Future prospects with cc/bb/tt final states and inclusive B production

Rhorry Gauld

Implications of LHCb measurements
and future prospects 2016

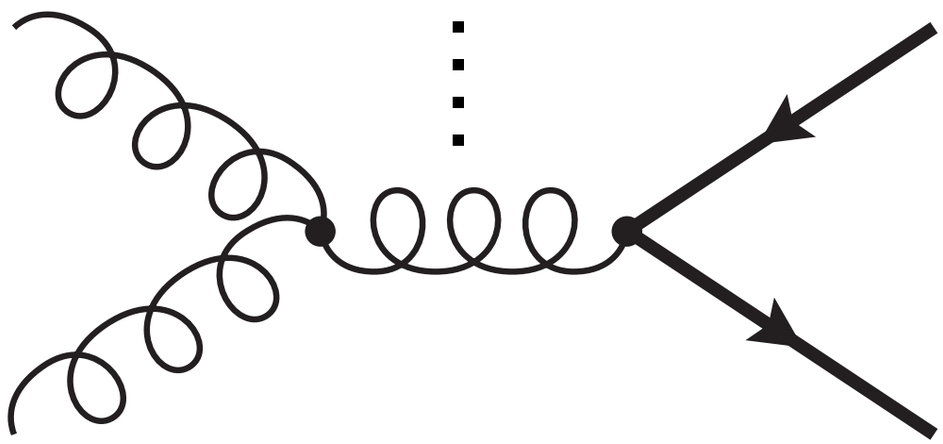
- **Motivations:**
    - benefits of forward measurements
- **Heavy quark pair observables:**
    - c/b-pairs
    - top-pairs
- **Impact/prospects of inclusive B production:**
    - understanding the R13/7 data
    - future checks

Motivations:

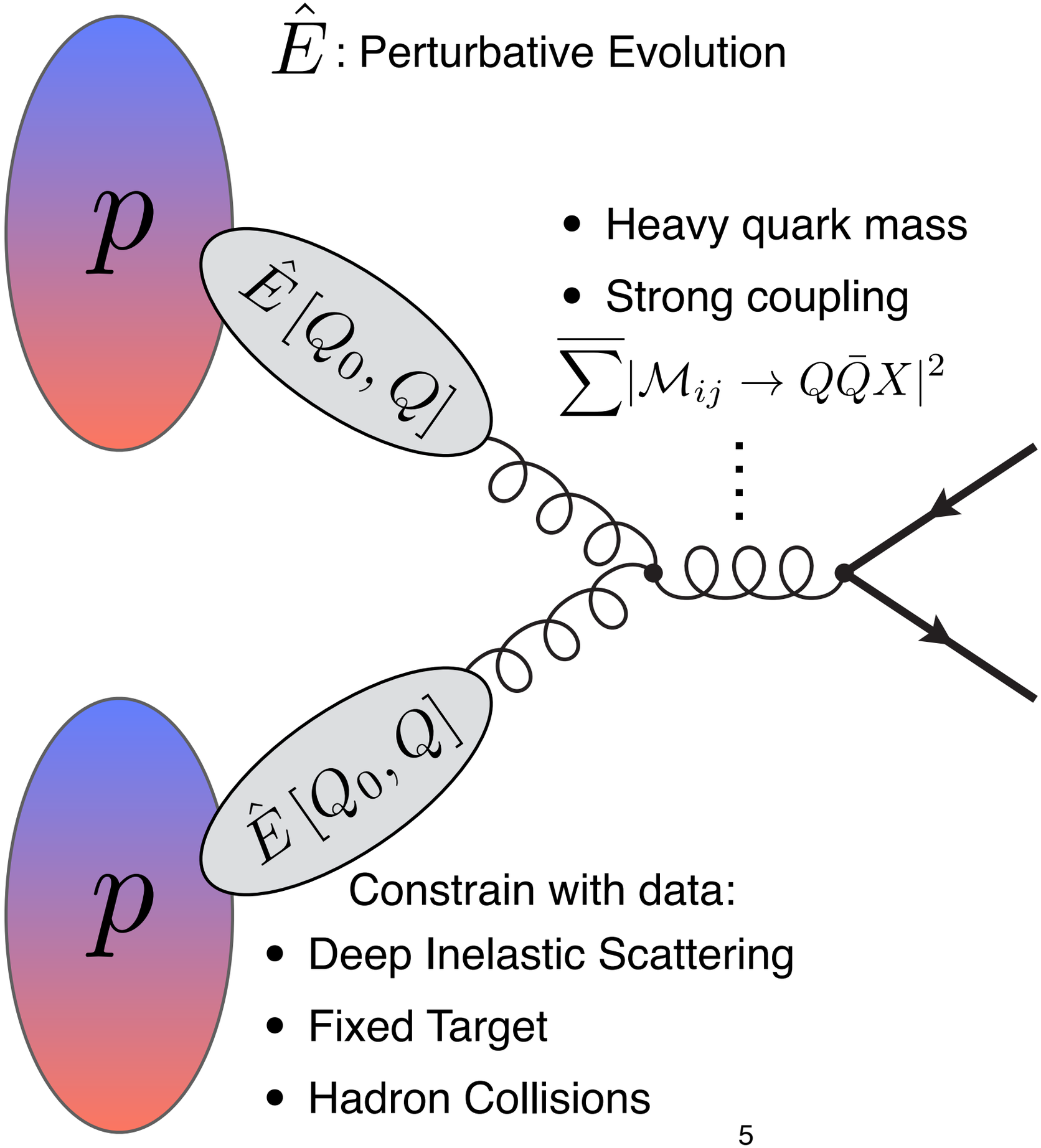
benefits of forward heavy flavour measurements

- Heavy quark mass
- Strong coupling

$$\overline{\sum}|\mathcal{M}_{ij} \to Q\bar{Q}X|^2$$



$\hat{E}$: Perturbative Evolution



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$\vdots$

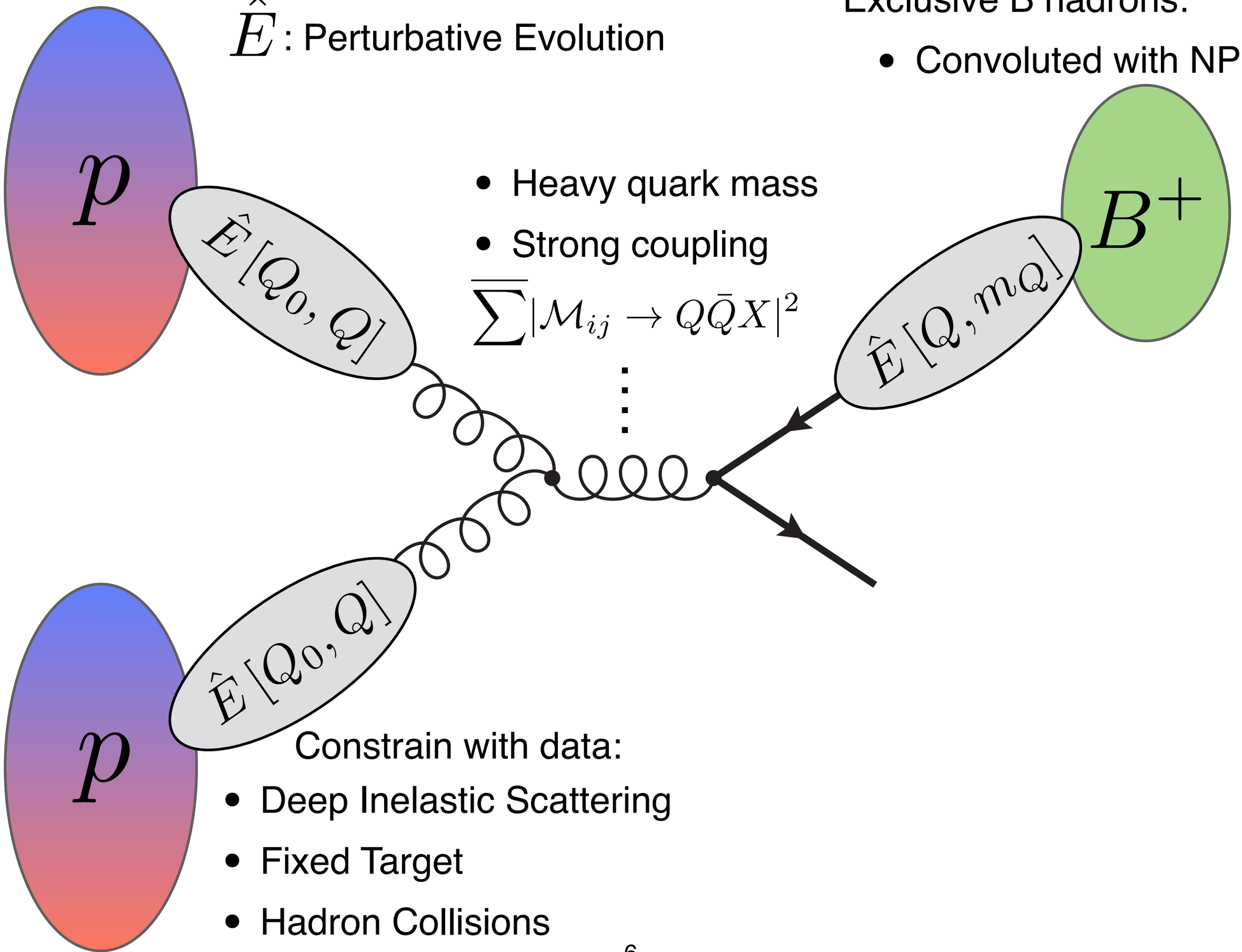
Constrain with data:

