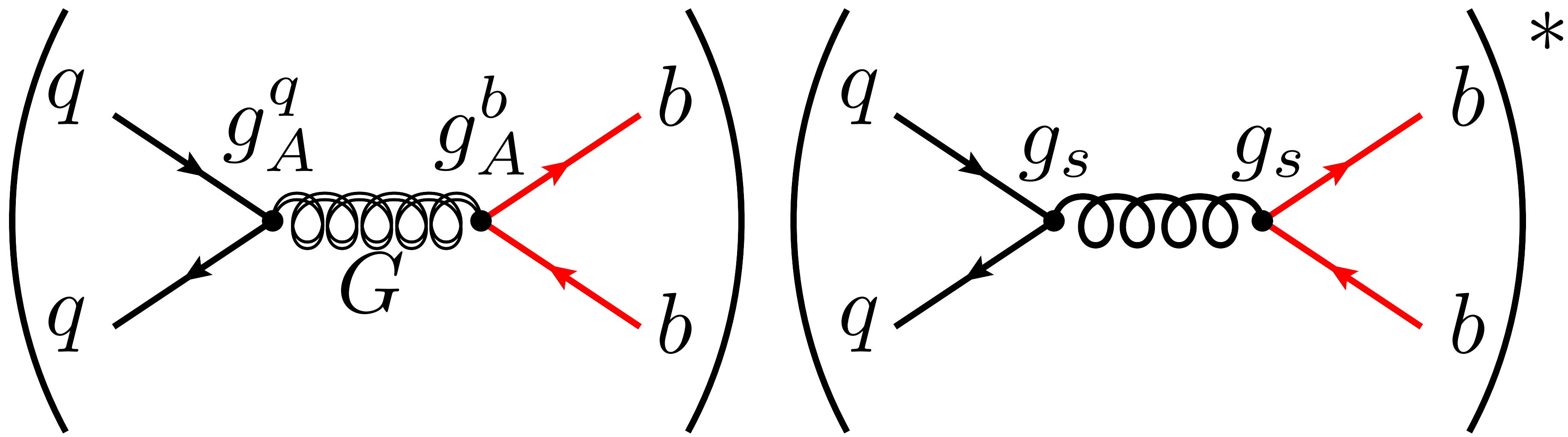
Future measurements at 13 TeV



Example: ‘light axigluon’ with flavour universal couplings
G. Marques Tavares, M. Schmaltz, Phys. Rev. D 84 (2011) 054008

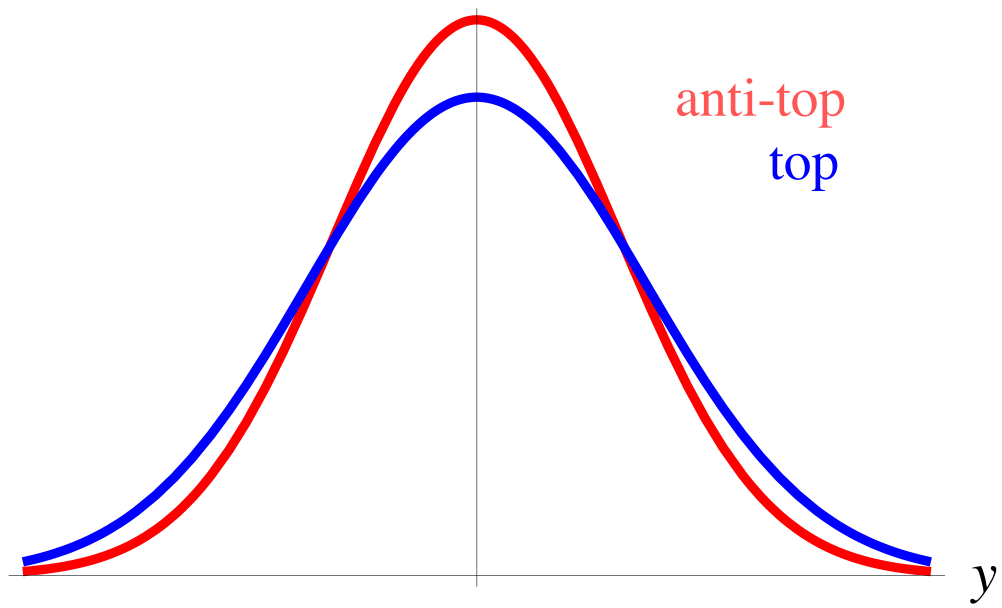
$$M_G < M_{t\bar{t}}\,, \qquad g_A^q g_A^{b,t} > 0$$

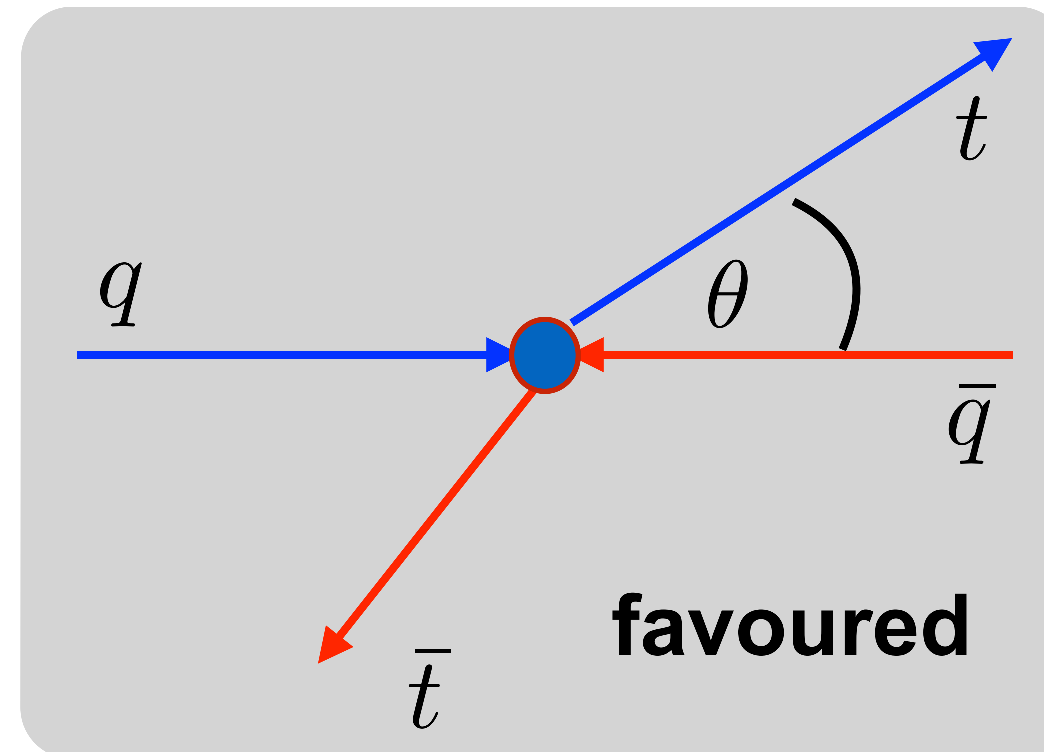
What about tension in precision Electroweak observables?

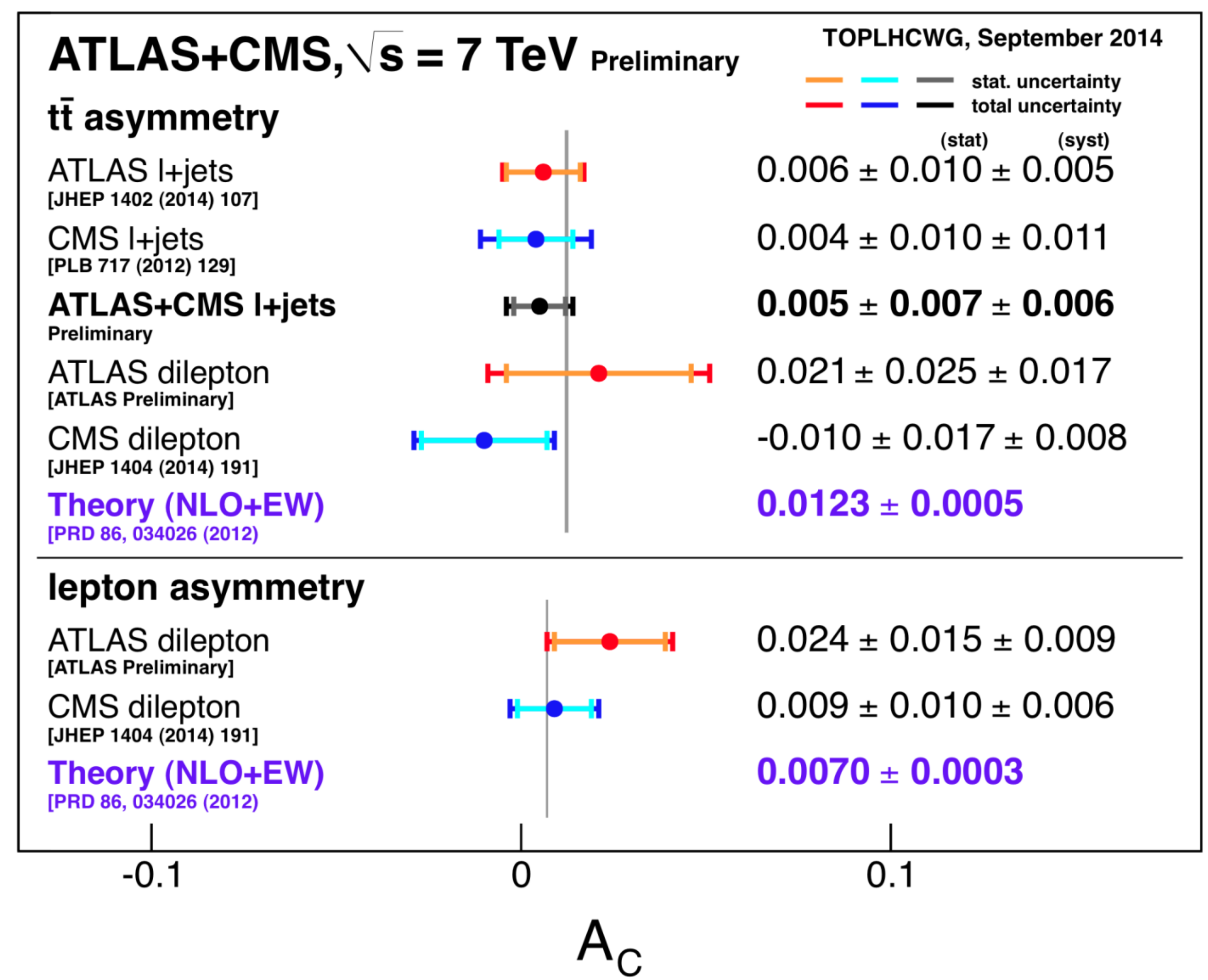
	SM	Exp.
A_{FB}^b	$0.1032^{+0.0004}_{-0.0006}$	0.0992 ± 0.0016
R_b	0.21474 ± 0.00003	0.21629 ± 0.00066

Results from ATLAS/CMS

$\mathrm{LHC} \quad pp \to t\bar{t}$







- Results consistent with SM / 0
- Heavily diluted by gluon-fusion

$$A_{\mathrm{C}} < 1\%\,, \quad \delta A_{\mathrm{sys}} \simeq 0.5\%$$

- Need better observables

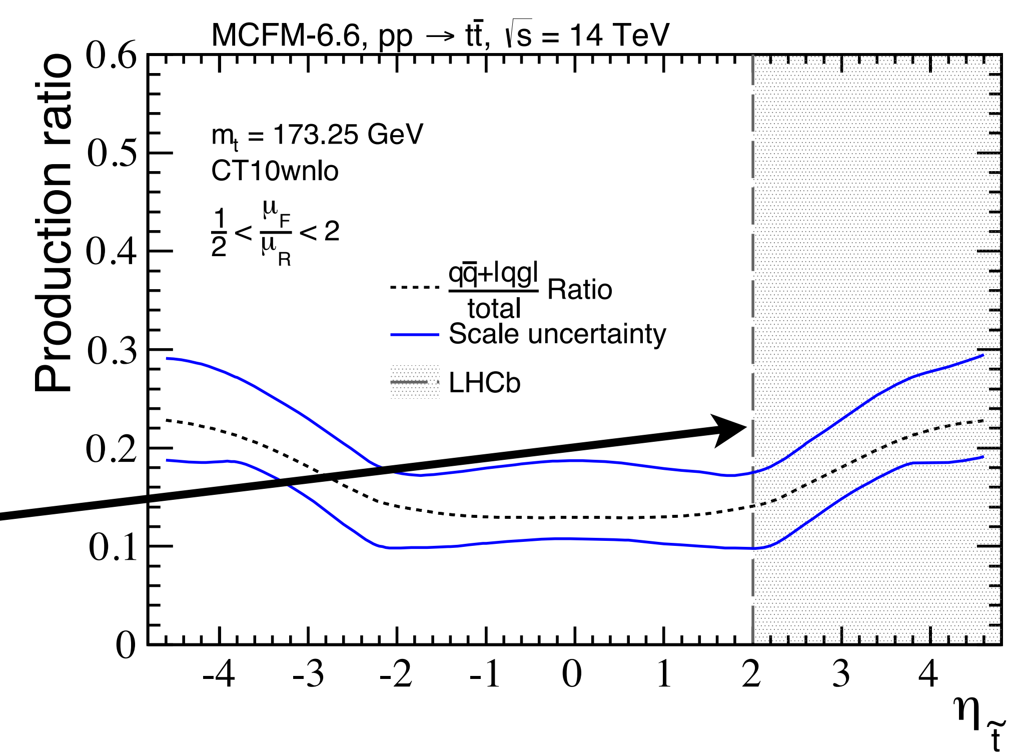
Proposals to overcome dilution

- S. Berge and S. Westhoff, JHEP 1307 (2013) 179
  “Incline asymmetry” and the “Energy asymmetry”
- J. Anguilar-Saavedra, E. Ivarez, A. Juste, and F. Rubbo. JHEP 1404 (2014) 188
  Associated production $pp \to t\bar{t}\gamma$
- F. Maltoni, M. Mangano, I. Tsinikos, M. Zaro. PLB 736 (2014) 252,
  Associated production $pp \to t\bar{t}W^{\pm}$
- A. L. Kagan, J. F. Kamenik, G. Perez, and S. Stone. Phys. Rev. Lett. 107 (2011) 082003
  Measure the asymmetry at LHCb

Production mechanism ratio:

$$\frac{q\bar{q} + |qg|}{total}$$

LHCb probes unique region



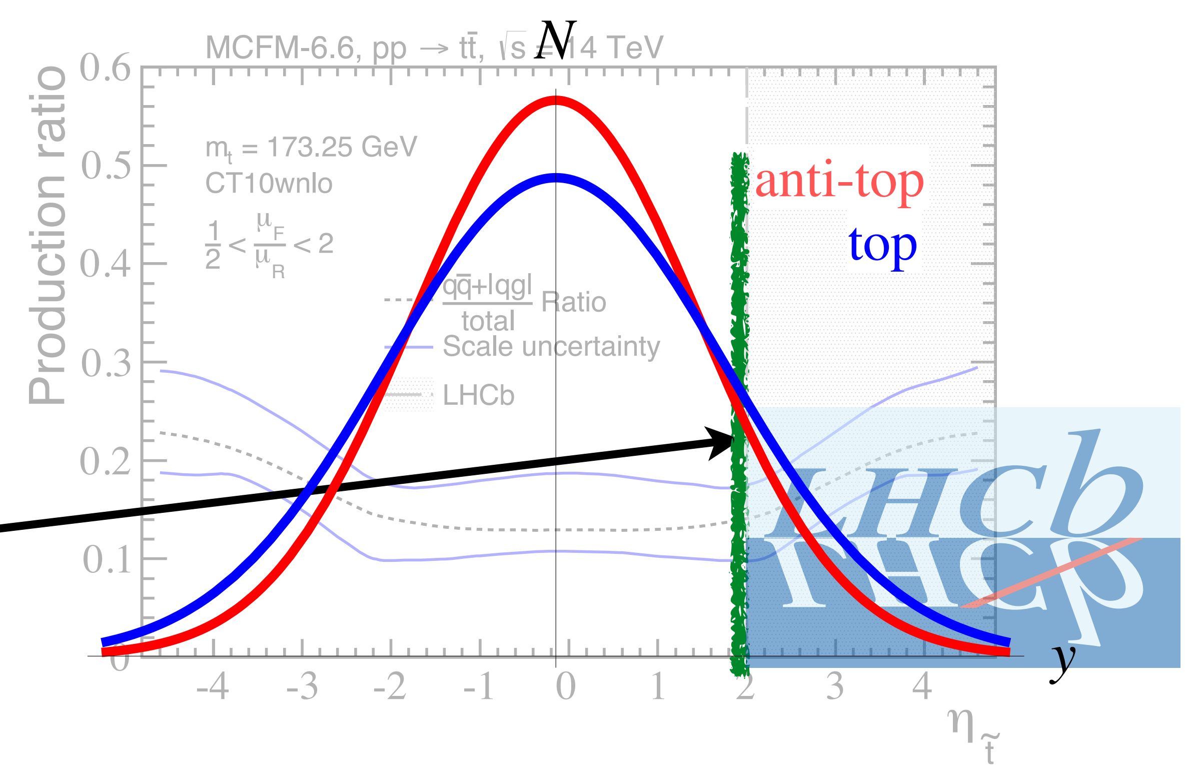
Proposals to overcome dilution

- S. Berge and S. Westhoff, JHEP 1307 (2013) 179
  "Incline asymmetry" and the "Energy asymmetry"
- J. Anguilar-Saavedra, E. Ivarez, A. Juste, and F. Rubbo. JHEP 1404 (2014) 188
  Associated production $pp \to t\bar{t}\gamma$
- F. Maltoni, M. Mangano, I. Tsinikos, M. Zaro. PLB 736 (2014) 252,
  Associated production $pp \to t\bar{t}W^{\pm}$
- A. L. Kagan, J. F. Kamenik, G. Perez, and S. Stone. Phys. Rev. Lett. 107 (2011) 082003
  Measure the asymmetry at LHCb

Production mechanism ratio:

$$\frac{q\bar{q} + |qg|}{total}$$

LHCb probes unique region



Asymmetry prediction for LHCb

Main contribution - interference of NLO amplitudes!

$$A = \frac{\alpha_s^3 \sigma_a^{s(1)} + \alpha_s^2 \alpha_{e/w} \sigma_a^{e/w(1)} + \alpha_{e/w}^2 \sigma_a^{e/w(0)} + \cdots}{\alpha_s^2 \sigma_s^{s(0)} + \alpha_s^3 \sigma_s^{s(1)} + \cdots},$$

$$= \alpha_s \frac{\sigma_a^{s(1)}}{\sigma_s^{s(0)}} + \alpha_{e/w} \frac{\sigma_a^{e/w(1)}}{\sigma_s^{s(0)}} + \frac{\alpha_{e/w}^2}{\alpha_s^2} \frac{\sigma_a^{e/w(0)}}{\sigma_s^{s(0)}} + \cdots.$$

$\sigma_s^{s(0)}$ = <u>symmetric</u> LO cross section (coupling stripped)

$\sigma_a^{x(1)}$ = <u>asymmetric</u> NLO cross section (coupling stripped)

arXiv:hep-ph/9802268, arXiv:hep-ph/9807420, arXiv:1109.6830, J.H.Kuhn, G. Rodrigo

arXiv:1107.2606, W. Hollik and D. Pagani,

arXiv:1205.6580, W. Bernreuther and Z.-G. Si

arXiv:1302.6995, B. Grinstein, C. W. Murphy

arXiv:1409.8631, RG

Asymmetry prediction for LHCb

Main contribution - interference of NLO amplitudes!

$$A = \frac{\alpha_s^3 \sigma_a^{s(1)} + \alpha_s^2 \alpha_{e/w} \sigma_a^{e/w(1)} + \alpha_{e/w}^2 \sigma_a^{e/w(0)} + \cdots}{\alpha_s^2 \sigma_s^{s(0)} + \alpha_s^3 \sigma_s^{s(1)} + \cdots},$$

$$= \alpha_s \frac{\sigma_a^{s(1)}}{\sigma_s^{s(0)}} + \alpha_{e/w} \frac{\sigma_a^{e/w(1)}}{\sigma_s^{s(0)}} + \frac{\alpha_{e/w}^2}{\alpha_s^2} \frac{\sigma_a^{e/w(0)}}{\sigma_s^{s(0)}} + \cdots .$$

1) Obtain QCD from MCFM, arXiv:1204.1513 J. Campbell, R. K. Ellis

2) Apply rescaling of couplings and colour factors

$$R_{q\bar{q}}^X(\mu) = \frac{36 Q_q^X Q_t^X \alpha_e}{5\alpha_s}, \quad R_{qg}^X(\mu) = \frac{24 Q_q^X Q_t^X \alpha_e}{5\alpha_s}.$$

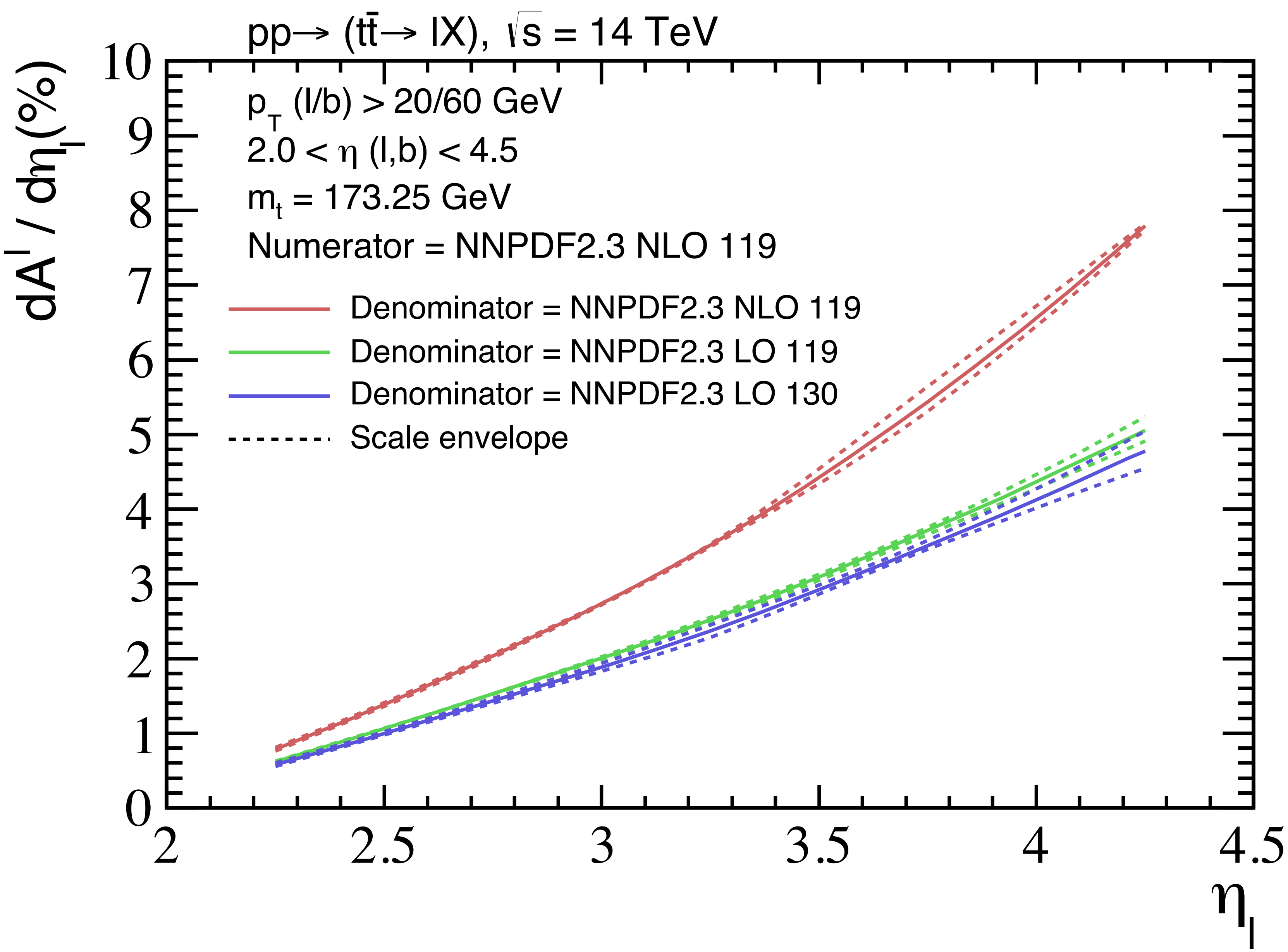
$$Q^w = (2\tau^3 - 4 s_w^2 Q^e)/4 s_w c_w$$

3) Its just LO…

Single-lepton asymmetry

$$A^l = \int_{2.0}^{4.5} d\eta_l \left(\frac{d\sigma^{l^+b}/d\eta_l - d\sigma^{l^-b}/d\eta_l}{d\sigma^{l^+b}/d\eta_l + d\sigma^{l^-b}/d\eta_l} \right)$$

$$2.0 < \eta(l,b) < 4.5$$
$$p_T(l/b) > 20/60 \text{ GeV}$$
$$\Delta R(l^\pm, \text{jet}) \geq 0.5$$



$$A^l = (1.4 - 2.0)\%$$

Backgrounds

$$A^l = \int_{2.0}^{4.5} d\eta_l \left(\frac{d\sigma^{l^+b}/d\eta_l - d\sigma^{l^-b}/d\eta_l}{d\sigma^{l^+b}/d\eta_l + d\sigma^{l^-b}/d\eta_l} \right)$$

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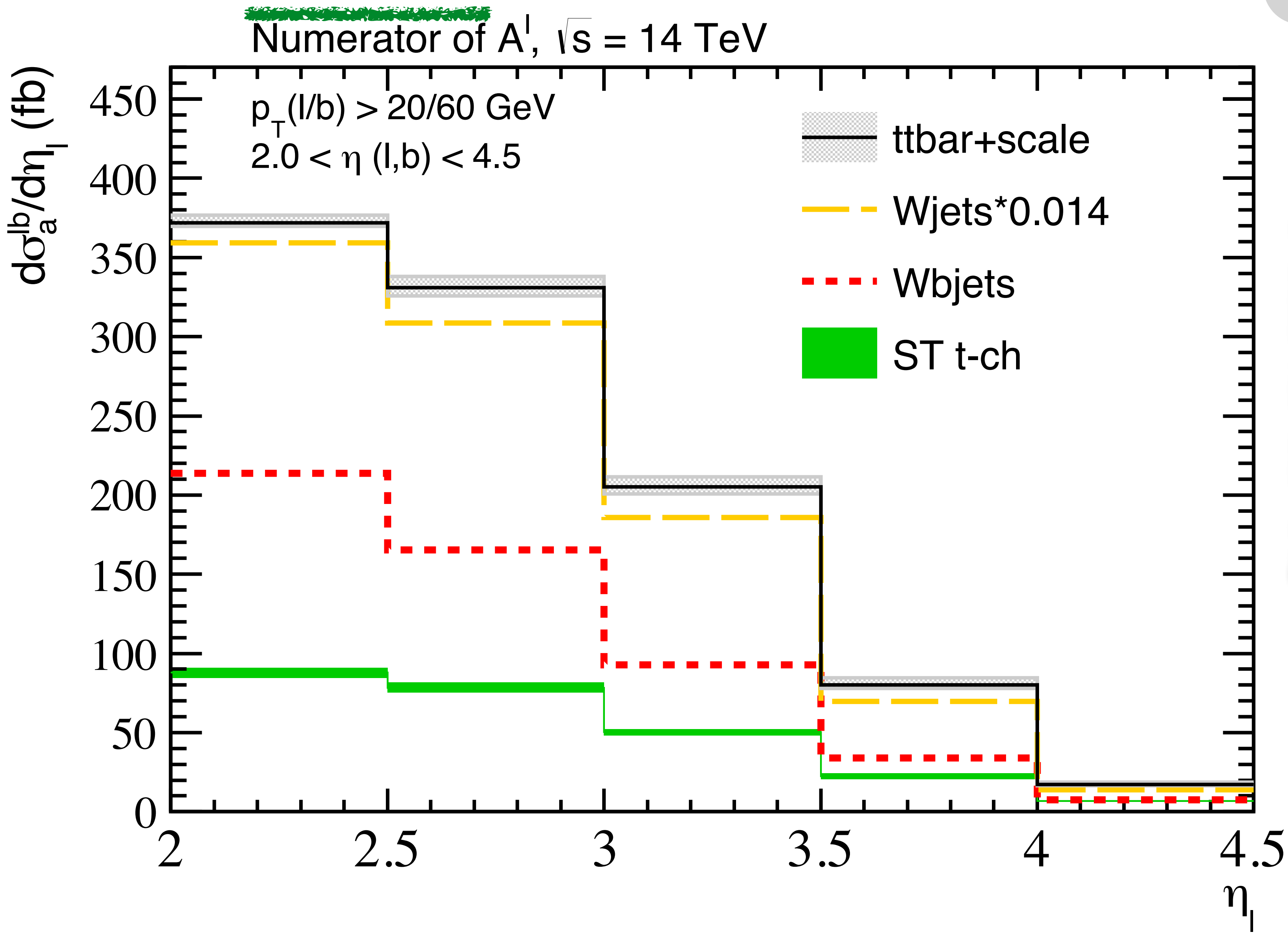


Fit backgrounds experimentally:

$$l^{\pm}j, l^{\pm}bj, l^{\pm}bb$$

control channels

Statistical feasibility

$$A^l = \int_{2.0}^{4.5} d\eta_l \left(\frac{d\sigma^{l^+b}/d\eta_l - d\sigma^{l^-b}/d\eta_l}{d\sigma^{l^+b}/d\eta_l + d\sigma^{l^-b}/d\eta_l} \right)$$

$$2.0 < \eta(l,b) < 4.5$$
$$p_T(l/b) > 20/60 \text{ GeV}$$
$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

If backgrounds can be controlled!

$$\sigma^{\text{LO}} \simeq 4.7 \text{ pb}$$

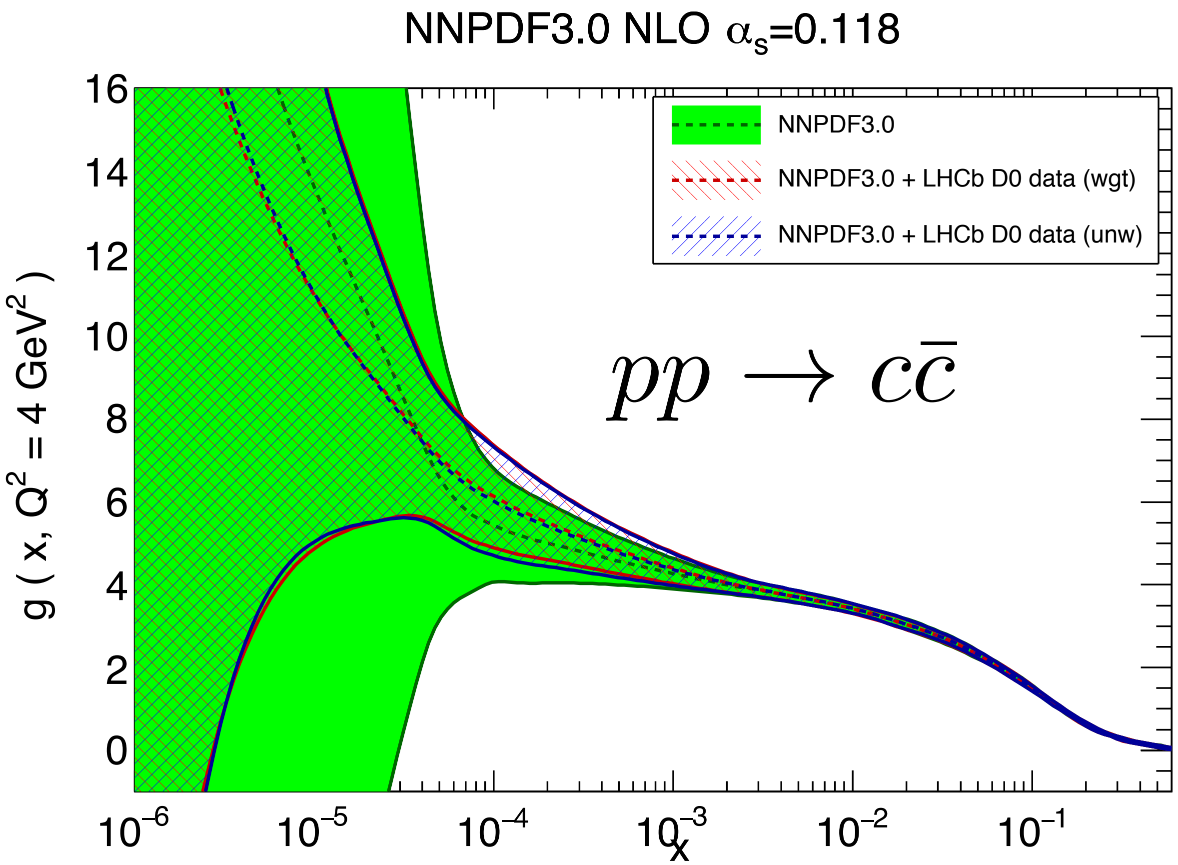
$$\int \mathcal{L} dt = 50 \text{ fb}^{-1}$$

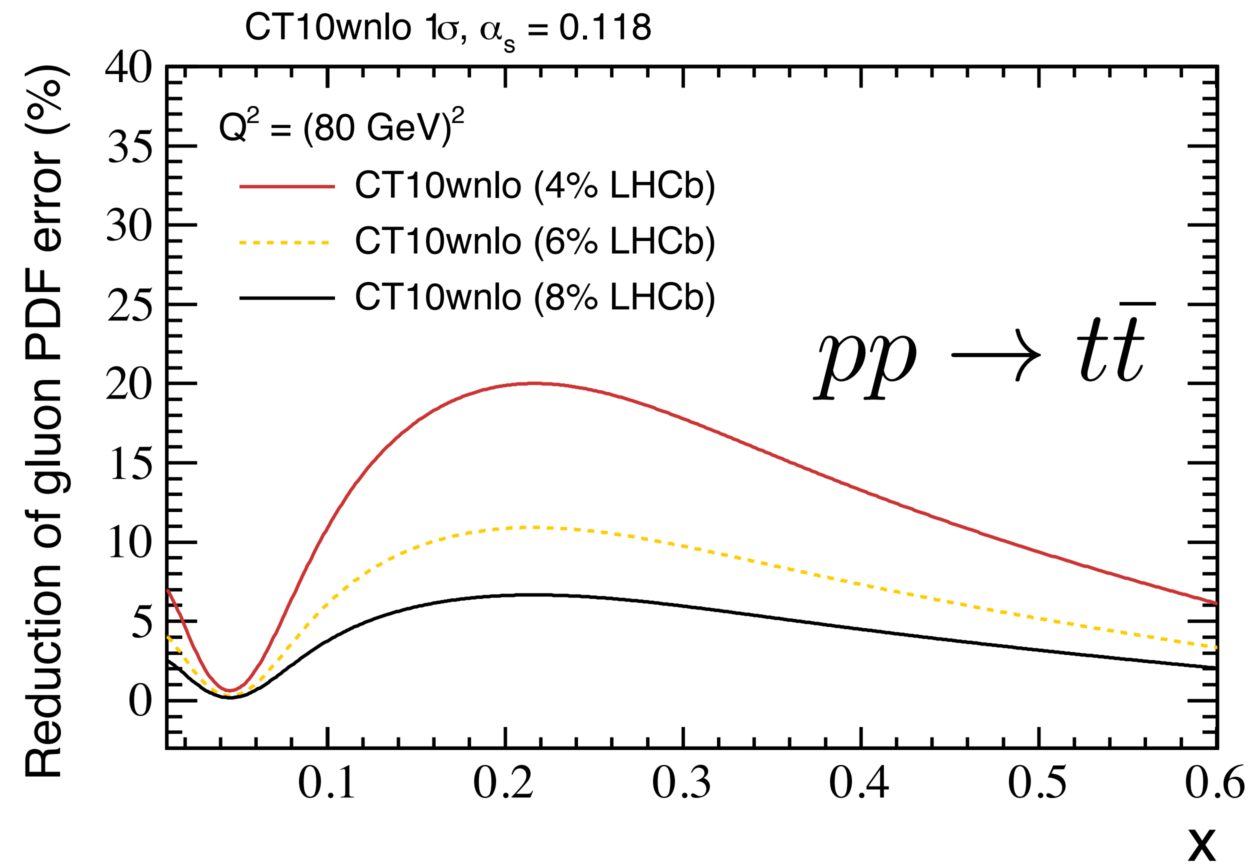
Apply b-tagging efficiency 0.7
Apply lepton efficiency 0.75