- Deep Inelastic Scattering
- Fixed Target
- Hadron Collisions

$\hat{E}$: Perturbative Evolution

Exclusive B hadrons:

- Convoluted with NP FF



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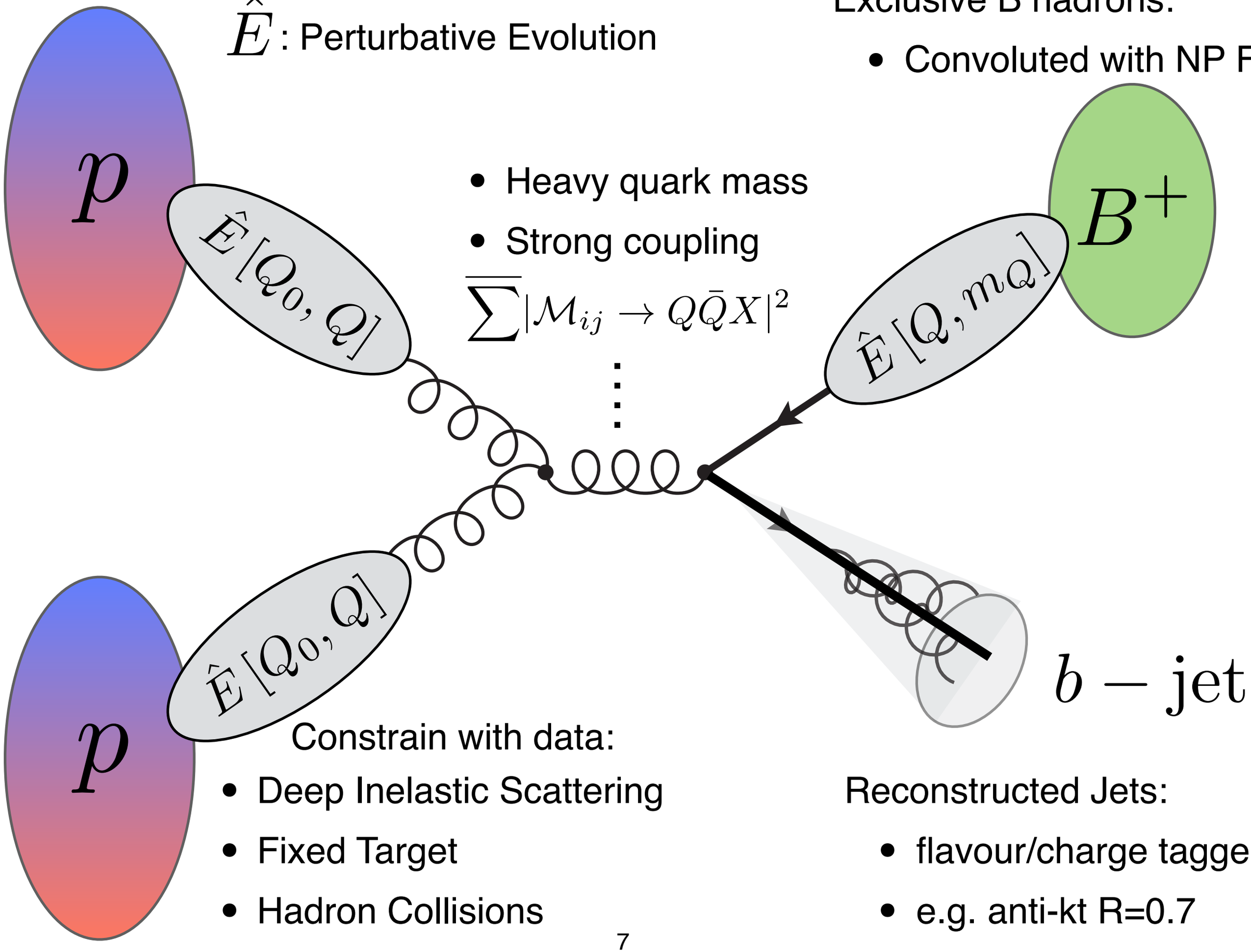

- Heavy quark mass
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$$\overline{\sum}|\mathcal{M}_{ij} \to Q\bar{Q}X|^2$$

$$\vdots$$

Constrain with data:

- Deep Inelastic Scattering
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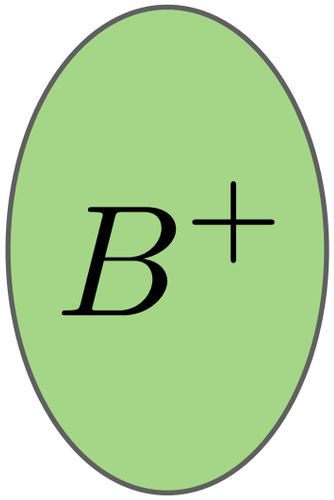
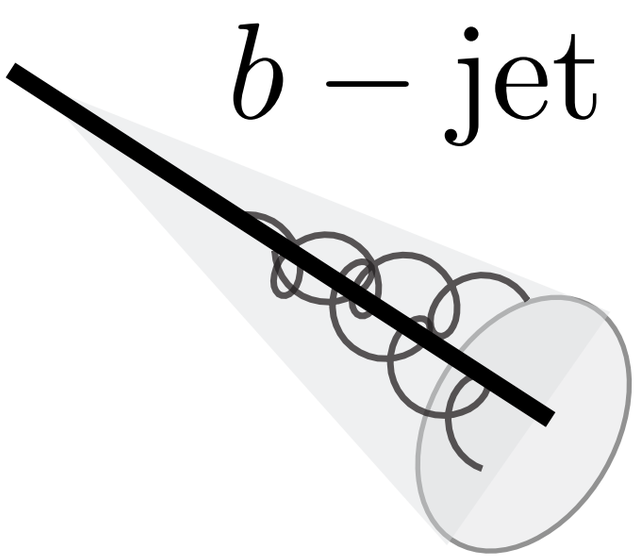
Reconstructed Jets:

- flavour/charge tagged
- e.g. anti-kt R=0.7



Fully reconstruct B-hadron:

- Data from $P_T^B > 0 \text{ GeV}$
- Efficiency poor
- Clean signal



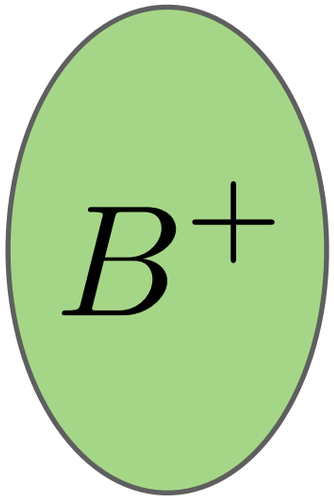
Reconstruct b-jet:

- Data from $P_T > 20 \text{ GeV}$
- Efficiency vs Mistag

e.g. $\epsilon_b = 0.65 \, , \, \not{\epsilon}_l = 0.003$

$$\eta_j \in [2.2, 4.2]$$

LHCb-PAPER-2015-016



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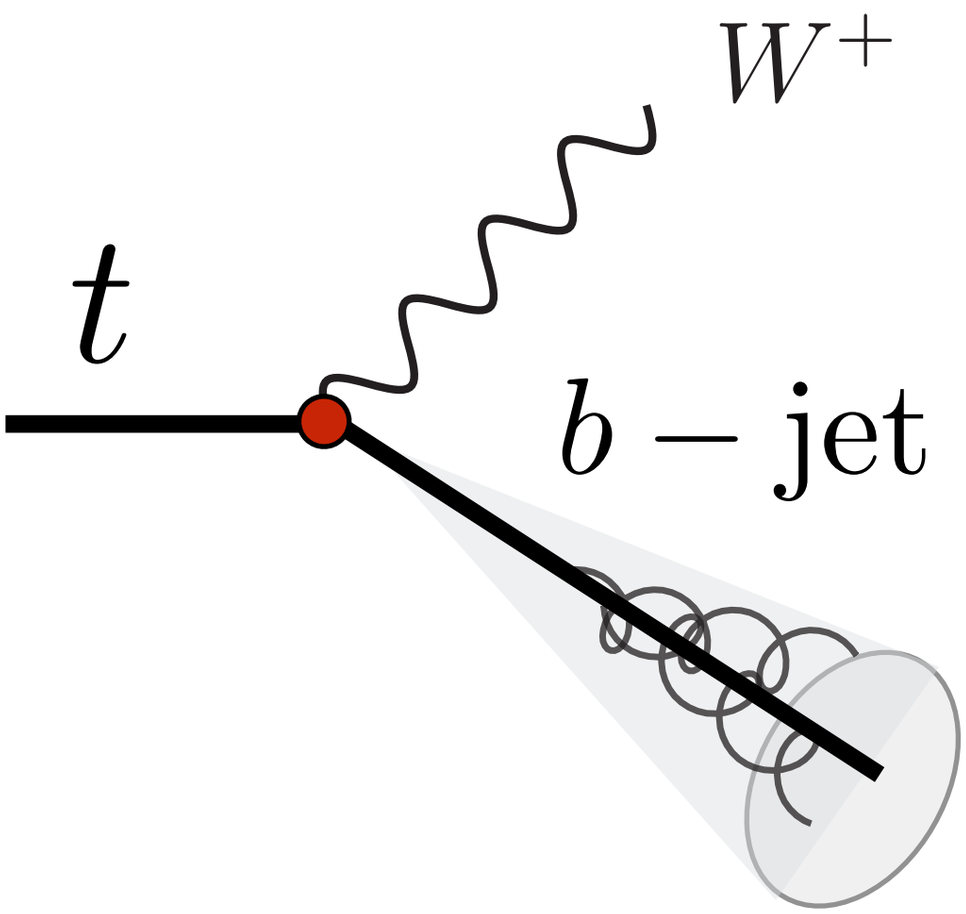