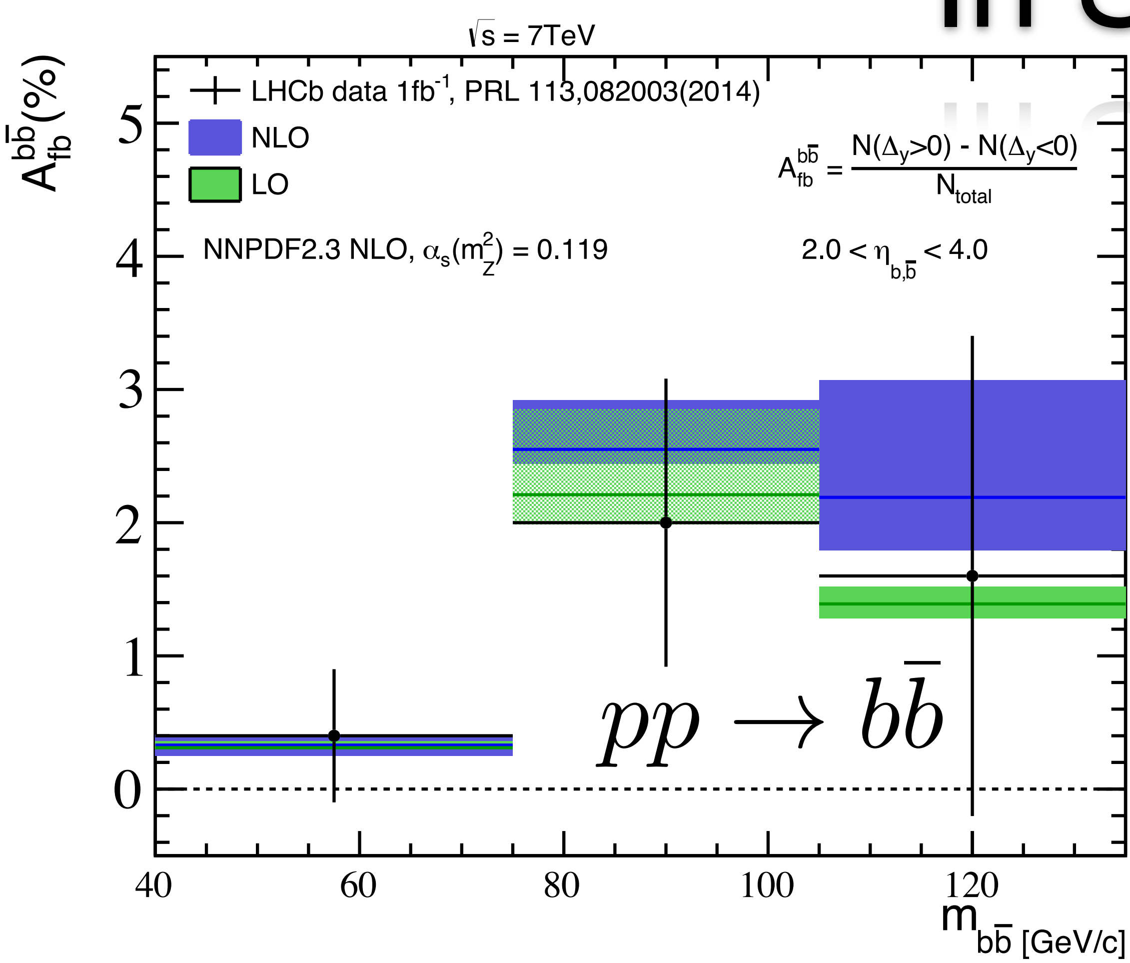
$$N_{\text{events}} \simeq 1.2e5$$

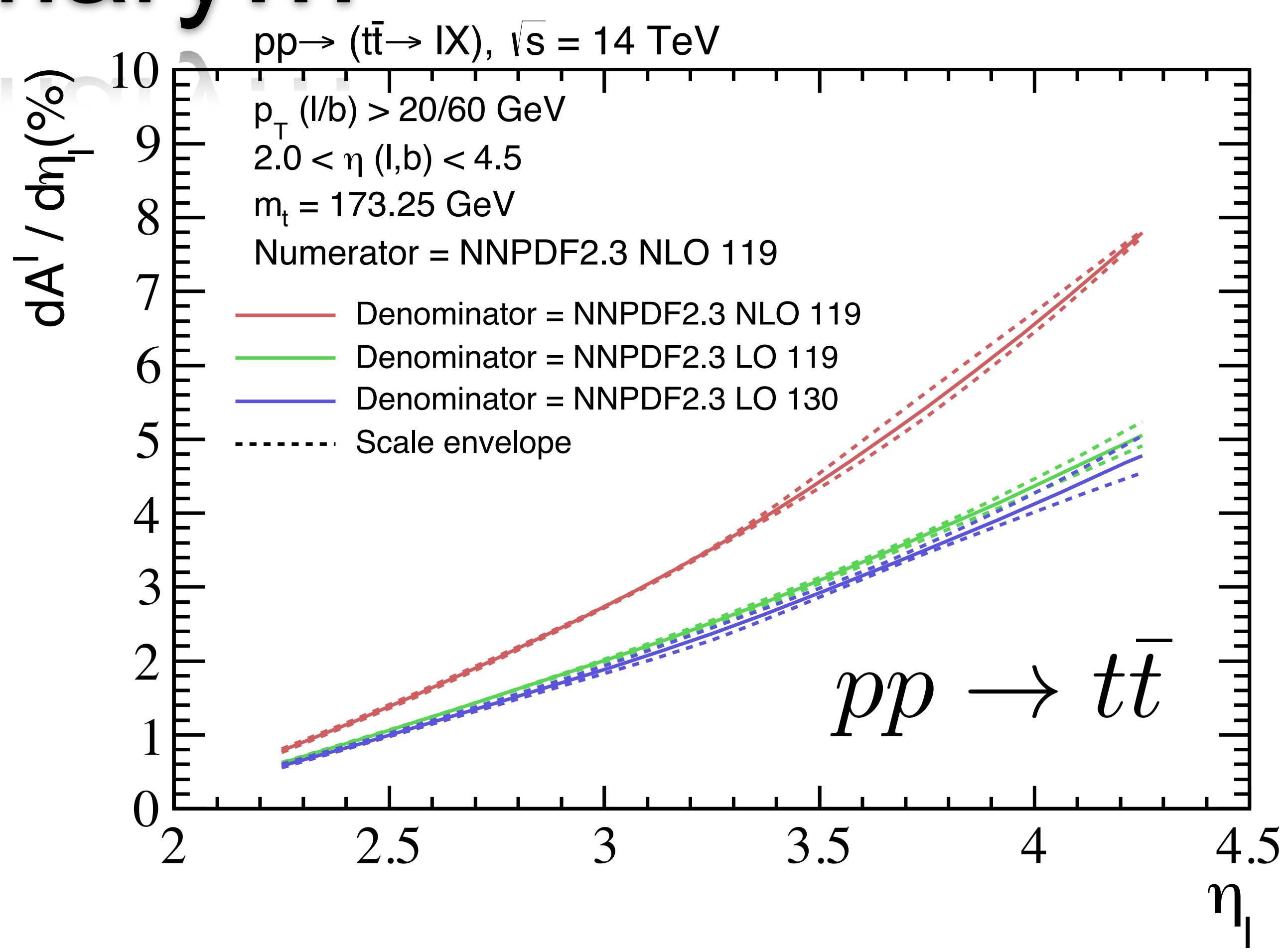
$$A^l = (1.4 - 2.0) \pm 0.3\%$$

In Summary…


NNPDF3.0 NLO α_s=0.118
NNPDF3.0
NNPDF3.0 + LHCb D0 data (wgt)
NNPDF3.0 + LHCb D0 data (unw)
$pp \to c\bar{c}$
g (x, Q^2 = 4 GeV^2)
x


CT10wnlo 1σ, α_s = 0.118
Q^2 = (80 GeV)^2
CT10wnlo (4% LHCb)
CT10wnlo (6% LHCb)
CT10wnlo (8% LHCb)
$pp \to t\bar{t}$
Reduction of gluon PDF error (%)
x


√s = 7TeV
LHCb data 1fb^{-1}, PRL 113,082003(2014)
NLO
LO
$A_{fb}^{b\bar{b}} = \frac{N(\Delta_y>0) - N(\Delta_y<0)}{N_{total}}$
NNPDF2.3 NLO, $\alpha_s(m_Z^2)$ = 0.119
2.0 < $\eta_{b,\bar{b}}$ < 4.0
$pp \to b\bar{b}$
$A_{fb}^{b\bar{b}}$(%)
$m_{b\bar{b}}$ [GeV/c]


pp→ ($t\bar{t}$→ lX), √s = 14 TeV
p_T (l/b) > 20/60 GeV
2.0 < η (l,b) < 4.5
m_t = 173.25 GeV
Numerator = NNPDF2.3 NLO 119
Denominator = NNPDF2.3 NLO 119
Denominator = NNPDF2.3 LO 119
Denominator = NNPDF2.3 LO 130
Scale envelope
$pp \to t\bar{t}$
$dA^l / d\eta_l$(%)
η_l

Thanks for listening

D measurement (arXiv: 1302.2864)

LHCb data compared with:

FONLL - Fixed-Order + Resummation

Cacciari, Greco, Nason hep/ph:9803400

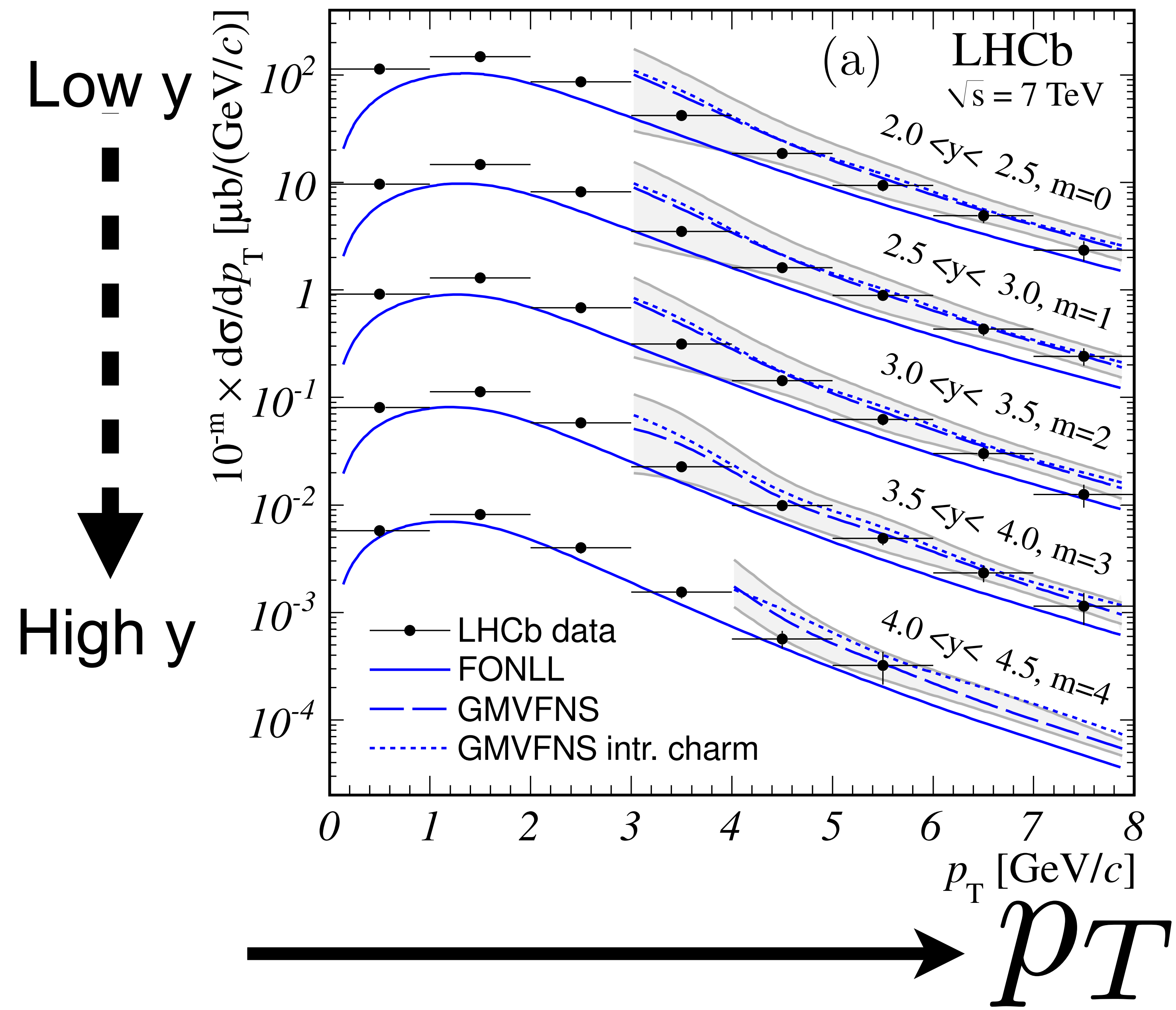
Web implementation:

http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html

Cacciari, Frixione, Houdeau, Mangano, Nason and Ridolfi hep-ph:1205.6344

GMVFNS - Generalised-Mass Variable-Flavour-Number-Scheme

Kniehl. Kramer, Schienbein, Spiesberger hep-ph: arxiv:0901.4130 and refs. therein



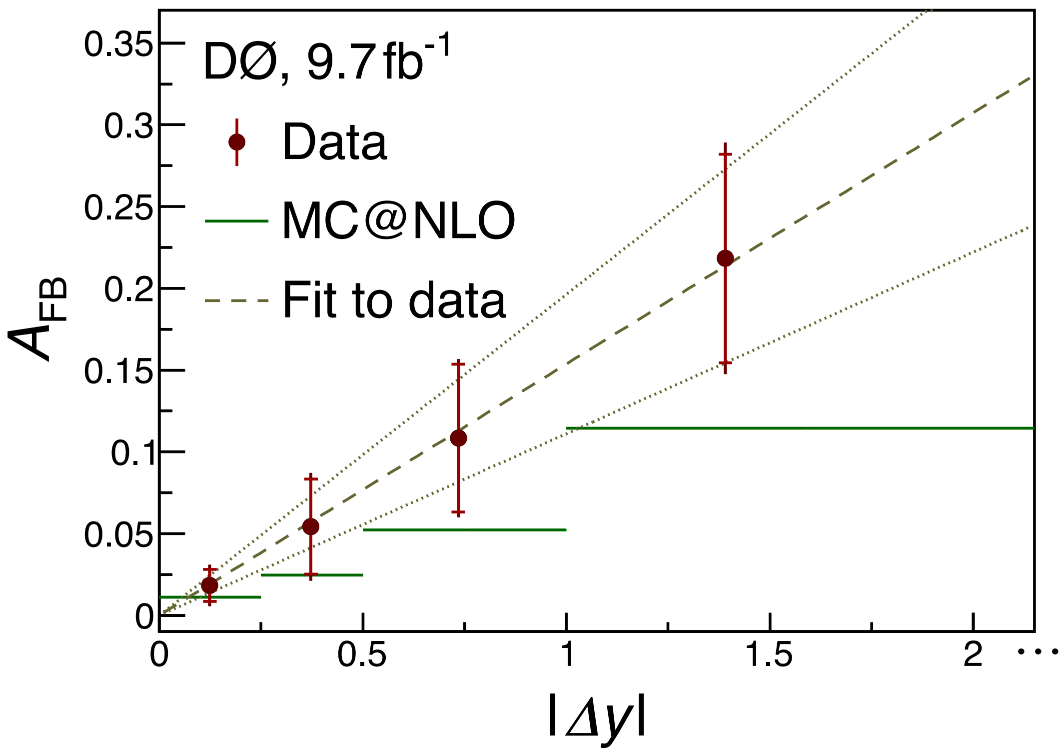
$$d\hat{\sigma}_D = d\hat{\sigma}_Q \otimes D^{\rm NP}_{Q\to D}$$

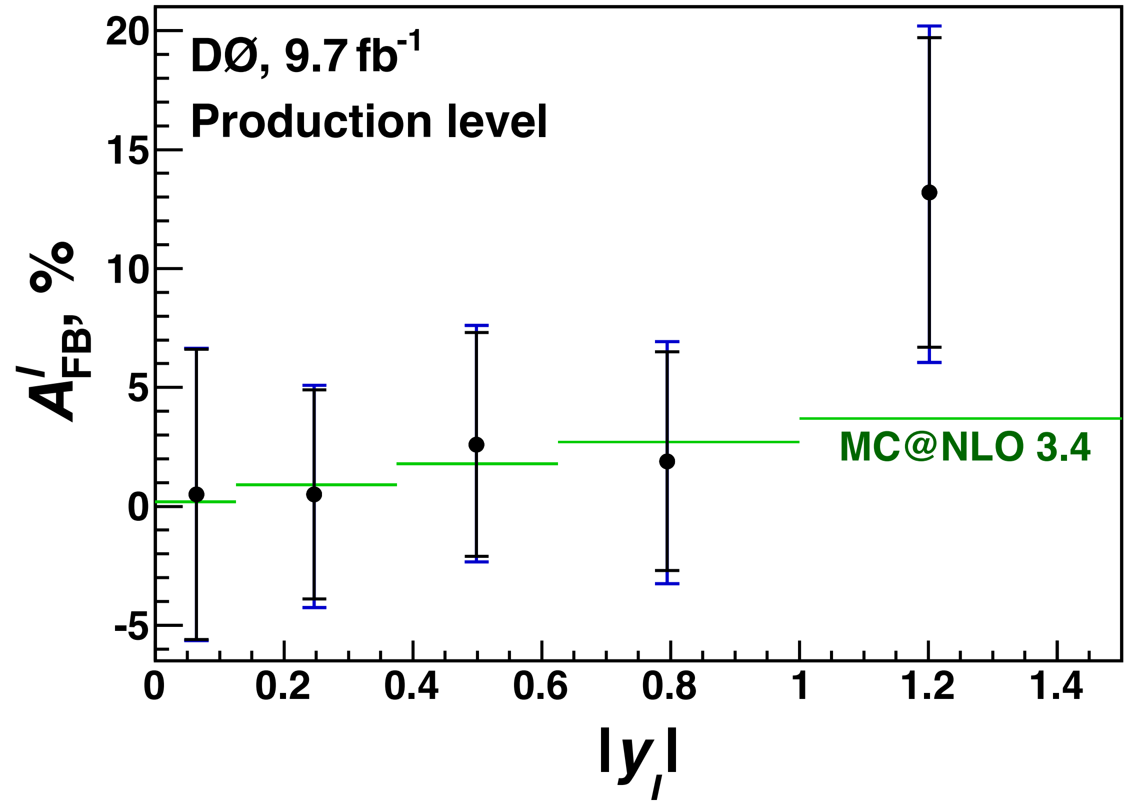
Determined from e^+e^- data

TeVatron results differentially

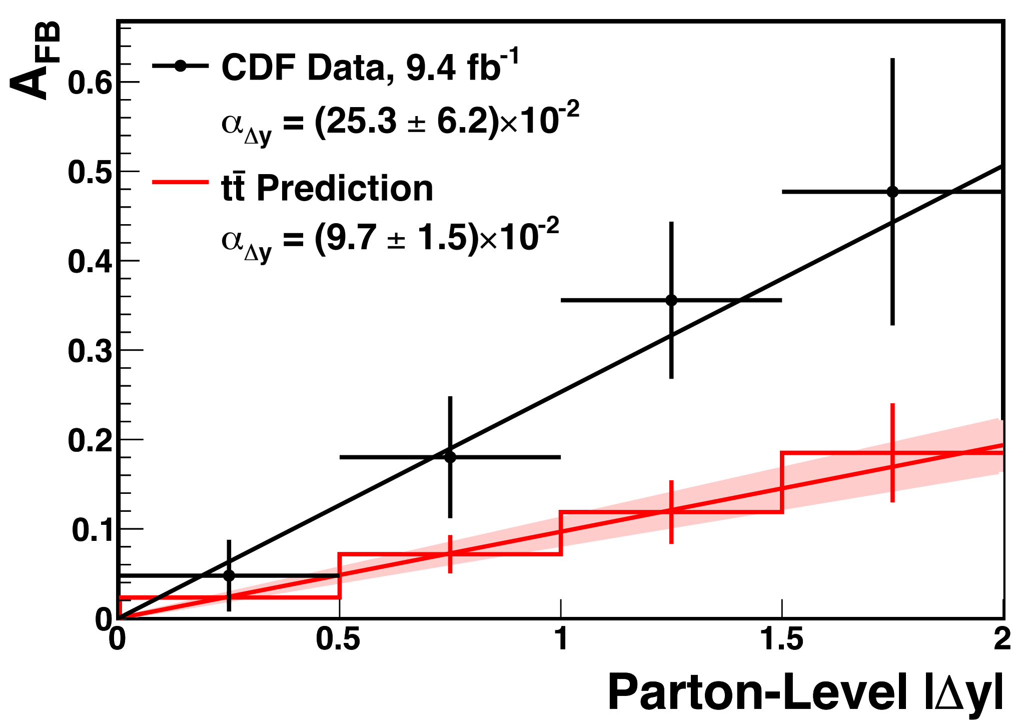
Parton level | **Lepton level**

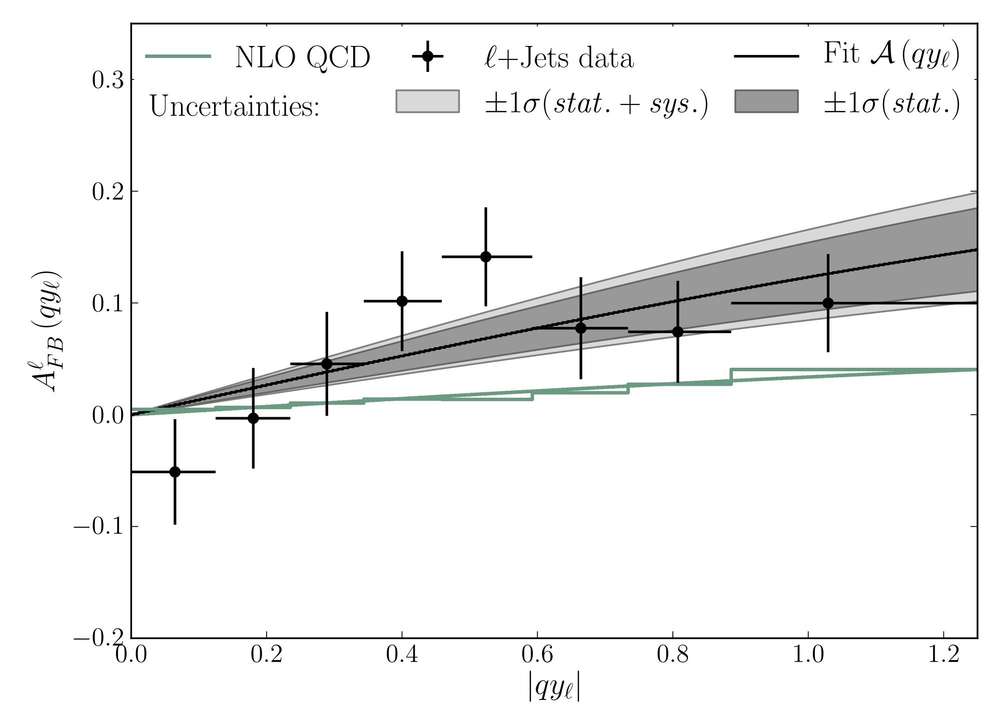
D0





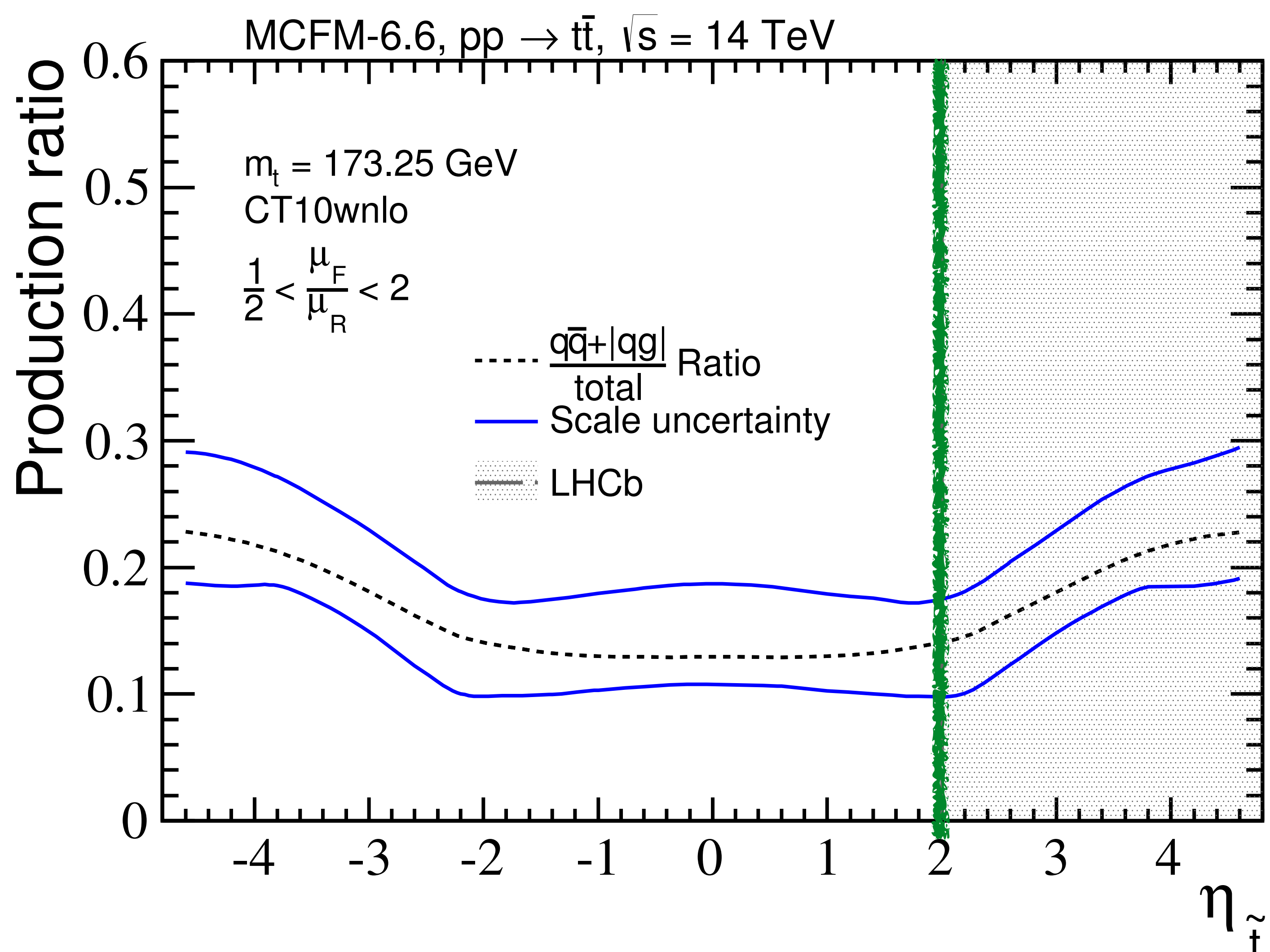
CDF





Enriched qX->t+Y sample at LHCb

less gg-dilution
in LHCb acceptance



Single-lepton backups

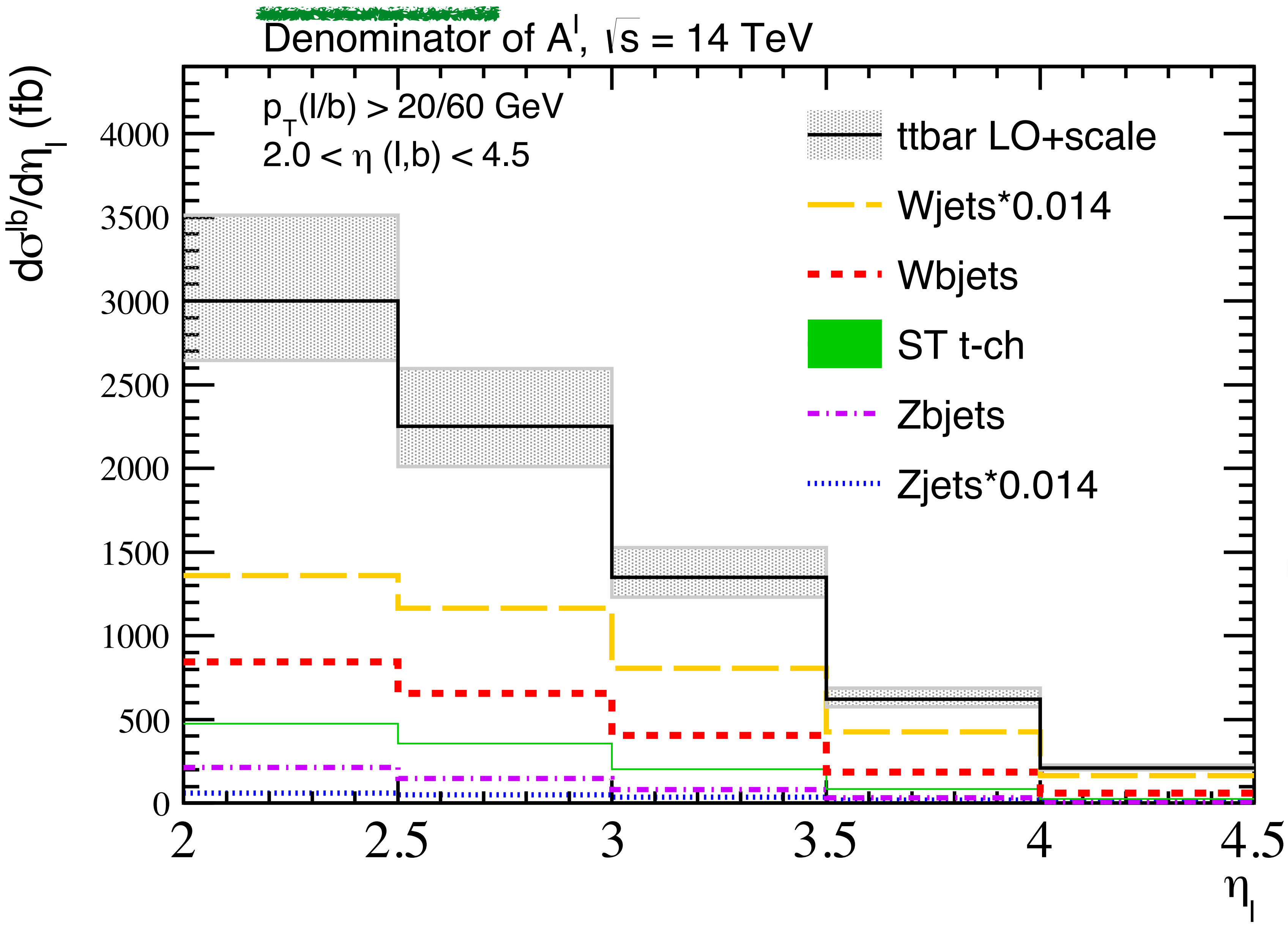
N^l (fb)		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	55.62	40.84	31.56
	$d\bar{d}$	23.15	16.99	13.05
	ug	1.79	1.02	0.65
	dg	0.72	0.45	0.26
$\mathcal{O}(\alpha_s^2\alpha_e)$		9.37	7.65	6.47
$\approx \mathcal{O}(\alpha_s^2\alpha_w)$		0.35	0.25	0.19
$\mathcal{O}(\alpha_{e/w}^2)$		0.81	0.78	0.77
Total		91.80	67.96	52.95

	D^l (fb), 14 TeV			
PDF	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$	A^l (%)
NLO 119	4626	3512	2742	1.95 (3)
LO 119	6225	4663	3586	1.47 (1)
LO 130	6761	4961	3752	1.38 (3)

Backgrounds

$$A^l = \int_{2.0}^{4.5} d\eta_l \left(\frac{d\sigma^{l^+b}/d\eta_l - d\sigma^{l^-b}/d\eta_l}{d\sigma^{l^+b}/d\eta_l + d\sigma^{l^-b}/d\eta_l} \right)$$

$$2.0 < \eta(l,b) < 4.5$$
$$p_T(l/b) > 20/60 \text{ GeV}$$
$$\Delta R(l^\pm, \text{jet}) \geq 0.5$$



Fit backgrounds experimentally:

$l^\pm j, l^\pm bj, l^\pm bb$

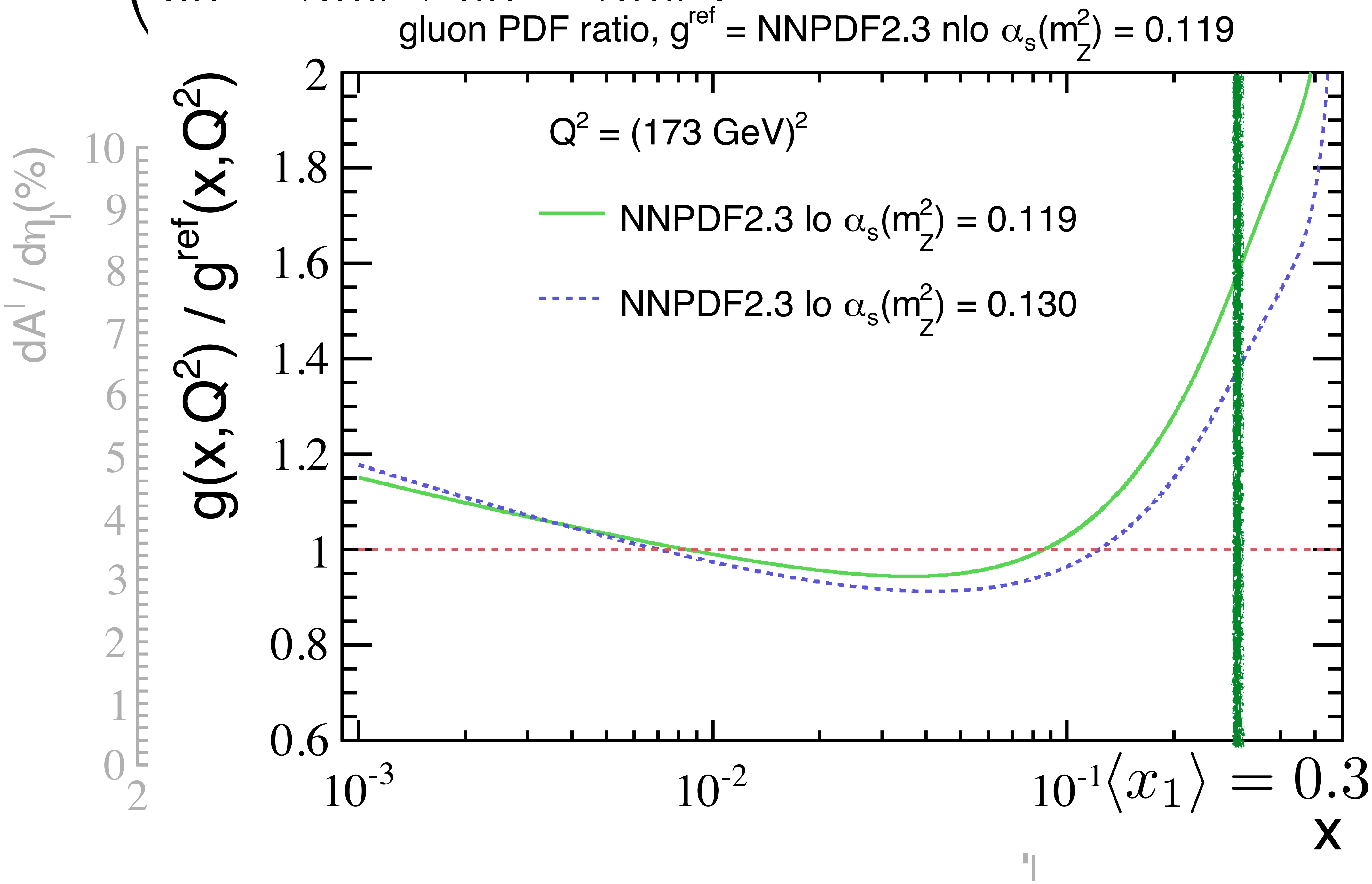
control channels

Single-lepton asymmetry

$$A^l = \int_{2.0}^{4.5} d\eta_l \left(\frac{d\sigma^{l^+ b}/d\eta_l - d\sigma^{l^- b}/d\eta_l}{d\sigma^{l^+ b}/d\eta_l + d\sigma^{l^- b}/d\eta_l} \right)$$

$$2.0 < \eta(l, b) < 4.5$$

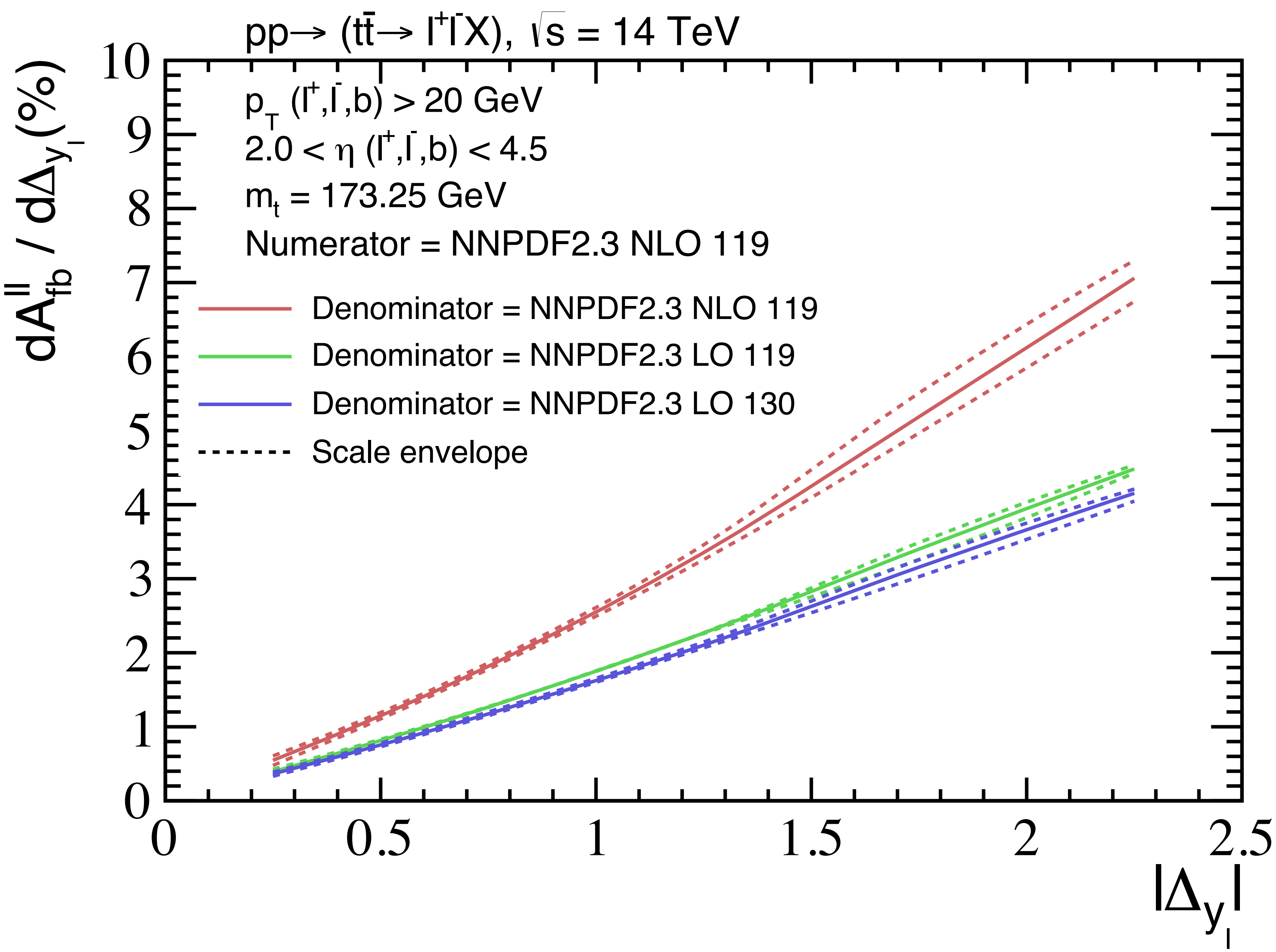
$$p_T(l/b) > 20/60 \text{ GeV}$$



Differential di-lepton asymmetry

$$A_{fb}^{ll} = \int d\Delta_y \frac{\left(d\sigma^{\mu eb}(\Delta_y > 0) - d\sigma^{\mu eb}(\Delta_y < 0)\right)/d\Delta_y}{d\sigma^{\mu eb}/d\Delta_y}$$

$$2.0 < \eta(e, \mu, b) < 4.5$$
$$p_T(e, \mu, b) > 20 \text{ GeV}$$
$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$