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$$\eta_j \in [2.2, 4.2]$$

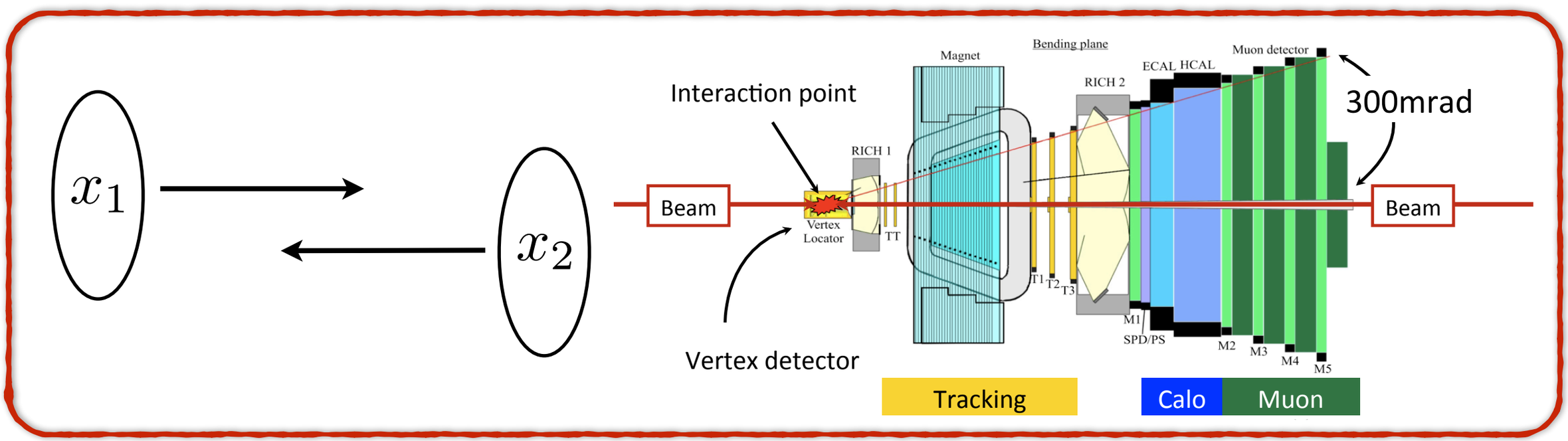
LHCb-PAPER-2015-016

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

x_i : fraction of momentum
y_j : rapidity
$\sqrt{S}$: hadronic COM
m_T : transverse mass

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

LHCb acceptance: $y_D \in [2.0, 4.5]$



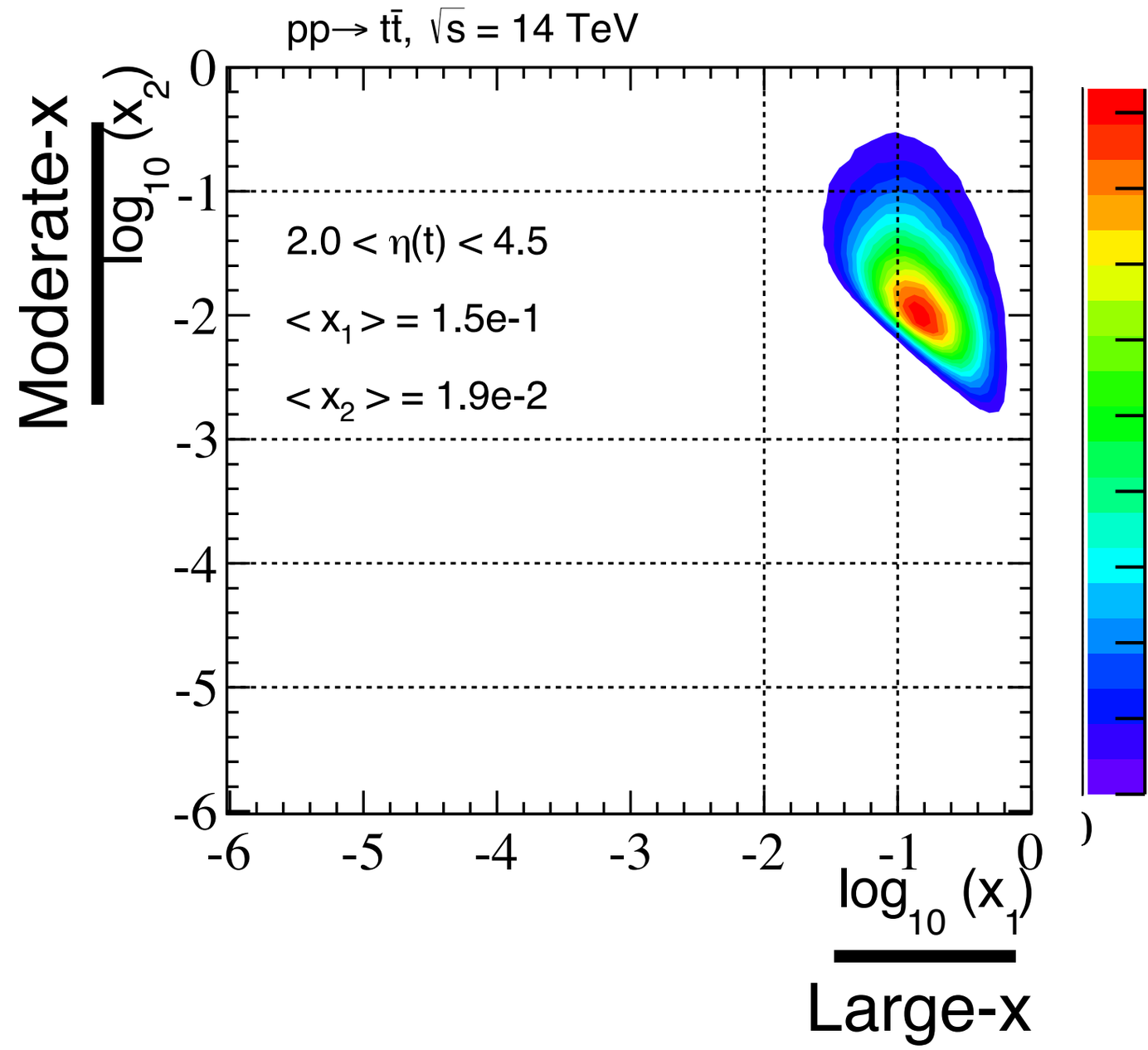
$pp \to t\bar{t}$

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

Require one of the top quarks within LHCb acceptance:

$$2.5 < \eta(t) < 4.5$$

$$m_t \simeq 173.0 \text{ GeV}$$



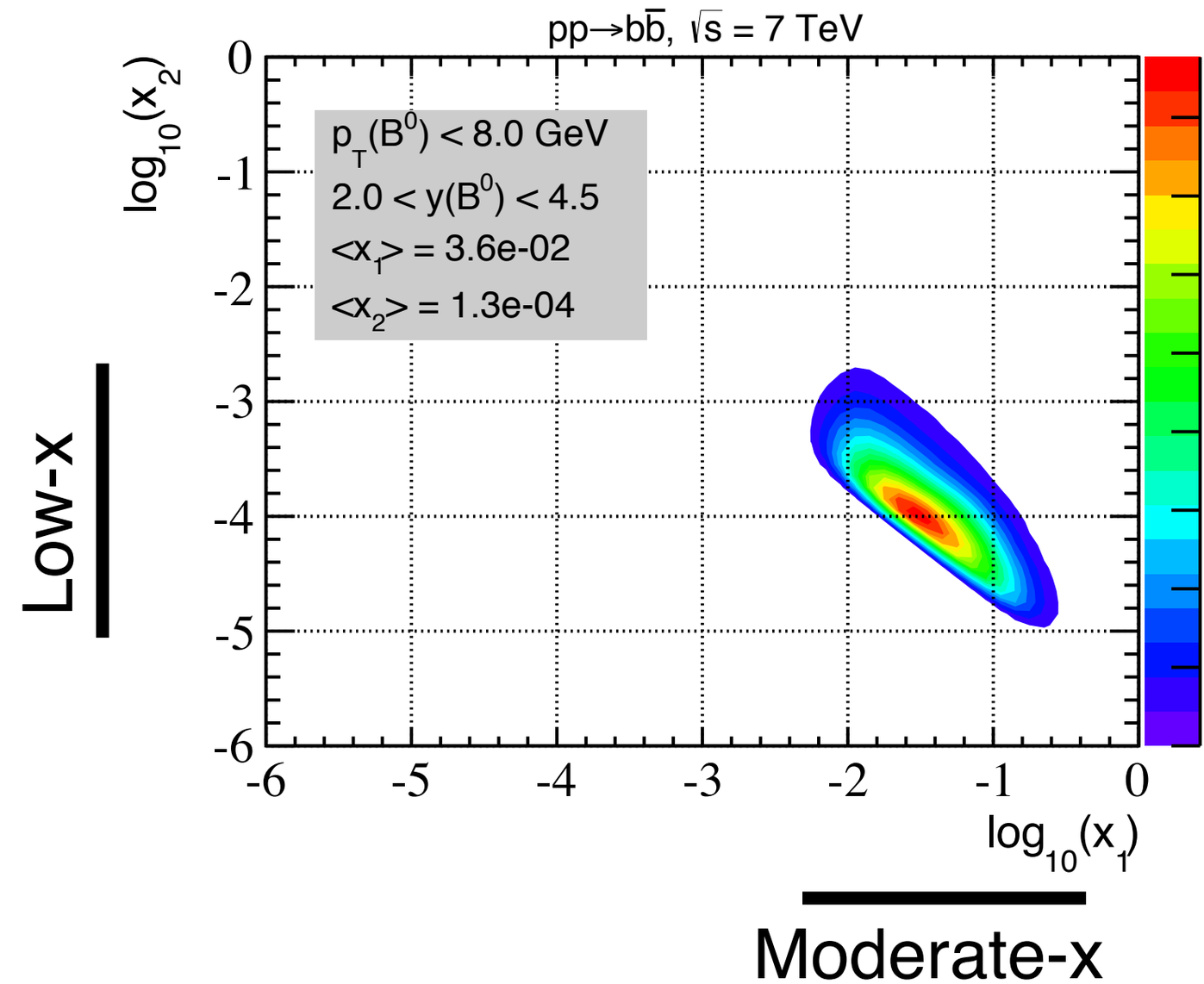
Forward top quark production discussed in:
hep-ex: LHCb - arXiv:1506.00903
hep-ph: Kagan et al. - arXiv:1103.3747, RG - arXiv:1311.1810, arXiv:1409.8631

$pp \to b\bar{b}$

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

Require one of the B hadrons within LHCb acceptance:

$$2.0 < y(B) < 4.5$$
$$0 < p_T(B)[\mathrm{GeV}] < 8$$
$$m_b = 4.75\ \mathrm{GeV}$$



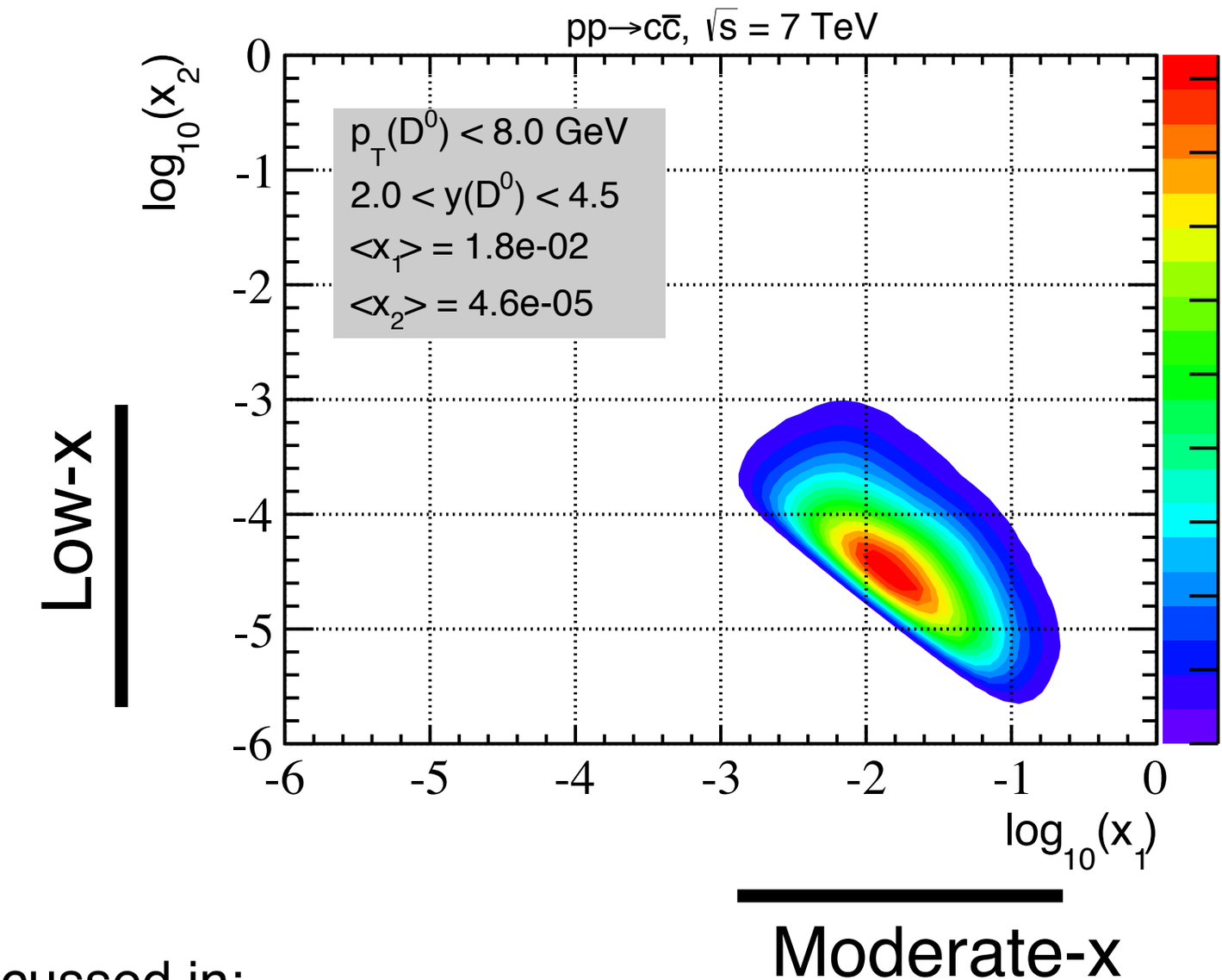
Forward beauty quark production discussed in:
hep-ex: LHCb B measurement (7 TeV) - arXiv:1306.3663
hep-ph: Cacciari et al. - arXiv 1205.6344, PROSA - arXiv:1503.04581

$pp \to c\bar{c}$

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

Require one of the D hadrons within LHCb acceptance:

$$2.0 < y(D) < 4.5$$
$$0 < p_T(D)[\mathrm{GeV}] < 8$$
$$m_c = 1.5\ \mathrm{GeV}$$

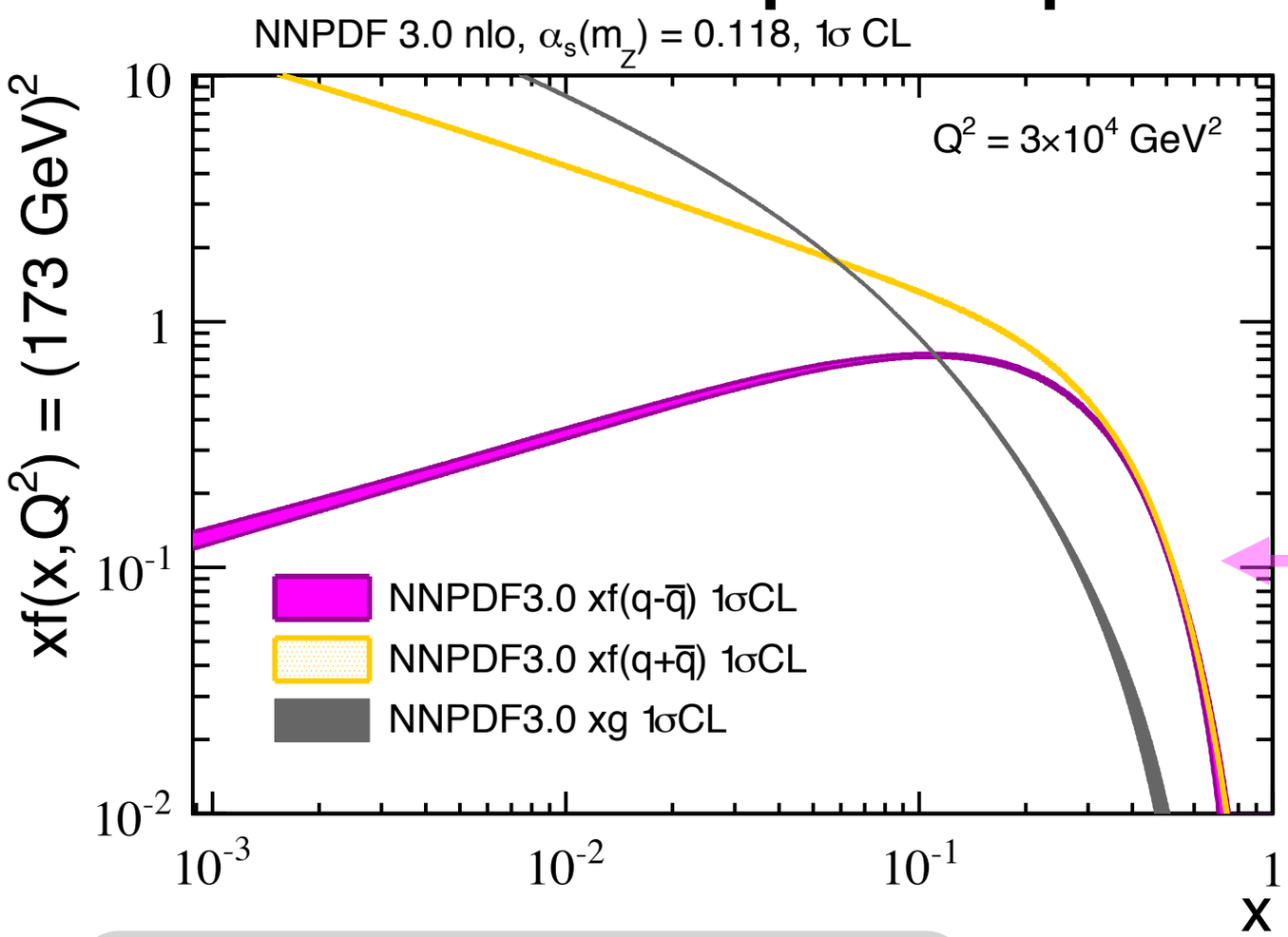


Forward charm quark production discussed in:
hep-ex: LHCb measurement (7/13 TeV) - arXiv:1302.2864 / 1510.01707
hep-ph: Kniehl et al. - arXiv:1202.0439, Cacciari et al. - arXiv 1205.6344, PROSA - arXiv:1503.04581, Gauld et al. - arXiv 1506.08025, Cacciari et al. - arXiv:1507.06197