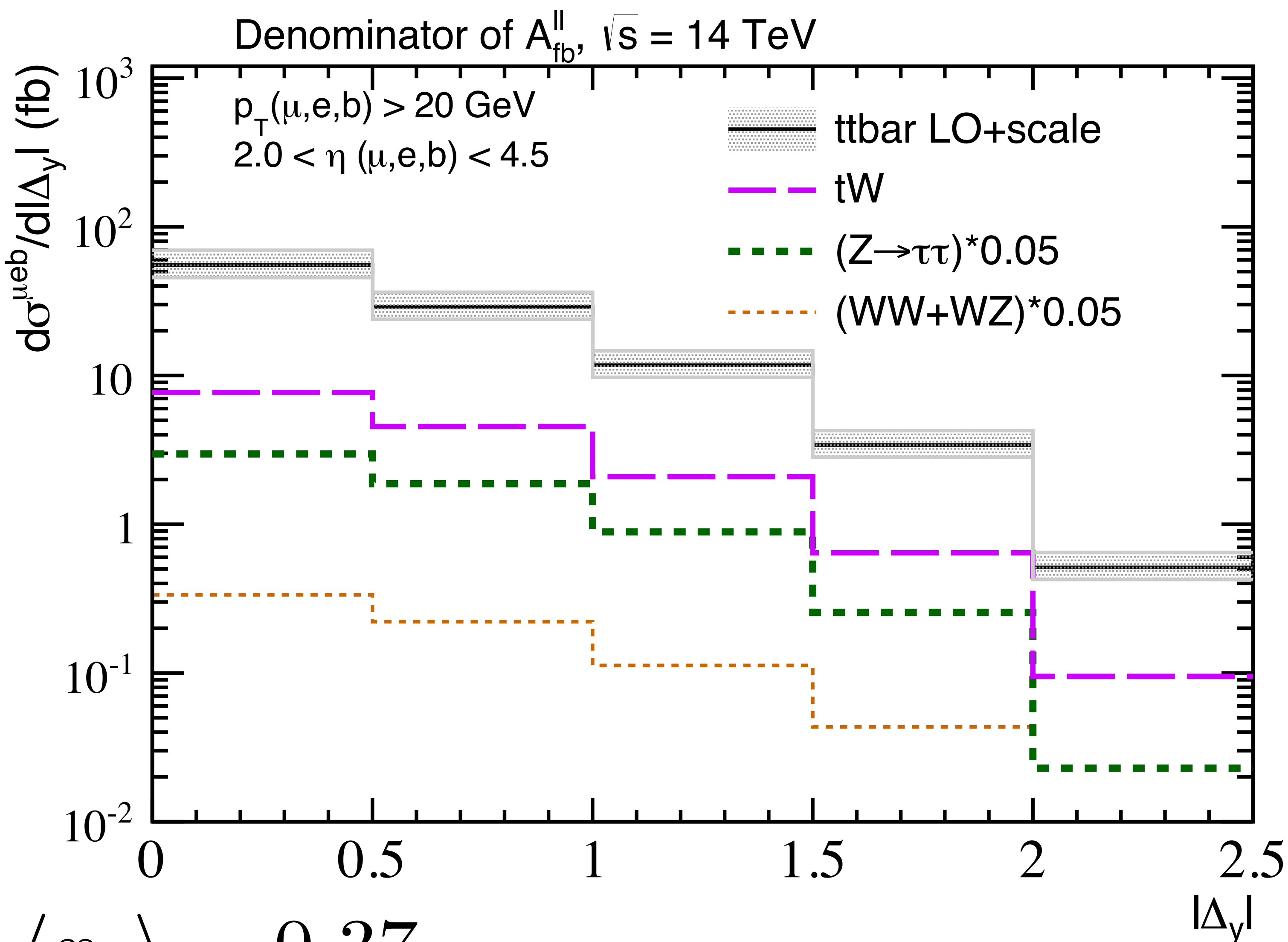
$$A_{fb}^{ll} = (0.9 - 1.4)\%$$

Integrated di-lepton asymmetry

N_{fb}^{ll} (fb)		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	0.977	0.709	0.536
	$d\bar{d}$	0.344	0.239	0.181
	ug	0.095	0.070	0.045
	dg	0.031	0.021	0.013
$\mathcal{O}(\alpha_s^2\alpha_e)$		0.179	0.146	0.120
$\approx \mathcal{O}(\alpha_s^2\alpha_w)$		0.009	0.007	0.006
$\mathcal{O}(\alpha_{e/w}^2)$		0.006	0.005	0.005
Total		1.642	1.198	0.907

	D_{fb}^{ll} (fb), 14 TeV			
PDF	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$	A_{fb}^{ll} (%)
NLO 119	110.4	85.0	67.4	1.41 (8)
LO 119	160.7	120.7	93.3	0.99 (3)
LO 130	176.6	130.0	98.8	0.92 (1)

Dilepton + b-jet



$$\langle x_1 \rangle = 0.37$$

$$\delta\sigma_{\rm stat}(\rm 1year) = 6\%$$

$$t\bar{t} \to \mu^{\pm} e^{\mp} b X$$

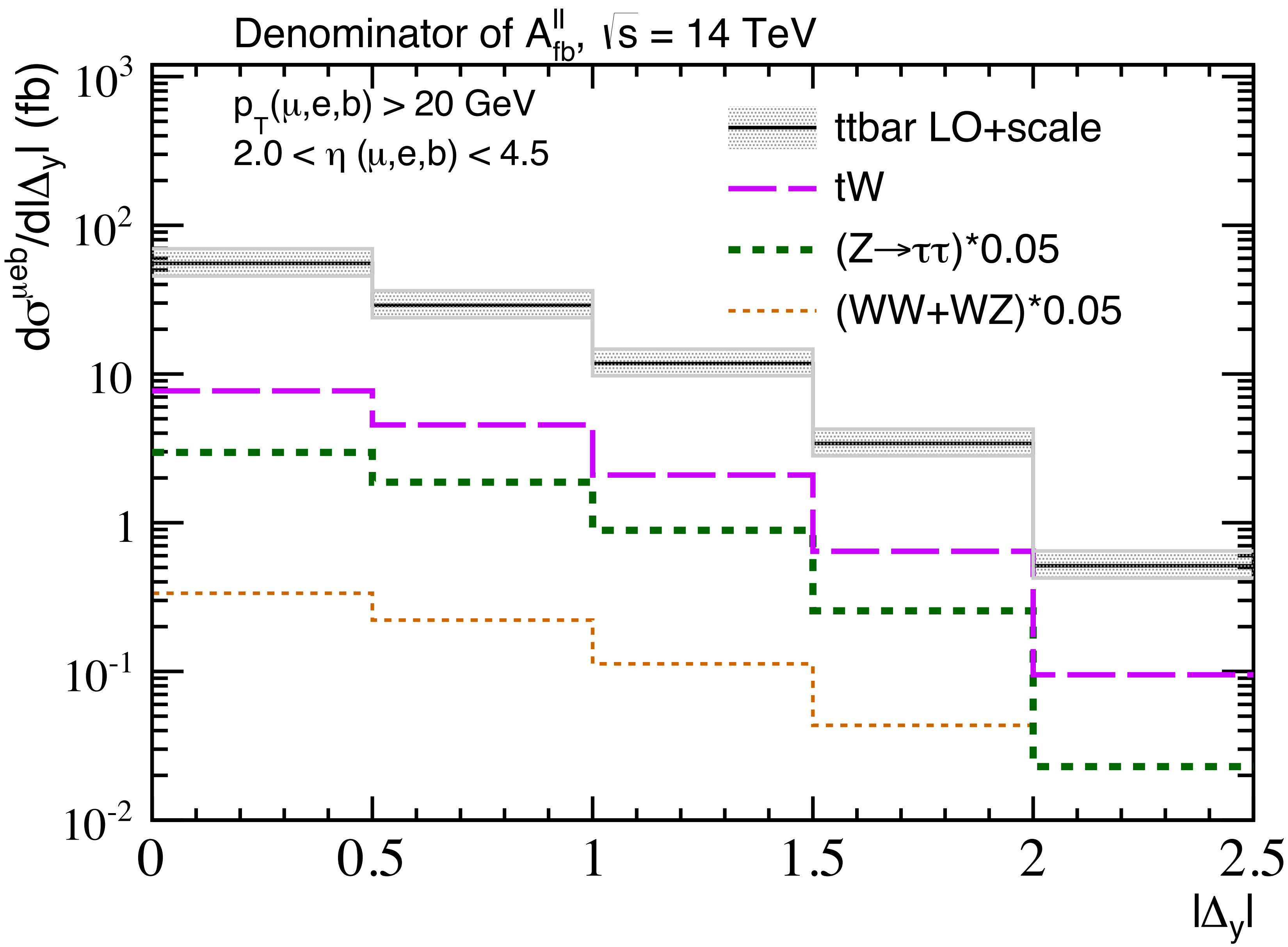
14 TeV

$$2.0 < \eta(l,b) < 4.5$$

$$p_T(l,b) > 20 \text{ GeV}$$

$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

Di-lepton asymmetry

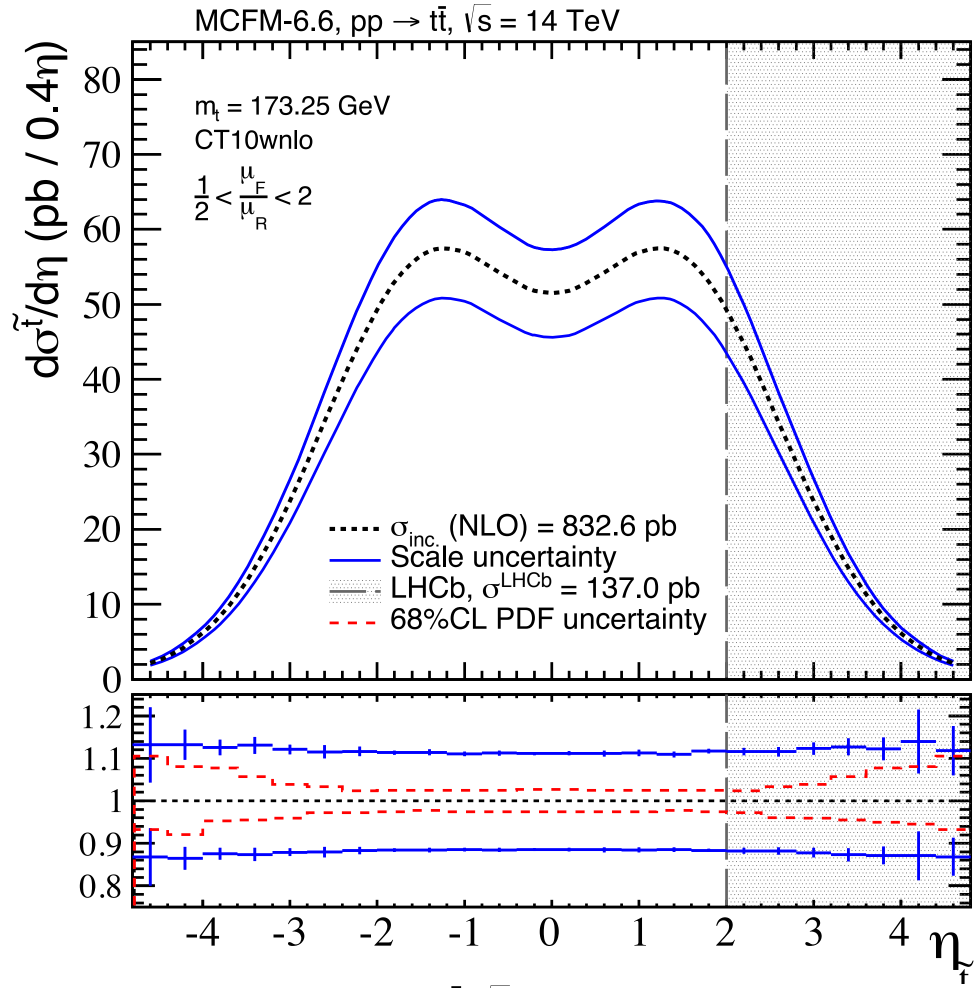


$$A_{fb}^{ll} = (0.9 - 1.4) \pm 1.6\%$$

stat. 50 fb-1

Parton level theoretical systematics

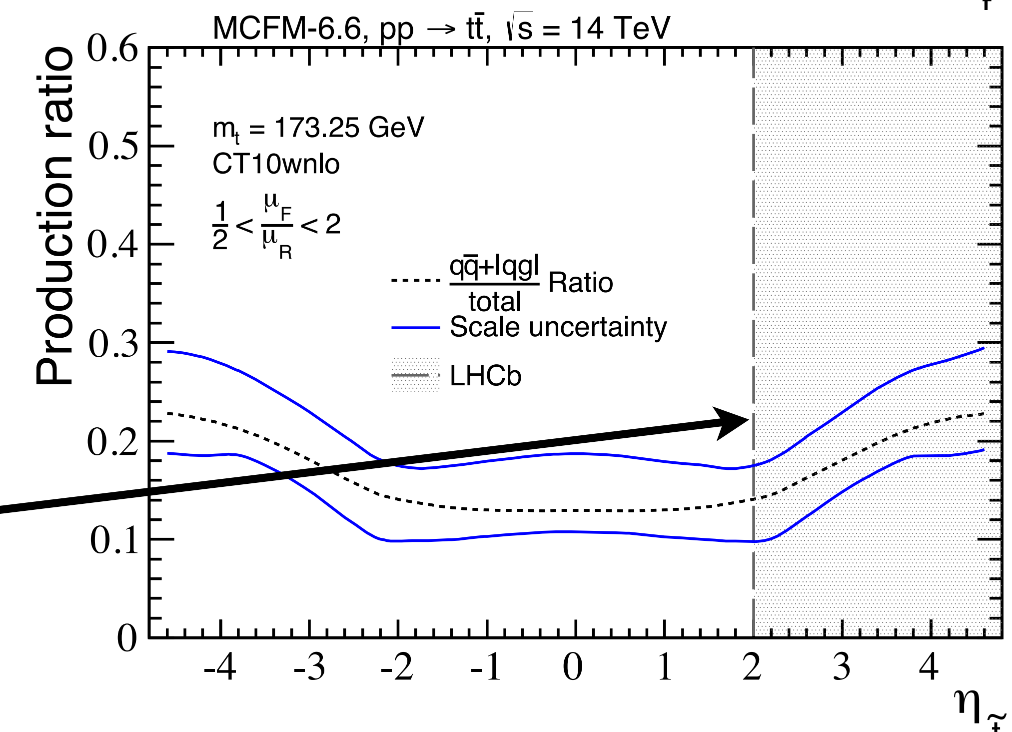
$$\frac{d\sigma^{\tilde{t}}}{dX} = \frac{1}{2}\left(\frac{d\sigma^{t}}{dX} + \frac{d\sigma^{\bar{t}}}{dX}\right)$$



Production mechanism ratio:

$$\frac{q\bar{q} + |qg|}{total}$$

LHCb probes unique region



Theoretical systematics for forward ttbar?

$$\sigma = \sum_{i,j} \int dx_i dx_j f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) \frac{d\hat{\sigma}\left(m, \mu_F^2, \alpha_s(\mu_R), \mu_R^2\right)}{d\eta} d\eta$$

$$\frac{d\hat{\sigma}^{\mathrm{LHCb}}}{d\eta} = \frac{1}{2}\left[\frac{d\hat{\sigma}}{d\eta_t} + \frac{d\hat{\sigma}}{d\eta_{\bar{t}}}\right]_{\eta\in[2,5]}$$

$$\frac{1}{2} < \frac{\mu_F}{\mu_R} < 2$$

$$\delta\mathrm{PDF} = 1\sigma\mathrm{CL}$$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