Heavy quark pair observables:

c/b/t-pairs

b/c-quark pair asymmetry

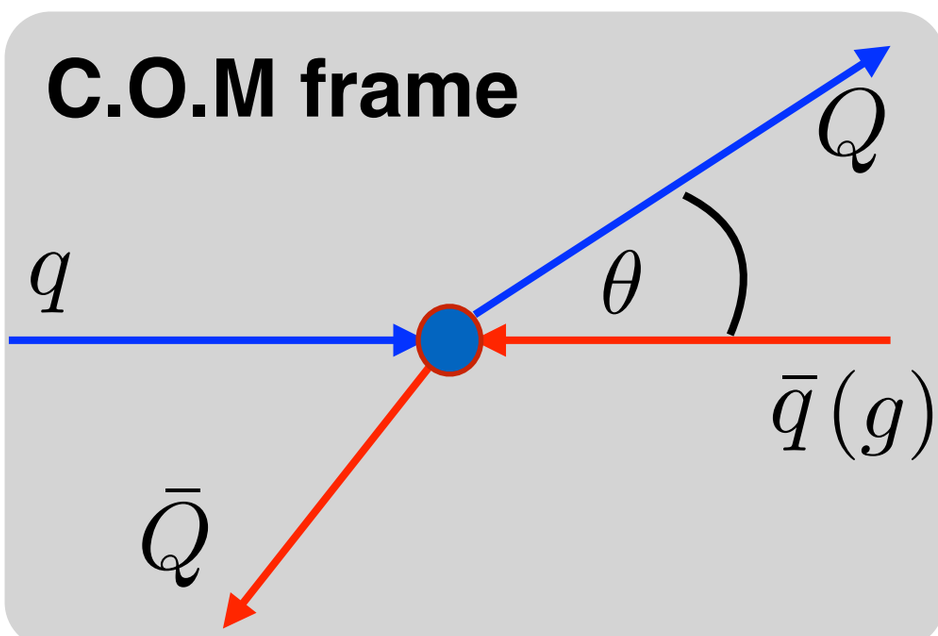


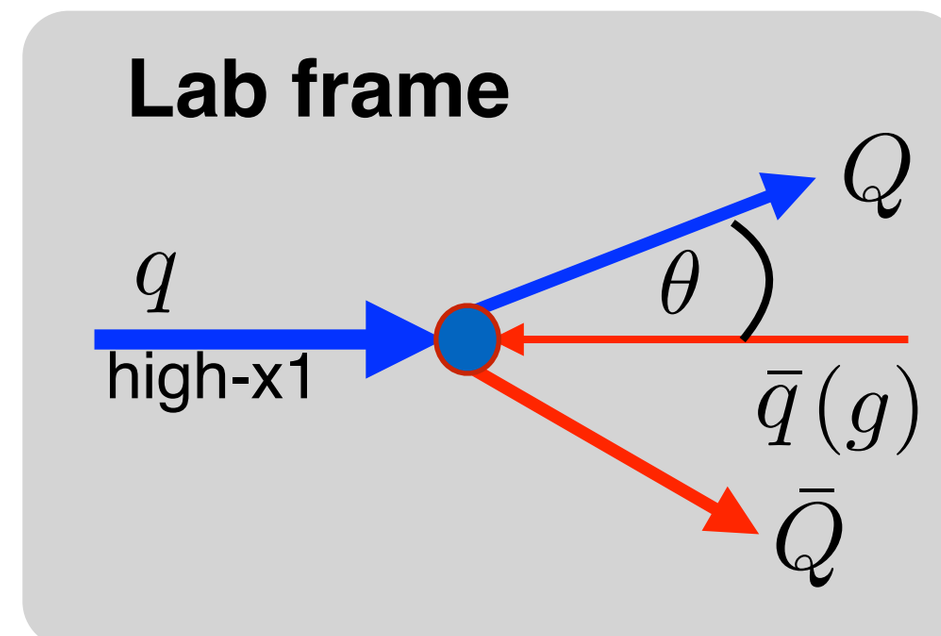
$gg \to X$ symmetric

$q\bar{q} \to X \quad f_q(x,Q) \neq f_{\bar{q}}(x,Q)$

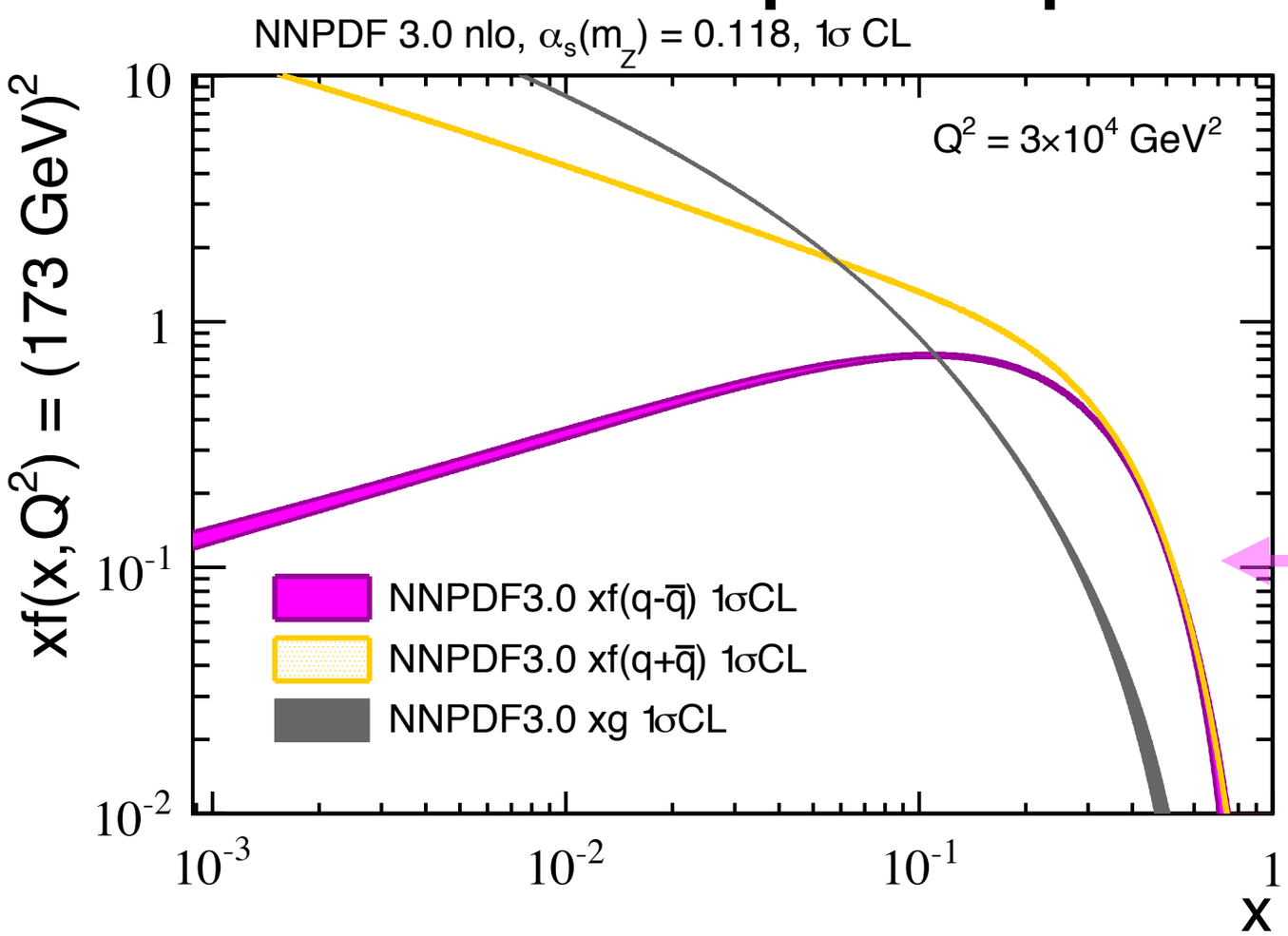
Large-x

- quark asymmetry large
- gluon dilution small





b/c-quark pair asymmetry



$gg \to X$ symmetric

$q\bar{q} \to X \quad f_q(x,Q) \neq f_{\bar{q}}(x,Q)$

Large-x

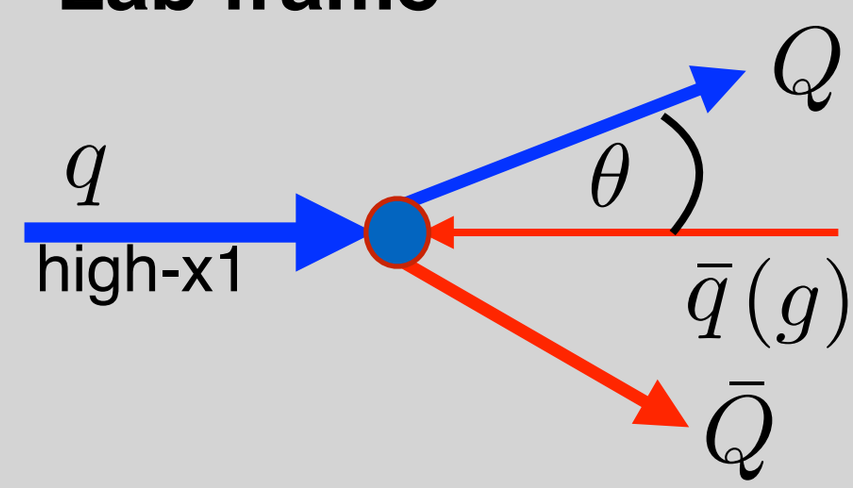
- quark asymmetry large
- gluon dilution small

Requiring MQQ cut such as:

$$m_{Q\bar{Q}} > 100\ \mathrm{GeV}$$

Pushes into high x1 region

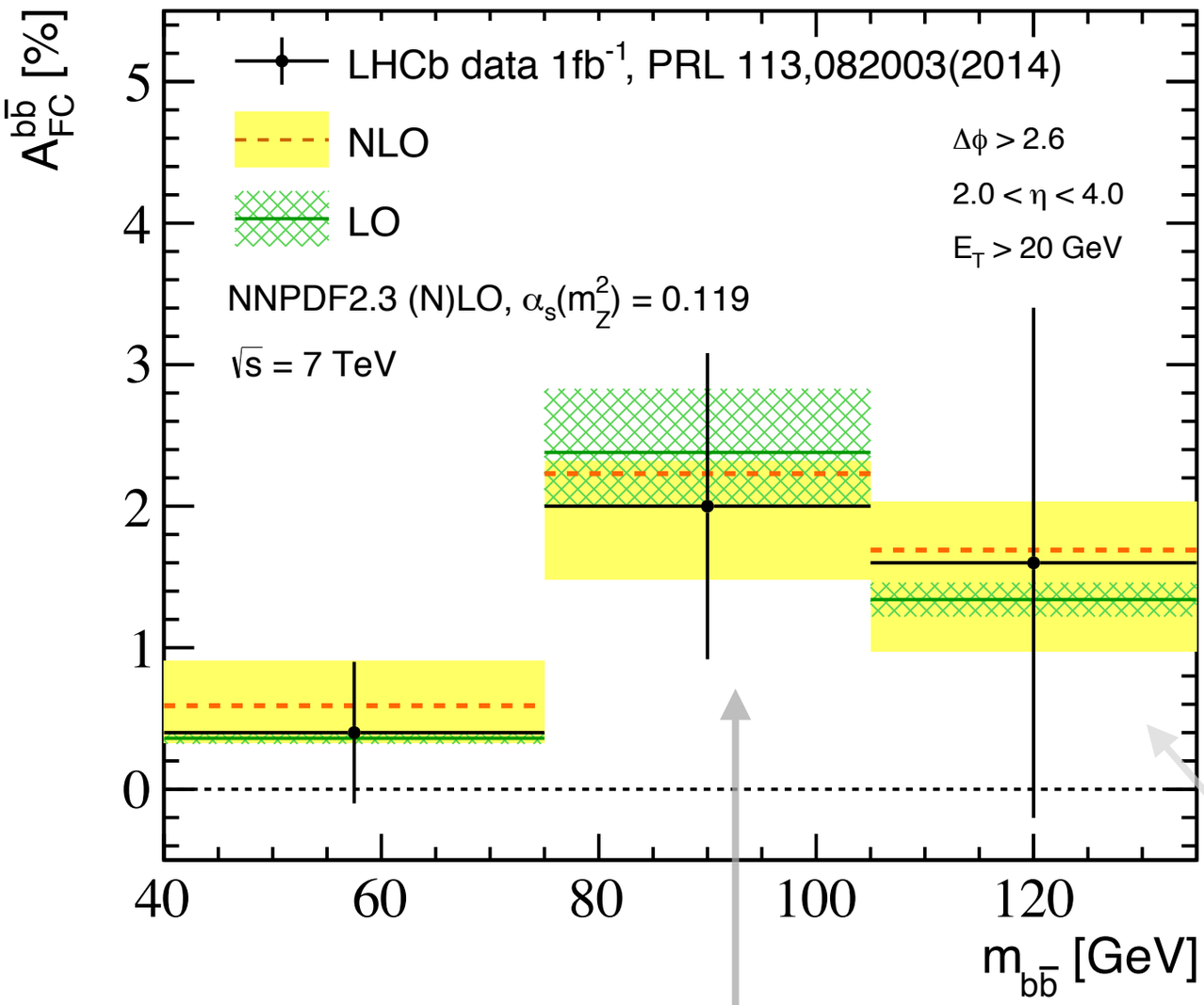
Lab frame



b-quark pair asymmetry (present)

RG, Ulrich Haisch, Ben D. Pecjak, Emanuele Re, arXiv: 1505.02429

see also Christopher Murphy arXiv:arXiv:1504.02493 (and Chris's talk)