$$\delta m_t = 1.5\ \mathrm{GeV}$$

Strong coupling

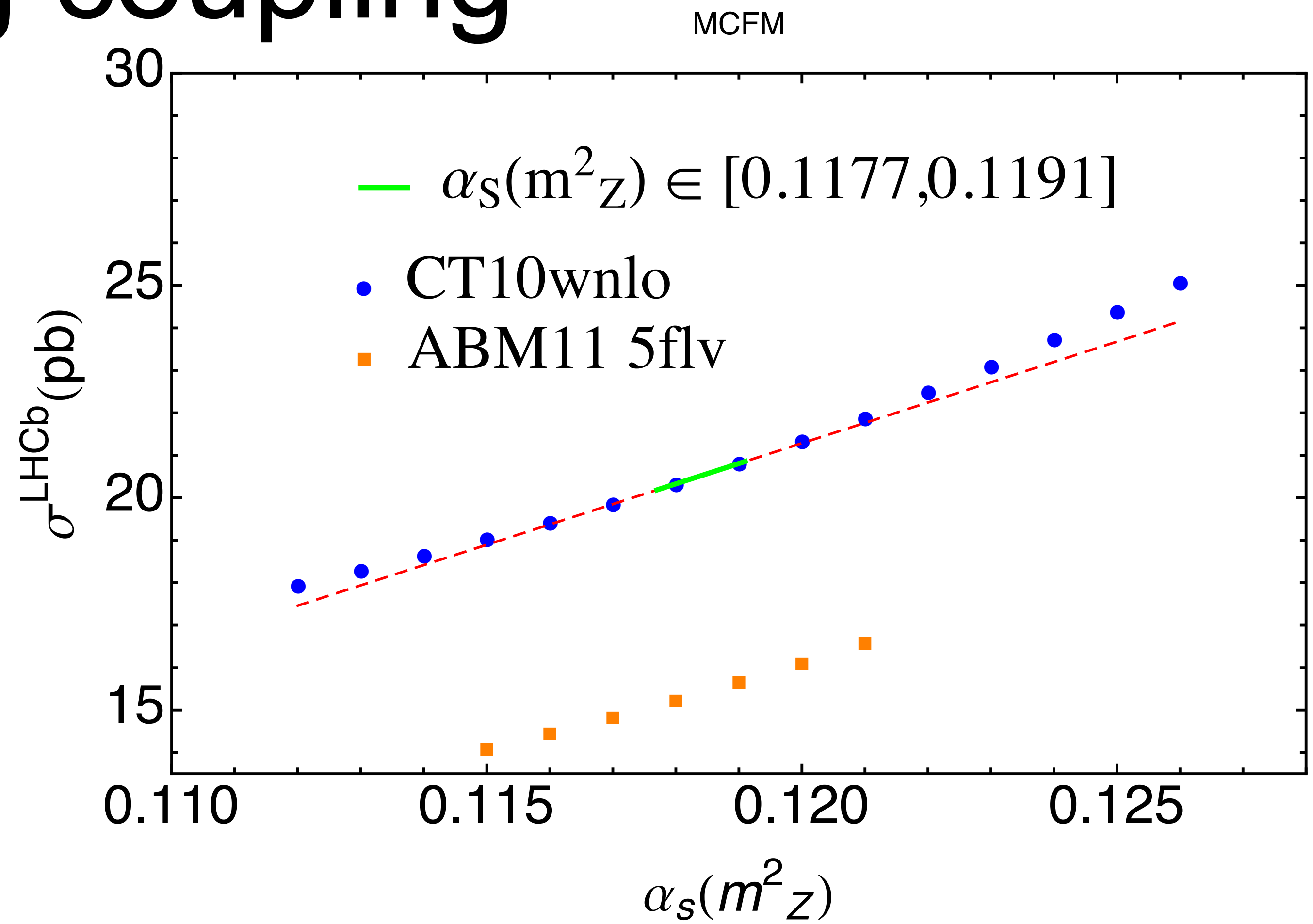
σ^{LHCb} vs. $\alpha_s(M_Z)$

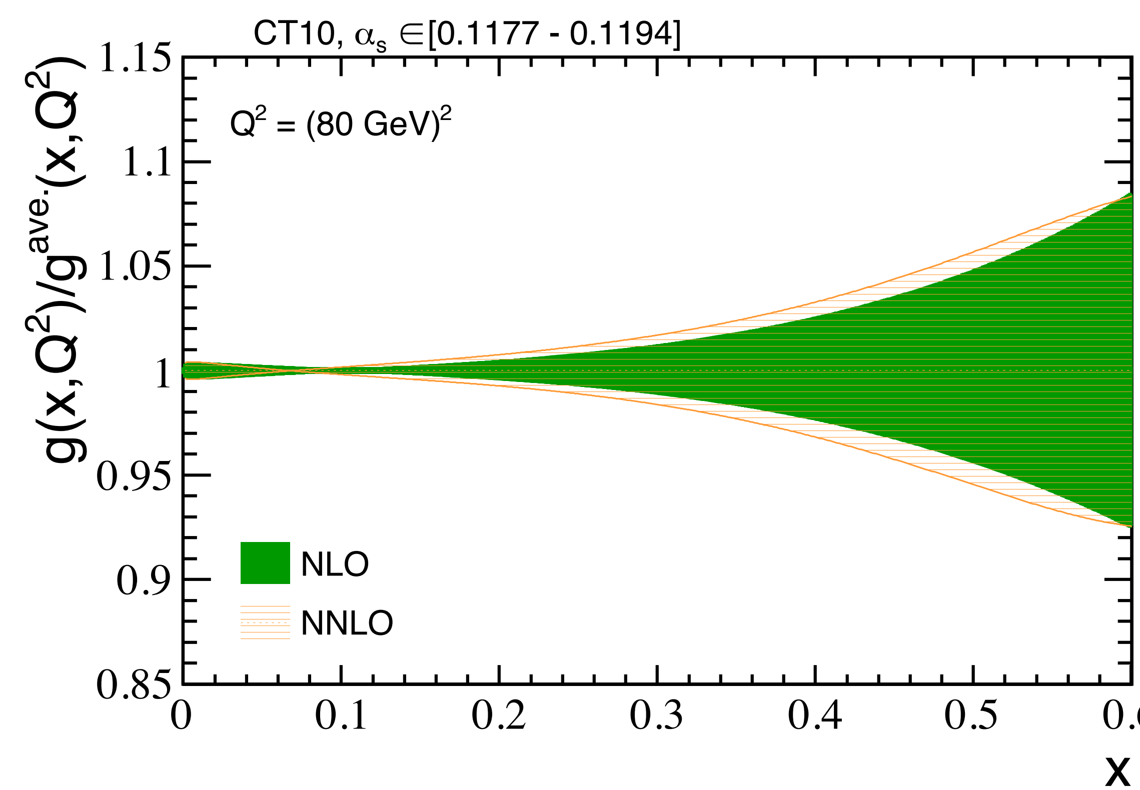
Current PDG value

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

gluon PDF uncertainty for $\delta\alpha_s$

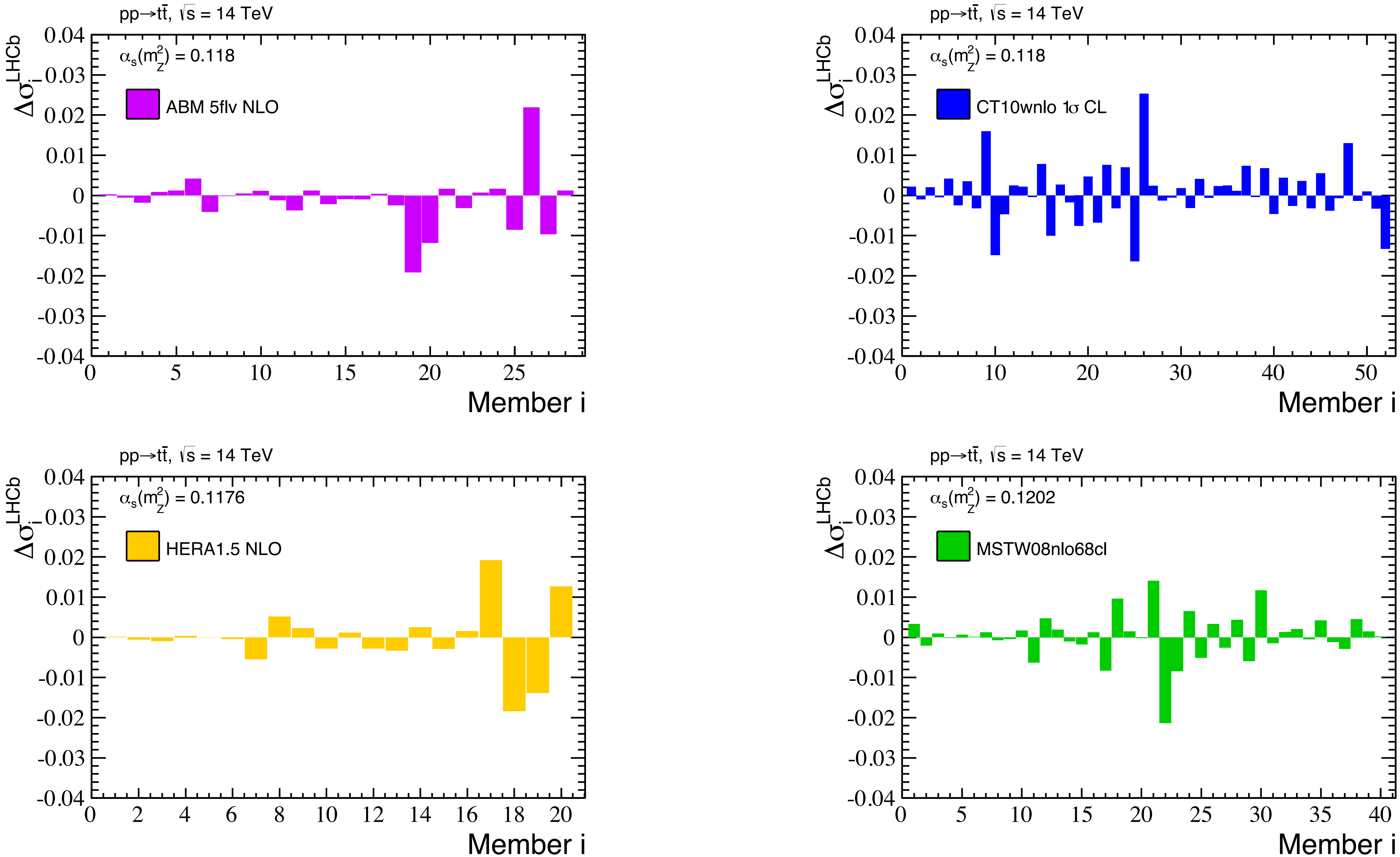
$$\delta\alpha_s \to \delta\sigma^{\mathrm{LHCb}} = 1.3\%$$





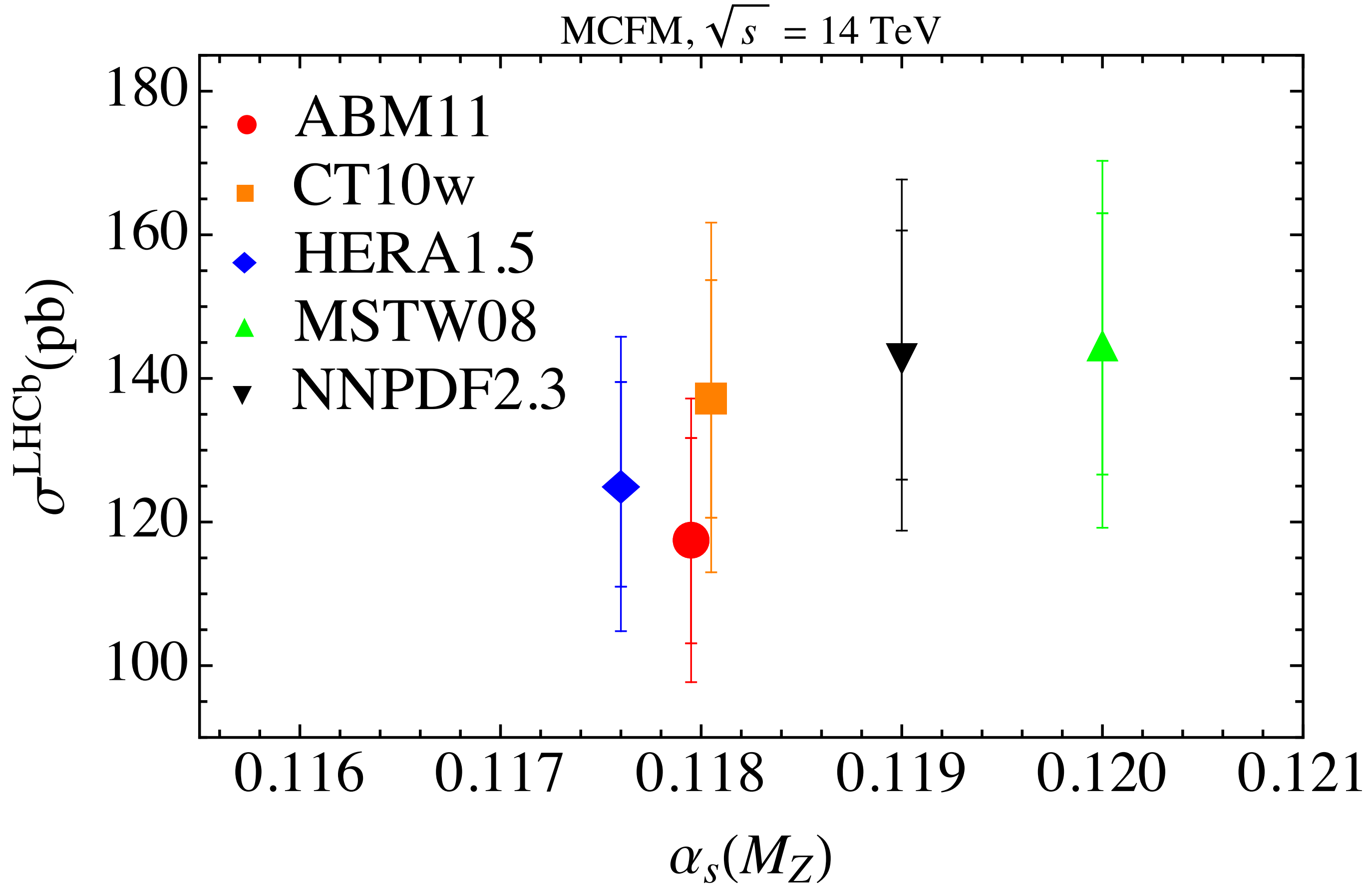
Order	PDF	σ(pb)	δ_{scale} (pb)	δ_{PDF} (pb)	δ_{α_s} (pb)	δ_{m_t} (pb)	δ_{total} (pb)
NNLO*(inc.)		832.0	+18.7 (+2.2%) −27.4 (−3.3%)	+25.1 (+3.0%) −25.1 (−3.0%)	+0.0 (+0.0%) −0.0 (−0.0%)	+34.9 (+4.2%) −33.7 (−4.1%)	+61.7 (+7.4%) −69.7 (−8.4%)
NLO(inc.)	ABM	771.9	+91.0 (+11.8%) −92.4 (−12.0%)	+9.4 (+1.2%) −9.4 (−1.2%)	+0.0 (+0.0%) −0.0 (−0.0%)	+32.3 (+4.2%) −31.9 (−4.1%)	+124.7 (+16.1%) −125.7 (−16.3%)
NLO(LHCb)		117.2	+14.5 (+12.3%) −14.1 (−12.0%)	+2.0 (+1.7%) −2.0 (−1.7%)	+0.0 (+0.0%) −0.0 (−0.0%)	+5.2 (+4.4%) −5.1 (−4.3%)	+20.0 (+17.1%) −19.5 (−16.7%)
NNLO*(inc.)		952.8	+23.3 (+2.4%) −34.5 (−3.6%)	+22.4 (+2.3%) −19.9 (−2.1%)	+14.0 (+1.5%) −14.0 (−1.5%)	+39.2 (+4.1%) −37.8 (−4.0%)	+70.6 (+7.4%) −79.5 (−8.3%)
NLO(inc.)	CT10	832.6	+97.0 (+11.7%) −96.7 (−11.6%)	+19.6 (+2.4%) −20.2 (−2.4%)	+9.2 (+1.1%) −9.2 (−1.1%)	+34.0 (+4.1%) −33.3 (−4.0%)	+137.4 (+16.5%) −136.6 (−16.4%)
NLO(LHCb)		137.0	+16.7 (+12.2%) −16.4 (−12.0%)	+5.0 (+3.6%) −4.6 (−3.4%)	+1.8 (+1.3%) −1.8 (−1.3%)	+5.9 (+4.3%) −5.8 (−4.2%)	+24.7 (+18.0%) −24.0 (−17.5%)
NNLO*(inc.)		970.5	+22.1 (+2.3%) −22.0 (−2.3%)	+15.7 (+1.6%) −25.7 (−2.6%)	+12.8 (+1.3%) −12.8 (−1.3%)	+39.6 (+4.1%) −38.4 (−4.0%)	+66.6 (+6.9%) −70.0 (−7.2%)
NLO(inc.)	HERA	804.2	+91.9 (+11.4%) −87.6 (−10.9%)	+16.1 (+2.0%) −21.9 (−2.7%)	+5.3 (+0.7%) −5.3 (−0.7%)	+33.4 (+4.1%) −32.4 (−4.0%)	+129.3 (+16.1%) −127.1 (−15.8%)
NLO(LHCb)		124.7	+14.8 (+11.8%) −13.7 (−11.0%)	+3.0 (+2.4%) −3.0 (−2.4%)	+1.1 (+0.9%) −1.1 (−0.9%)	+5.5 (+4.4%) −5.3 (−4.3%)	+21.1 (+16.9%) −19.9 (−15.9%)
NNLO*(inc.)		953.6	+22.7 (+2.4%) −33.9 (−3.6%)	+16.2 (+1.7%) −17.8 (−1.9%)	+12.8 (+1.3%) −12.8 (−1.3%)	+39.1 (+4.1%) −37.9 (−4.0%)	+66.9 (+7.0%) −77.7 (−8.1%)
NLO(inc.)	MSTW	885.6	+107.2 (+12.1%) −105.7 (−11.9%)	+16.0 (+1.8%) −19.4 (−2.2%)	+10.1 (+1.1%) −10.1 (−1.1%)	+36.2 (+4.1%) −35.3 (−4.0%)	+148.1 (+16.7%) −147.3 (−16.6%)
NLO(LHCb)		144.4	+18.6 (+12.8%) −17.8 (−12.3%)	+3.5 (+2.4%) −3.9 (−2.7%)	+1.9 (+1.3%) −1.9 (−1.3%)	+6.2 (+4.3%) −6.1 (−4.2%)	+25.9 (+18.0%) −25.2 (−17.5%)
NNLO*(inc.)		977.5	+23.6 (+2.4%) −35.4 (−3.6%)	+16.4 (+1.7%) −16.4 (−1.7%)	+12.2 (+1.3%) −12.2 (−1.3%)	+40.4 (+4.1%) −39.1 (−4.0%)	+68.9 (+7.0%) −80.0 (−8.1%)
NLO(inc.)	NNPDF	894.5	+107.6 (+12.0%) −101.0 (−11.3%)	+12.8 (+1.4%) −12.8 (−1.4%)	+9.9 (+1.1%) −9.9 (−1.1%)	+36.6 (+4.1%) −35.8 (−4.0%)	+147.6 (+16.5%) −140.3 (−15.7%)
NLO(LHCb)		142.5	+18.1 (+12.7%) −16.6 (−11.7%)	+3.0 (+2.1%) −3.0 (−2.1%)	+2.0 (+1.4%) −2.0 (−1.4%)	+6.2 (+4.4%) −6.1 (−4.3%)	+25.2 (+17.7%) −23.7 (−16.6%)

Summary of eigenvector sensitivity



$$\Delta X_j^{\pm} = \frac{X(\mathcal{S}_j^{\pm}) - X(\mathcal{S}_0)}{X(\mathcal{S}_0)}$$

Summary of theory systematics (NLO)



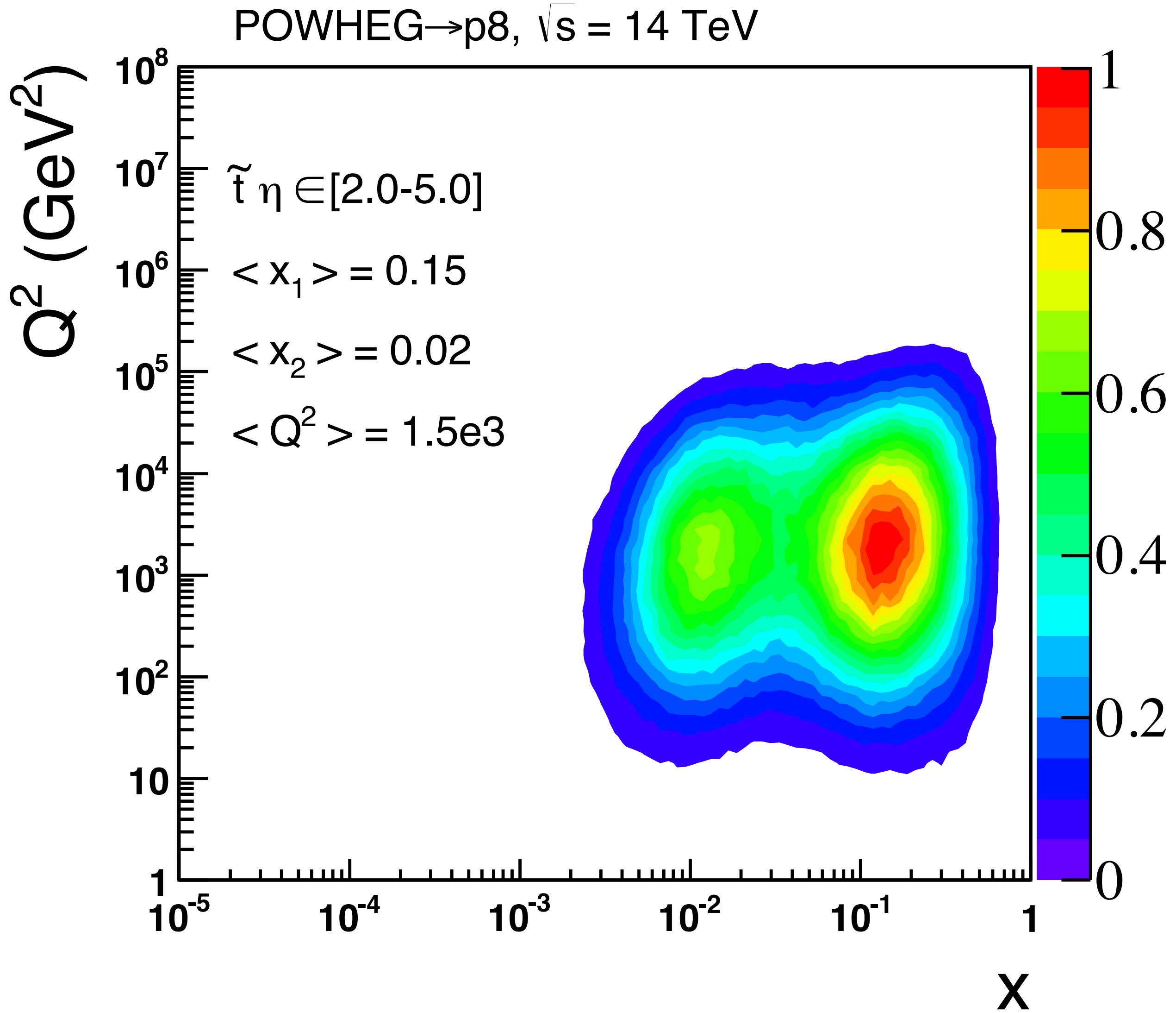
$$\delta_{\rm total} = \delta_{\rm scale} + (\delta^2_{\rm PDF} + \delta^2_{\alpha_s} + \delta^2_{m_t})^{\frac{1}{2}}$$