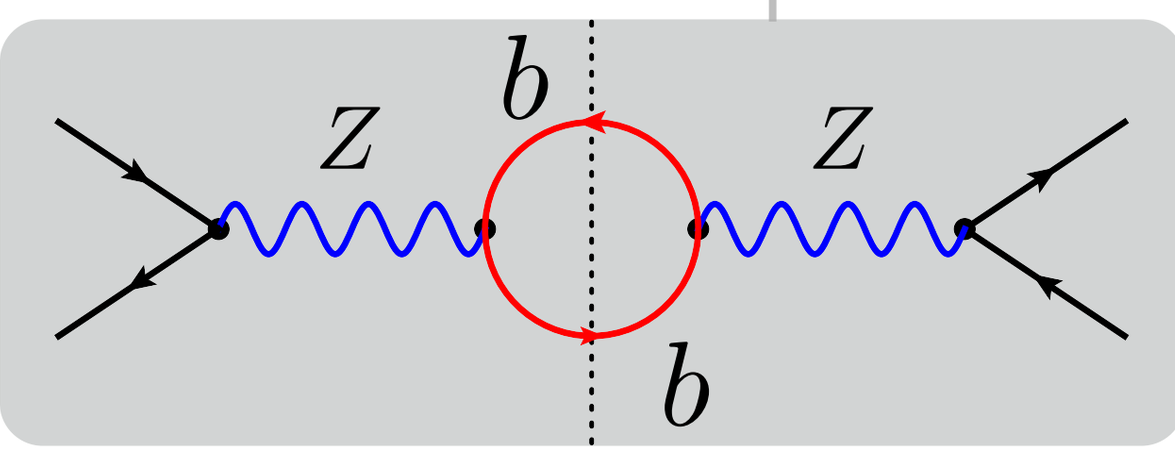


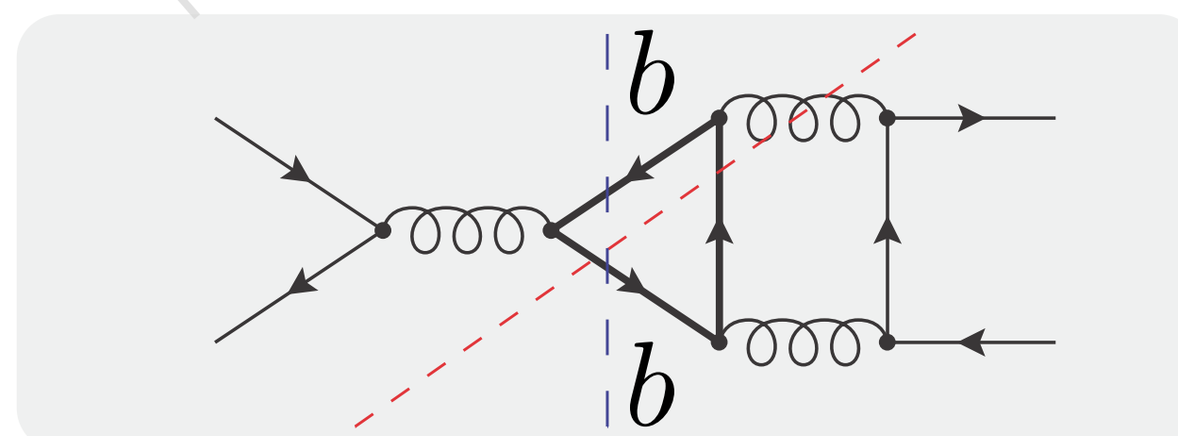
LHCb 7 TeV data - arXiv: 1406.4789

$$b_1 = 0.4 \pm 0.4(\text{stat.}) \pm 0.3(\text{sys.})\%$$

$$b_2 = 2.0 \pm 0.9(\text{stat.}) \pm 0.6(\text{sys.})\%$$

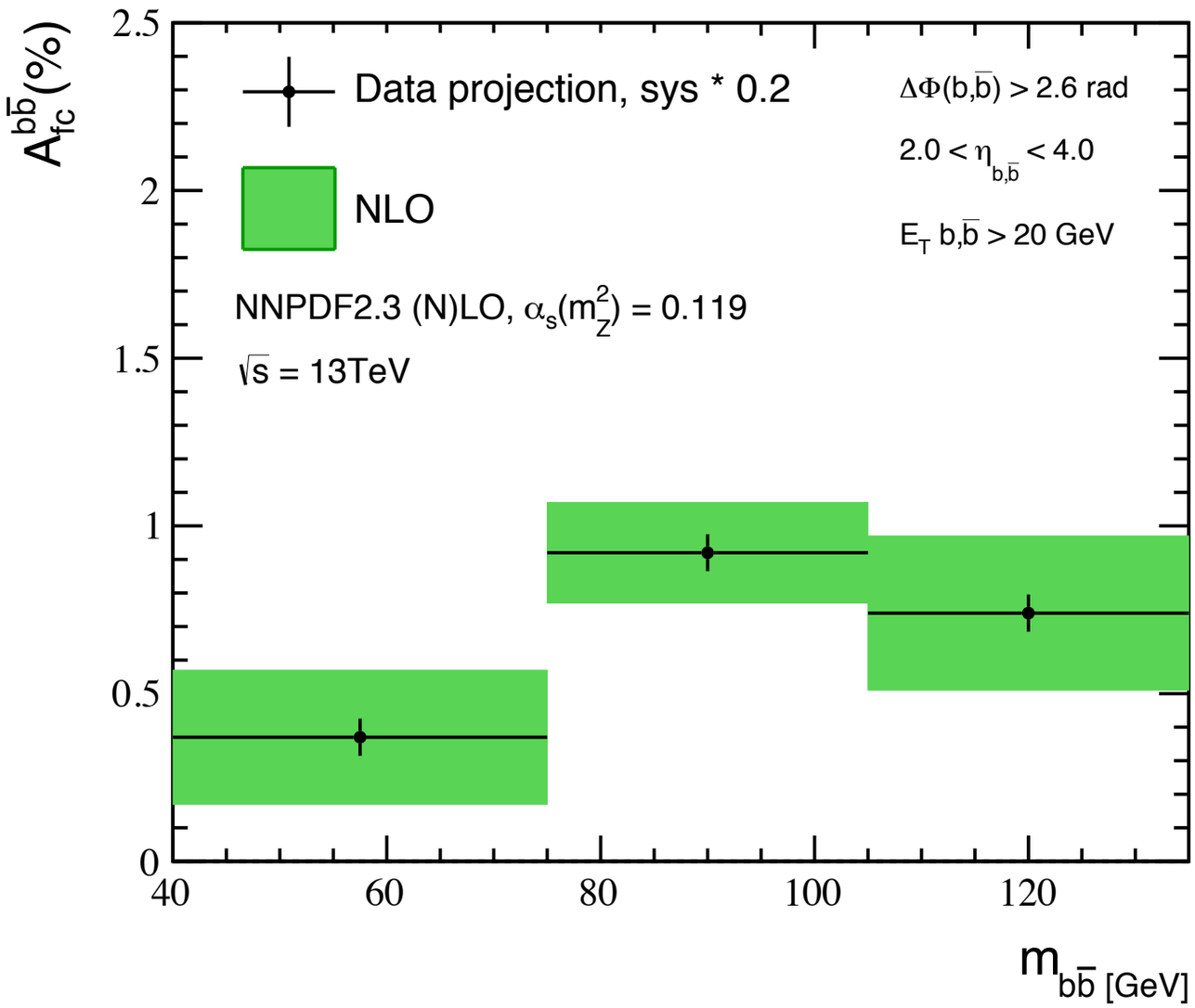
$$b_3 = 1.6 \pm 1.7(\text{stat.}) \pm 0.6(\text{sys.})\%$$

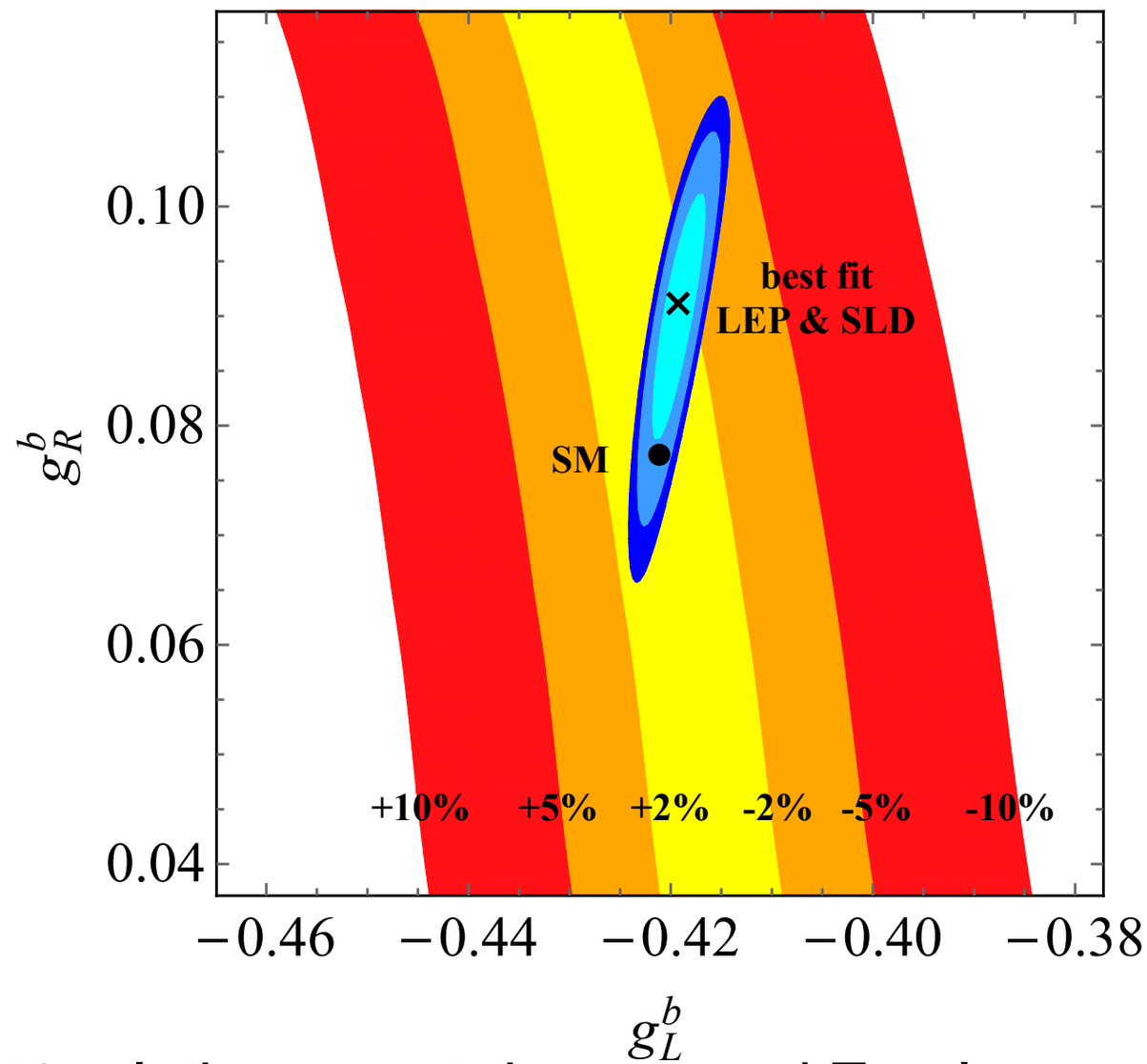




b-quark pair asymmetry (future)

RG and Haisch, unpublished





- 5x Improvement in systematic = 6% relative uncertainty around Z-pole
- Start to probe sensitivity of 'anomalous' LEP measurements at~ 1-2%
- Theory improvements necessary: NNLO QCD, mixed QCD-EW@NNLO

top-quark pair asymmetry
Czakon, Fielder, Mitov, arXiv: 1411.3007

both: $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s^3\alpha)$

t-quark pairs

Scenario 1 (Kagan,Kamenik,Perez,Stone - arXiv:1103.3747, RG - arXiv:1311.1810,1409.8631)

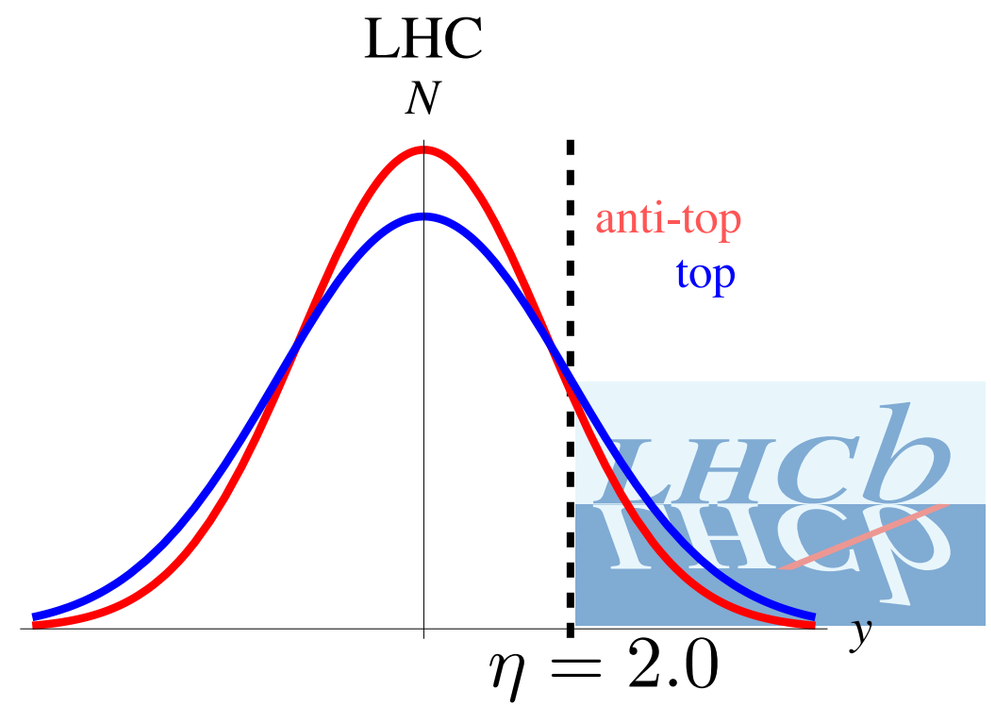
$$pp \to (t \to W^+ b)X \qquad vs \qquad pp \to (\bar{t} \to W^- b)X$$