$$\delta_X^{\rm ratio} = \frac{\delta_X^{\rm LHCb}}{\delta_X^{NLO}}$$

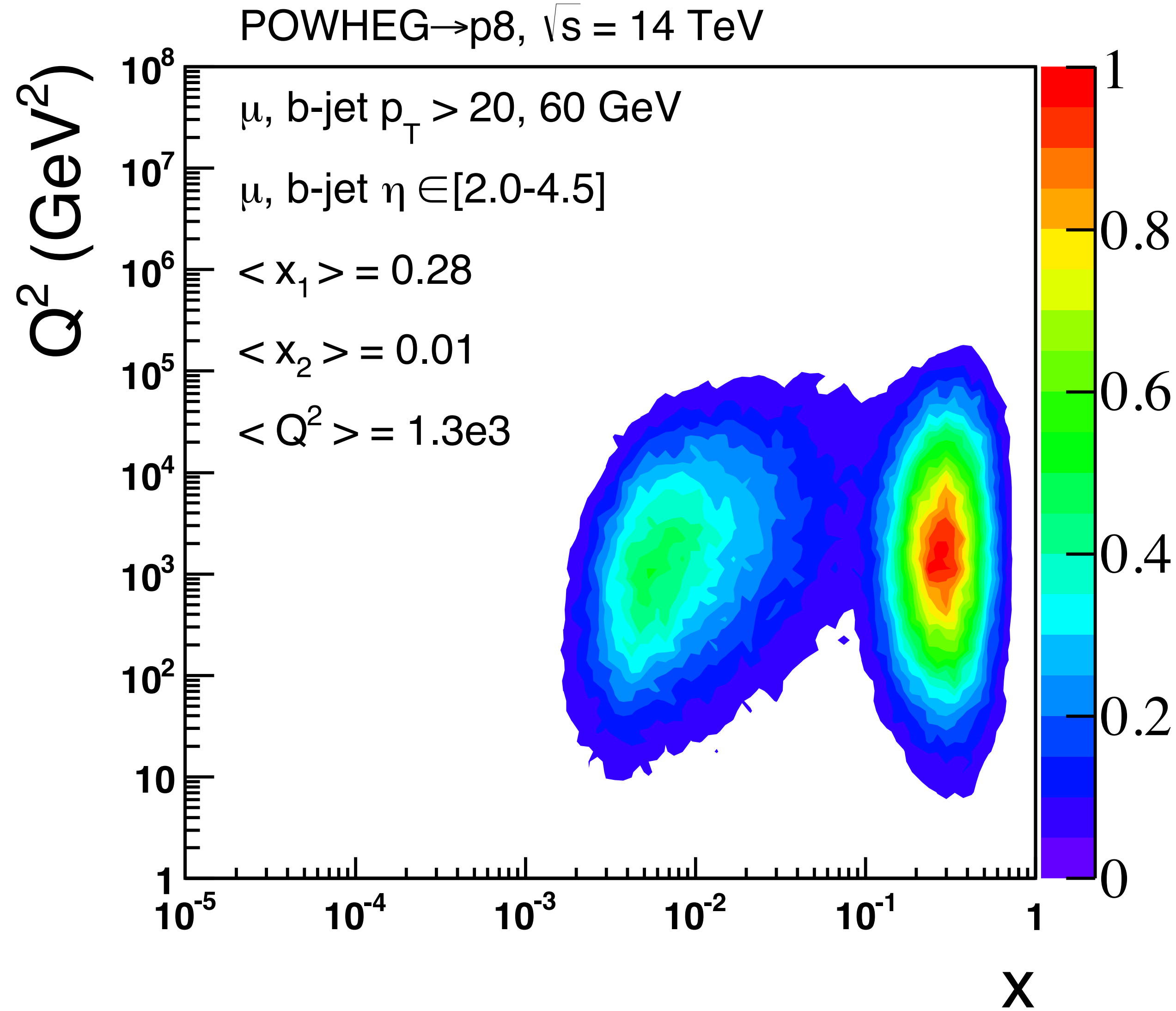
PDF	$\delta^{\rm ratio}_{\rm scale}$	$\delta^{\rm ratio}_{\rm PDF}$	$\delta^{\rm ratio}_{\alpha_s}$	$\delta^{\rm ratio}_{m_t}$	$\delta^{\rm ratio}_{\rm total}$
ABM	$^{+1.05}_{-1.00}$	$^{+1.40}_{-1.40}$	$^{+0.00}_{-0.00}$	$^{+1.05}_{-1.05}$	$^{+1.06}_{-1.02}$
CT10	$^{+1.05}_{-1.03}$	$^{+1.55}_{-1.40}$	$^{+1.20}_{-1.20}$	$^{+1.06}_{-1.05}$	$^{+1.09}_{-1.07}$
HERA	$^{+1.04}_{-1.01}$	$^{+1.19}_{-0.90}$	$^{+1.33}_{-1.33}$	$^{+1.07}_{-1.06}$	$^{+1.05}_{-1.01}$
MSTW	$^{+1.06}_{-1.03}$	$^{+1.35}_{-1.23}$	$^{+1.13}_{-1.13}$	$^{+1.05}_{-1.06}$	$^{+1.07}_{-1.05}$
NNPDF	$^{+1.05}_{-1.03}$	$^{+1.45}_{-1.45}$	$^{+1.27}_{-1.27}$	$^{+1.07}_{-1.07}$	$^{+1.07}_{-1.06}$

Impact of acceptance cuts (NLO)

parton level



kinematic cuts



Constraining the gluon PDF

Perform a bayesian reweighting based on statistical inference.
arXiv:1012.0836 NNPDF collaboration
arXiv:1205.4024 G. Watt, R. S. Thorne, applied technique to MSTW hessian set

I apply the technique to CT10w and NNPDF2.3 NLO sets

Recipe for Hessian reweighting

1) Calculate observables from eigenvector set

$$\{X_0(\mathcal{S}_0), X_1^-(\mathcal{S}_1^-), X_1^+(\mathcal{S}_1^+), ...X_N^-(\mathcal{S}_N^-), X_N^+(\mathcal{S}_N^+)\}$$

2) Generate random observables from these (storing random numbers)

$$X(\mathcal{S}_k) = X(\mathcal{S}_0) + \sum_{j=1}^{N}[X(\mathcal{S}_j^\pm) - X(\mathcal{S}_0)]|R_{kj}|$$

3) Apply a reweighting based on a 'measured' observable (e.g. cross-section)

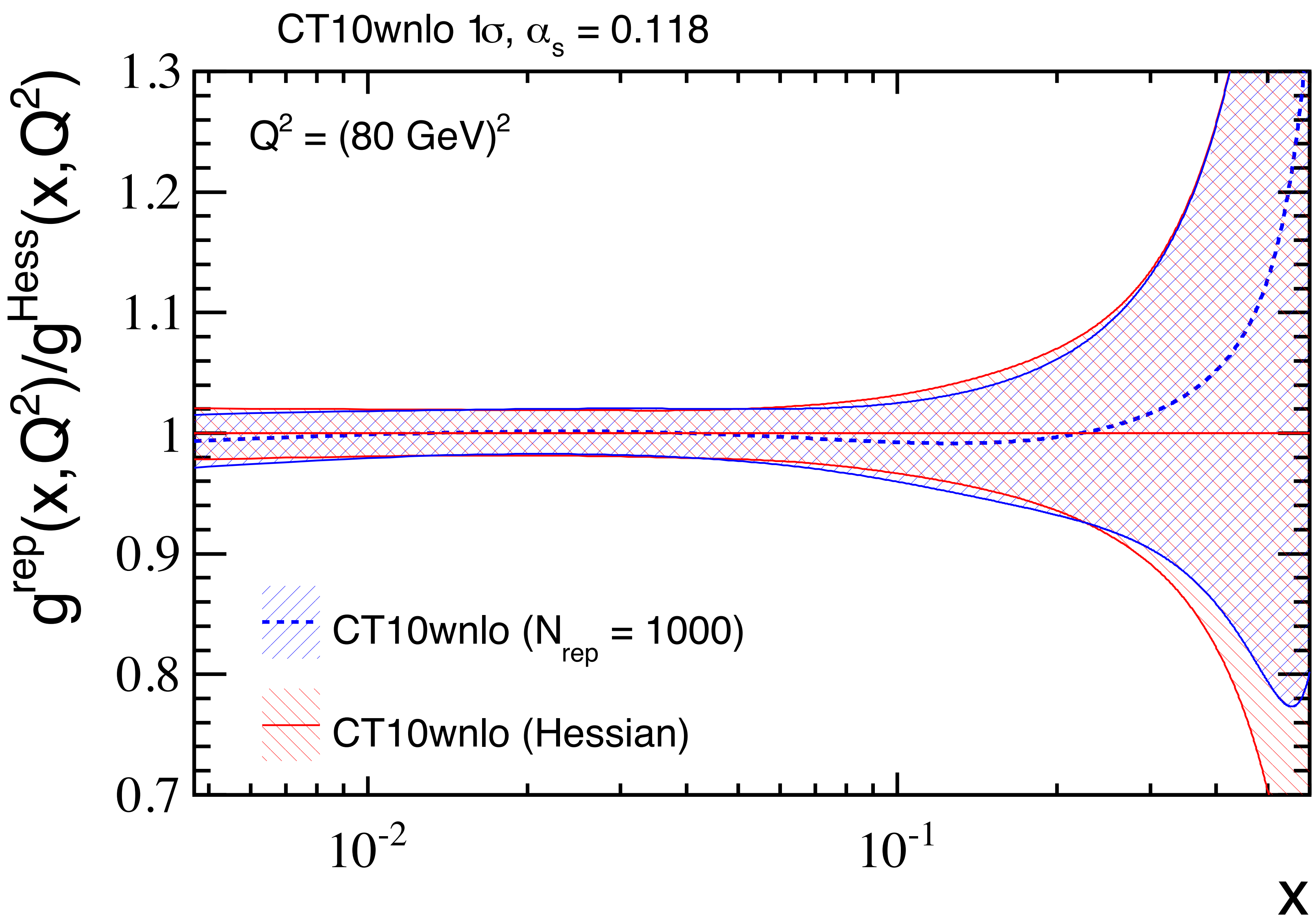
$$W_k(\chi_k^2) = (\chi_k^2)^{\frac{1}{2}(N_{pts.}-1)}\exp(-\frac{1}{2}\chi_k^2)$$

4) Apply these weights to the other observables (gluon PDF, ttbar asymmetry etc.)

Follow the recipe - steps 1, 2

1) Choose observable as evolved gluon PDF, $g^{\text{Hess}}(x, [Q = 80\ \text{GeV}]^2)$

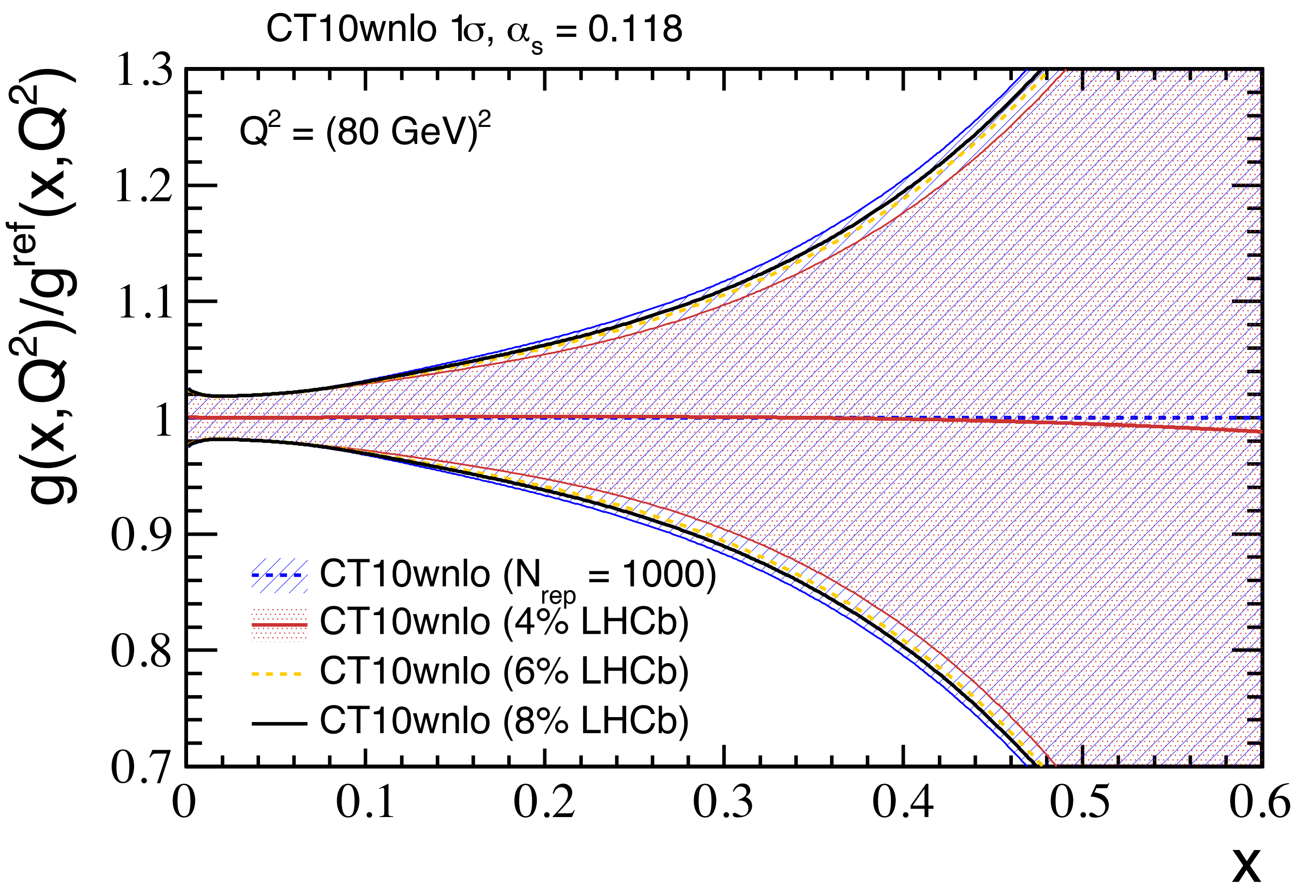
2) Generate 1000 Replicas and compare, $g^{\text{rep}}(x, [Q = 80\ \text{GeV}]^2)$

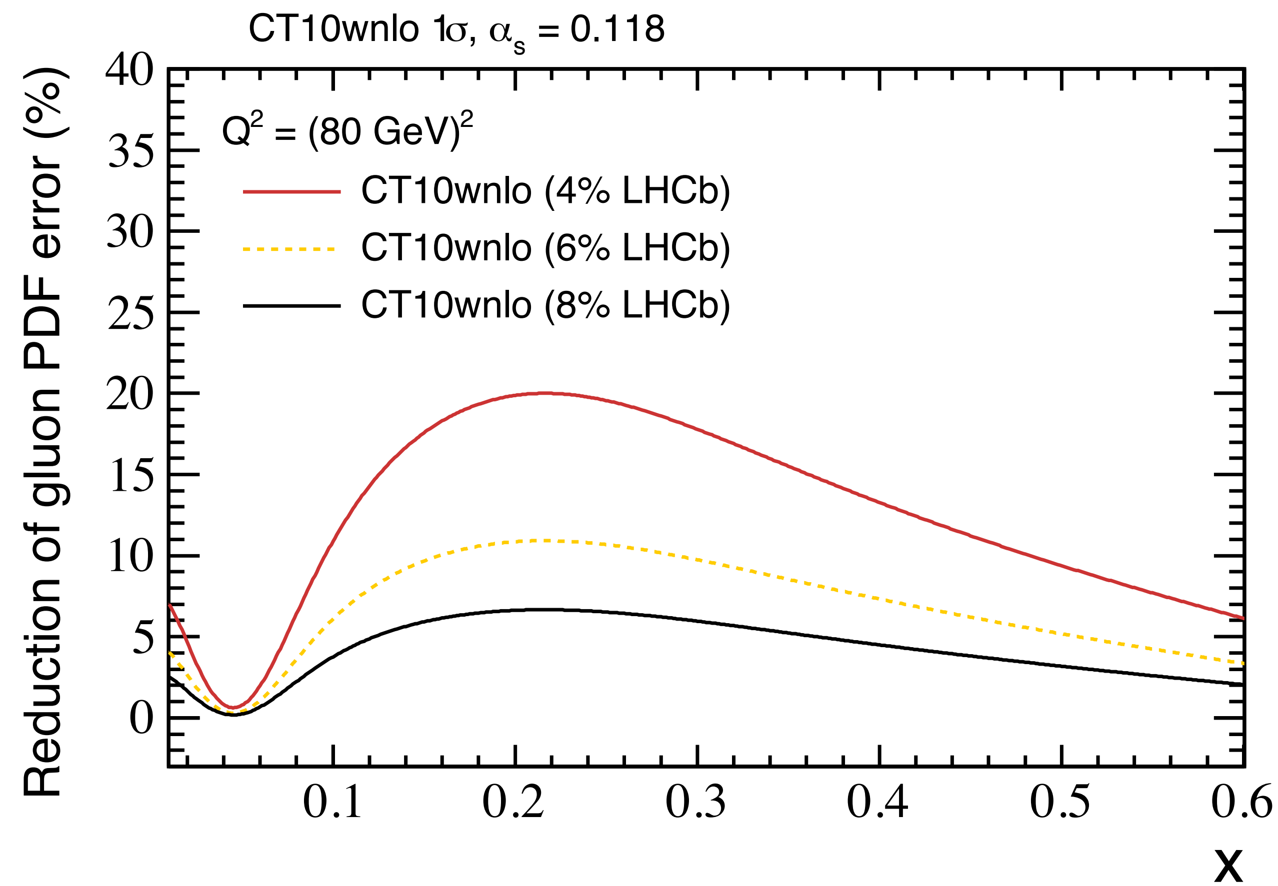


Follow the recipe - steps 3, 4

3) Pick some pseudo LHCb cross-section data, $\bar{X}_0 = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} X_0(\mathcal{S}_0)[1 + R_{k0}]$

4) Apply weights found using pseudodata to reweight evolved gluon PDF





Asymmetry when interfaced to PS?

arXiv:1205.1466 P.Z.Skands, B. R. Webber, J. Winter, QCD Coherence

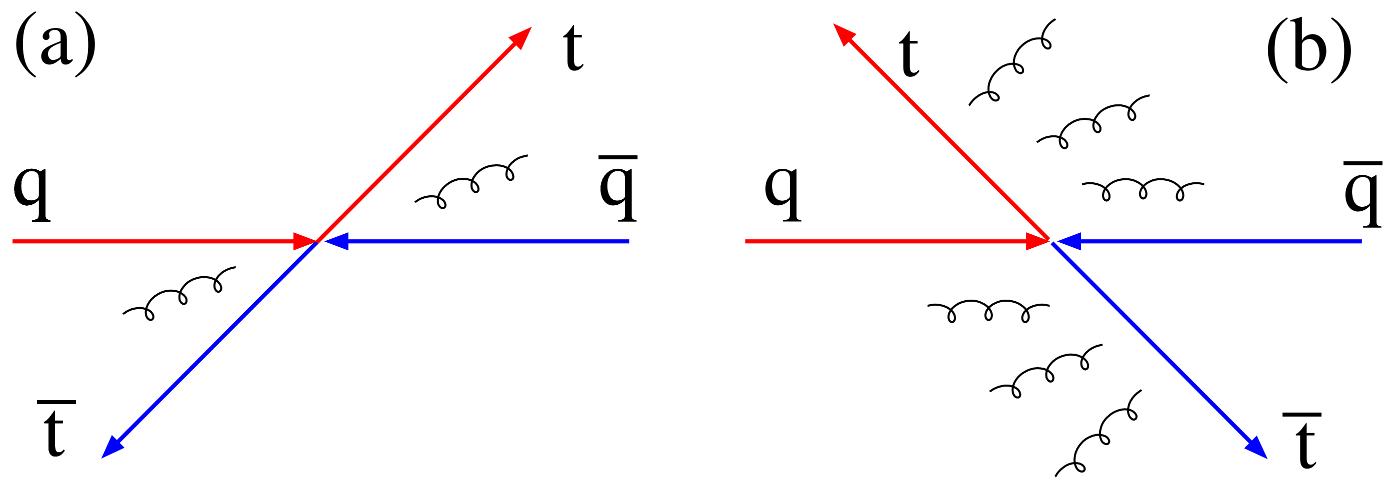


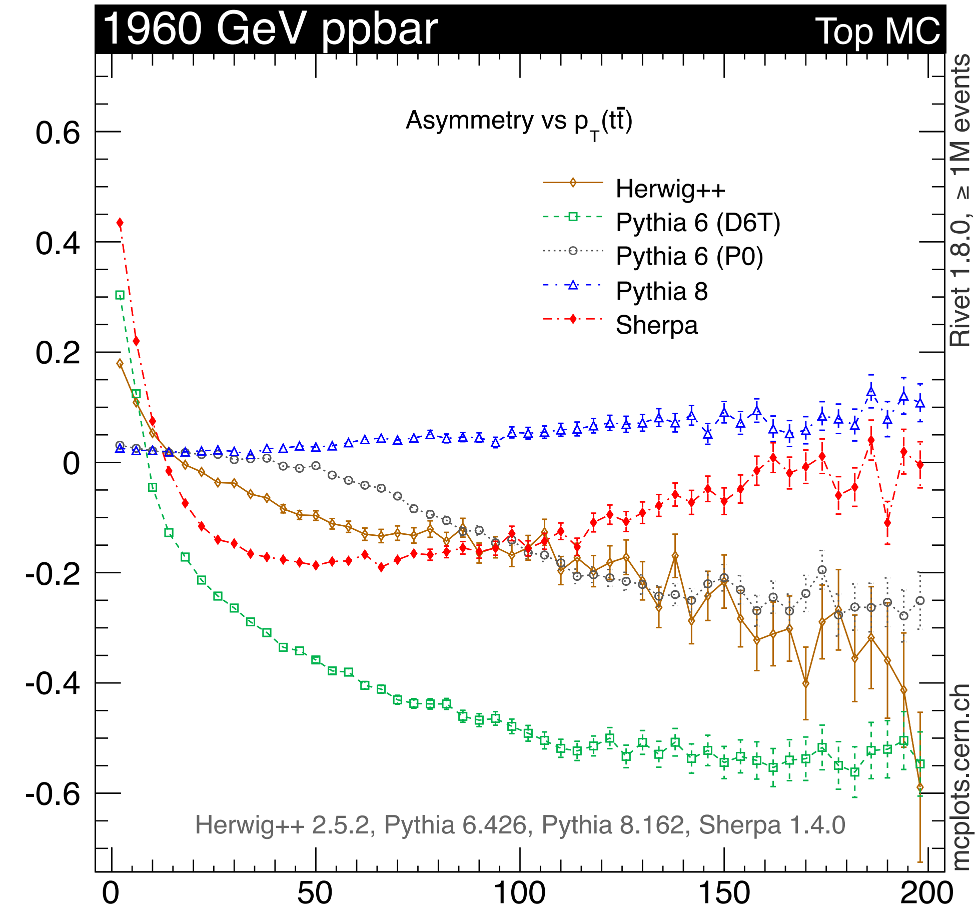
Figure 2: Colour flow and QCD radiation in (a) forward and (b) backward $t\bar{t}$ production.

Symmetric LO matrix elements

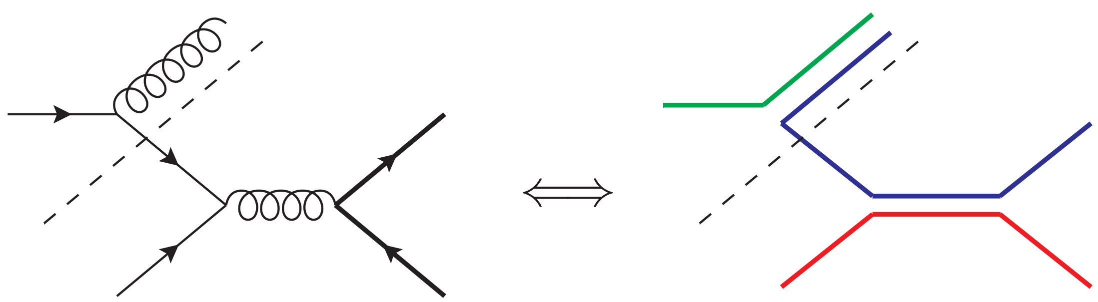
Different behaviour observed in Parton Shower (PS)

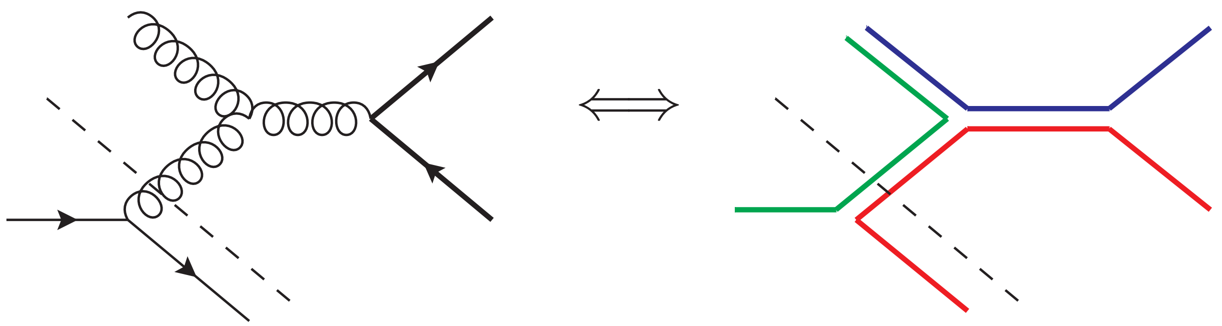
Though this was observed in qqbar (TeVatron)

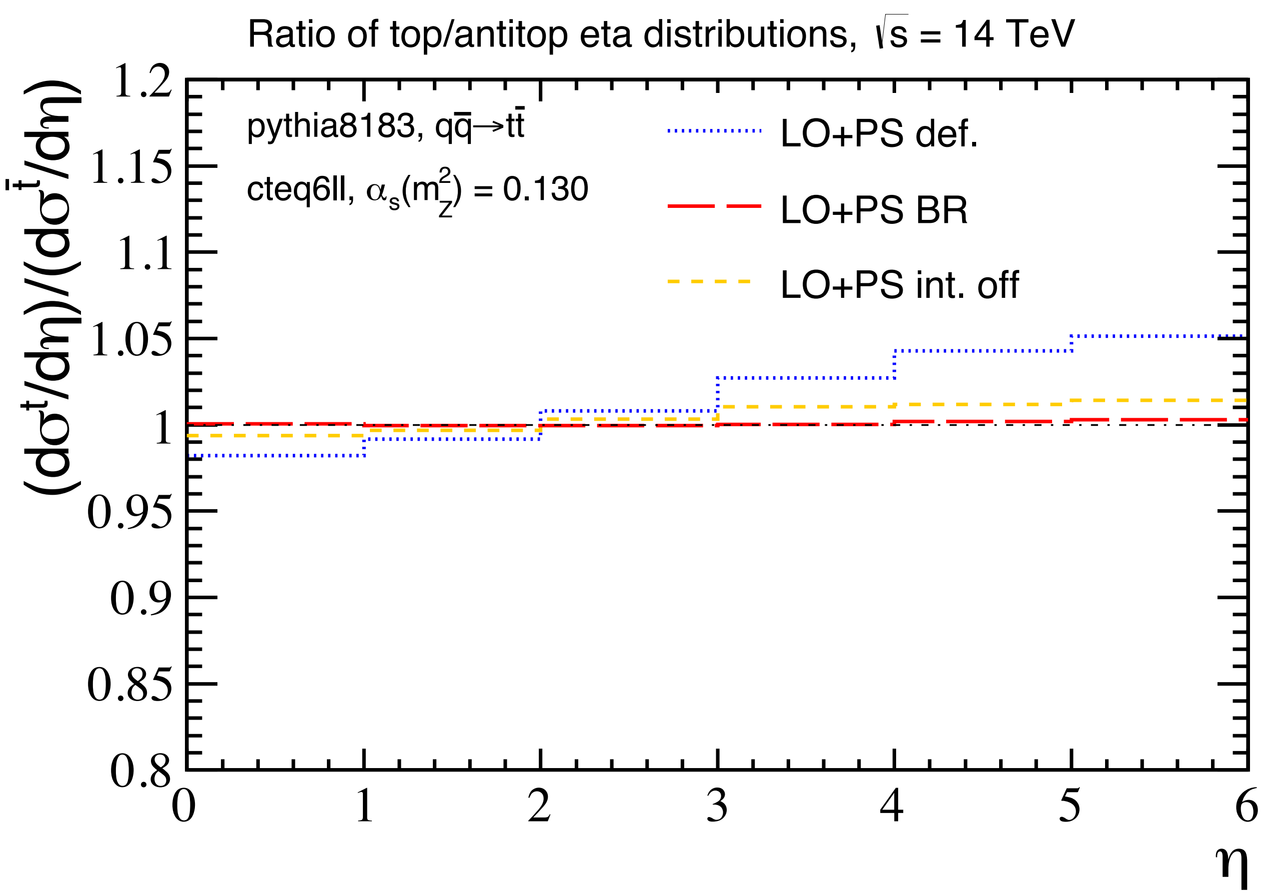
What about the LHC, gg dominated

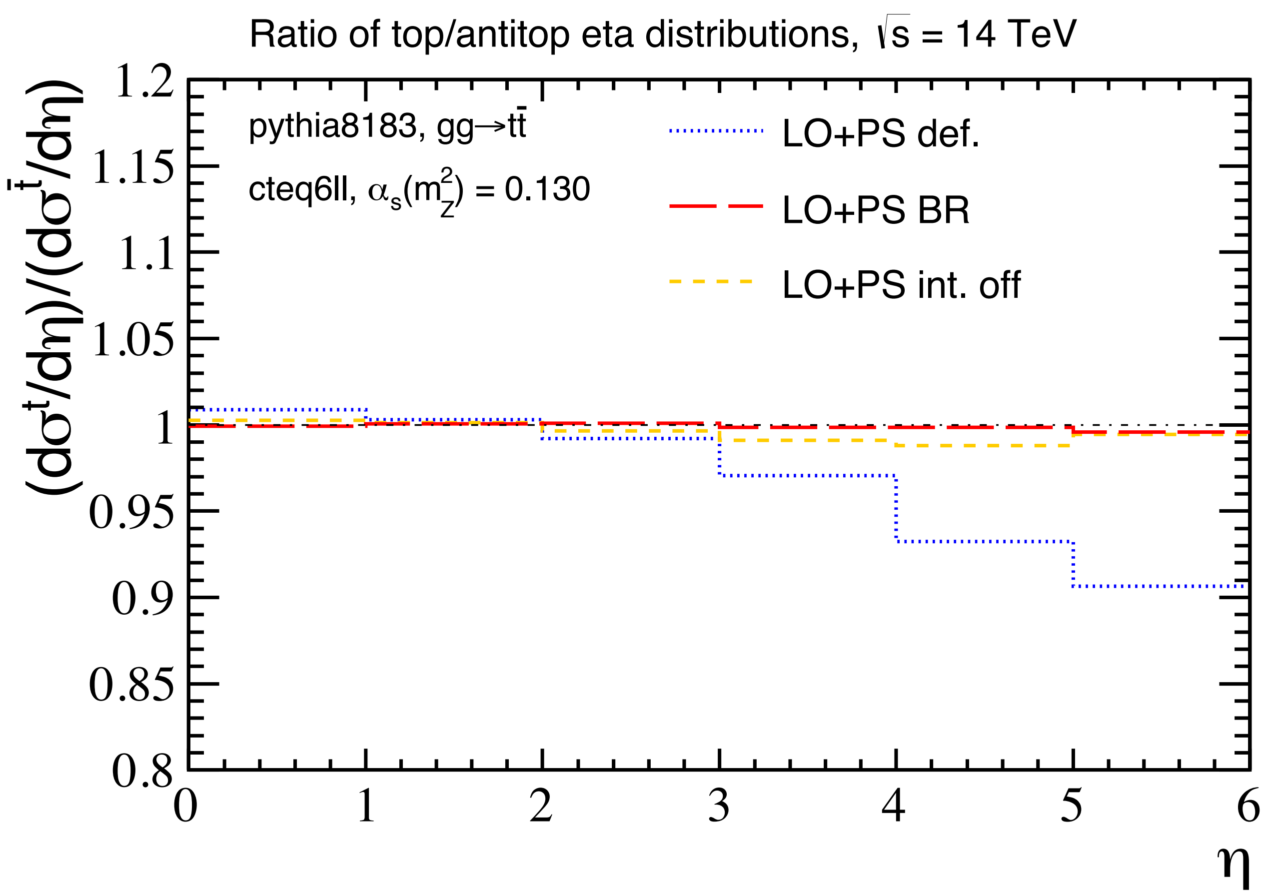


Asymmetry when interfaced to PS?

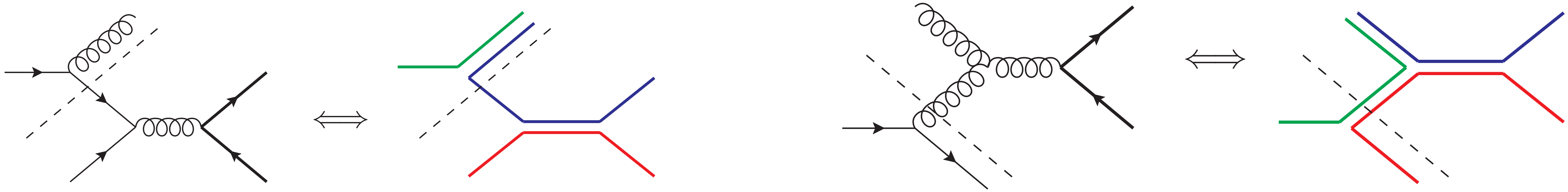


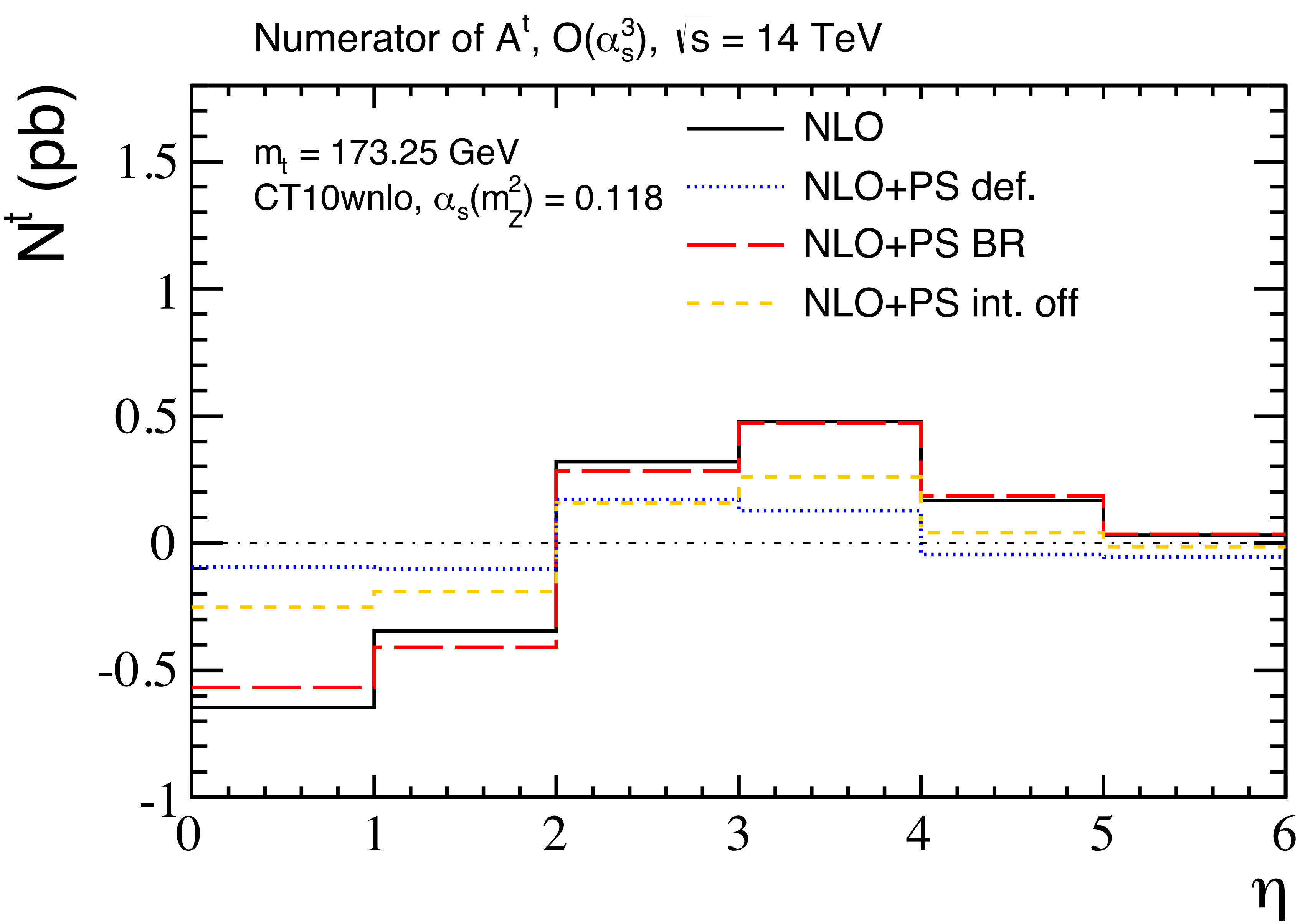






Asymmetry when interfaced to PS?

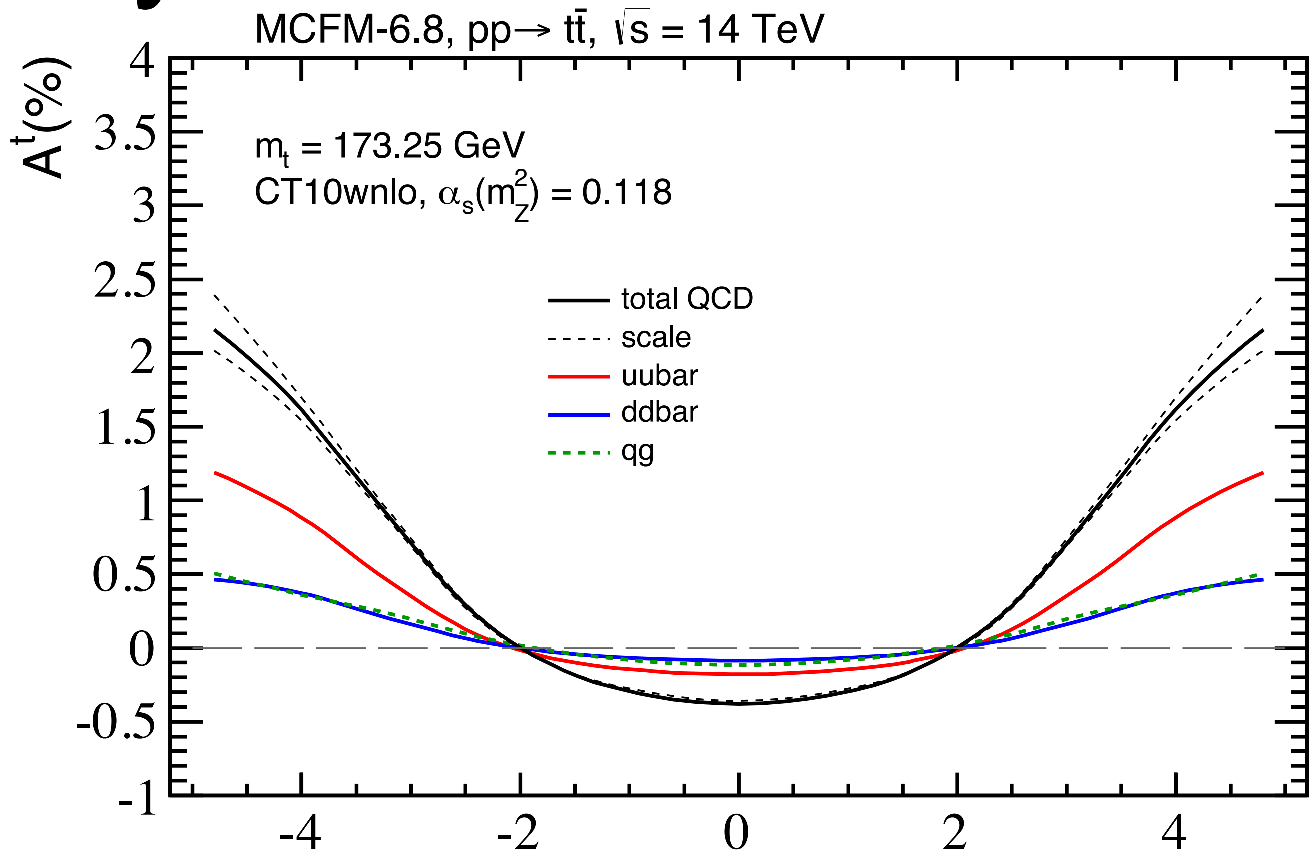




Stable top asymmetries

Parton level asymmetry

qqbar and qg separated



Parton level asymmetry

QCD / WEAK separated