- Count rate of top vs antitop
- Large stats (several 100k's)**

$$pp \to l^{\pm} b - \mathrm{jet} X$$

- Large asymmetric backgrounds

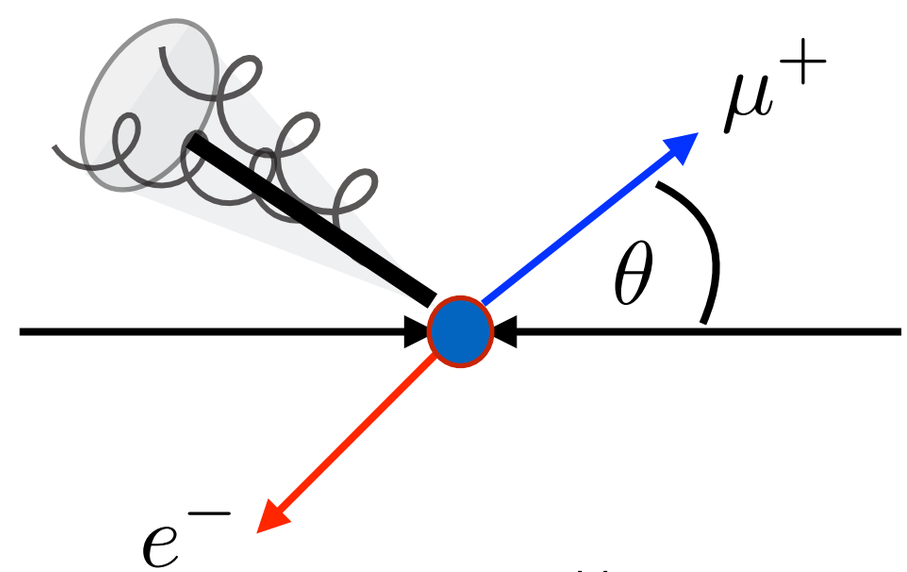
$$\{Wj\,, Wb\bar{b}\,, \mathrm{ST} - tch\}$$



Scenario 2 (RG: arXiv:1409.8631)

$$pp \to \mu^{\pm} e^{\mp} b - \mathrm{jet} X$$

- Small stats (10k's)**
- Very clean signal



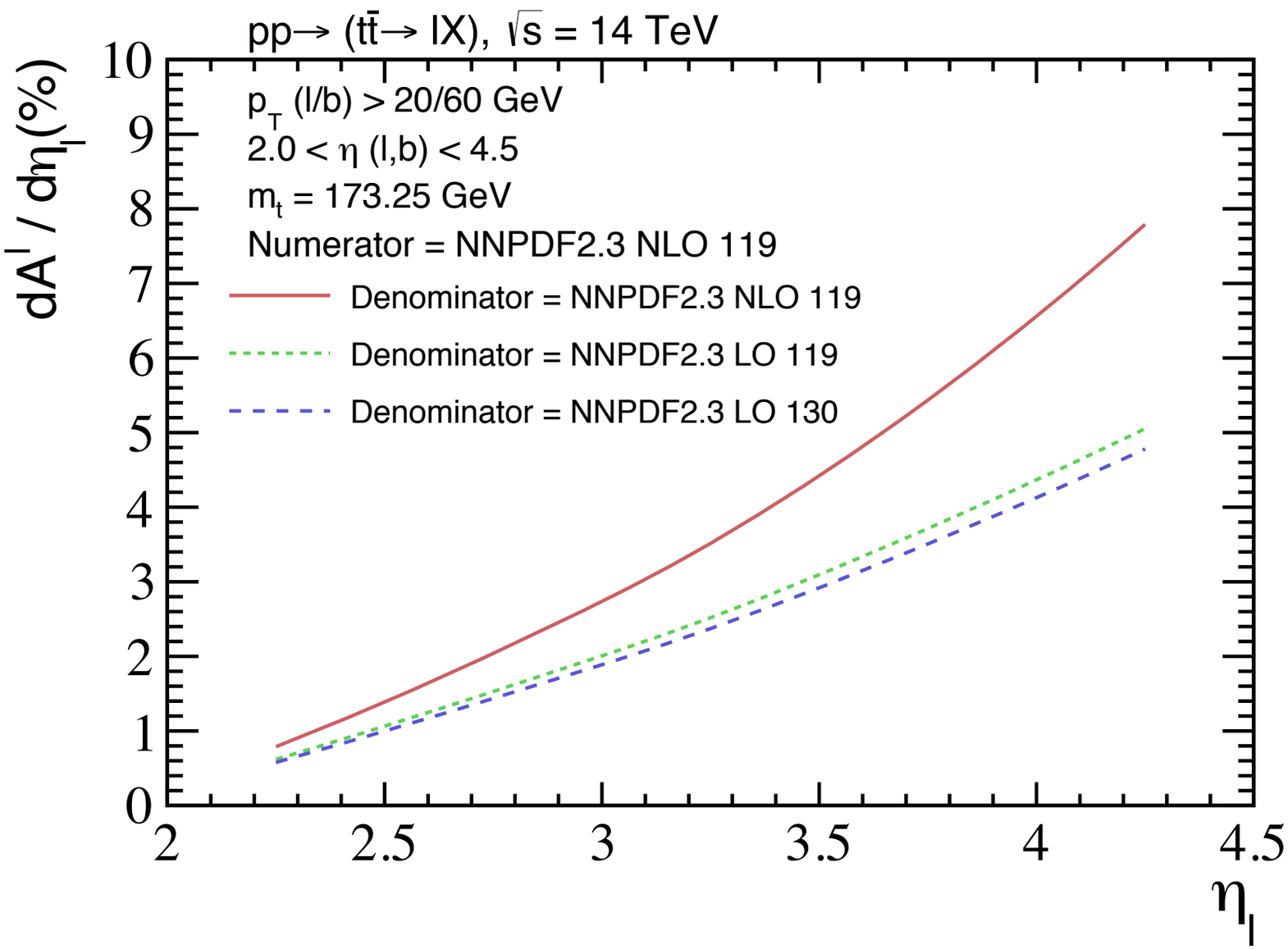
** Assume 300 ifb

t-quark pairs (scenario 1)

Scenario 1 (Kagan,Kamenik,Perez,Stone - arXiv:1103.3747, RG - arXiv:1311.1810,1409.8631)

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

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



- Stats not an issue

$$\mathcal{O}(10^5) \text{ events}$$

- Problem is controlling backgrounds

t-quark pairs (scenario 1)

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$$> 20/60 \text{ GeV}$$

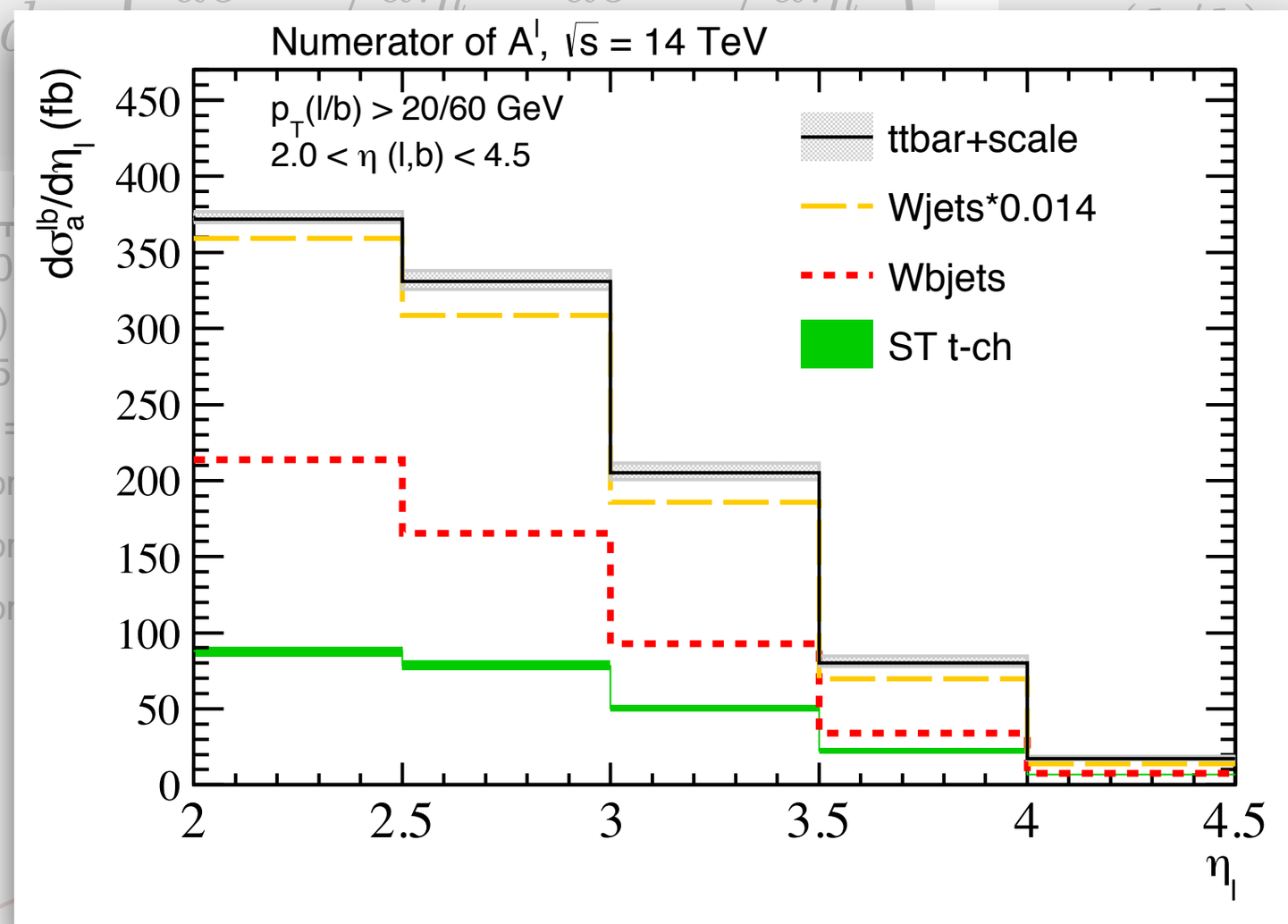
$$, \text{jet}) \geq 0.5$$

not an issue

$$10^5) \text{ events}$$

em is controlling

rounds



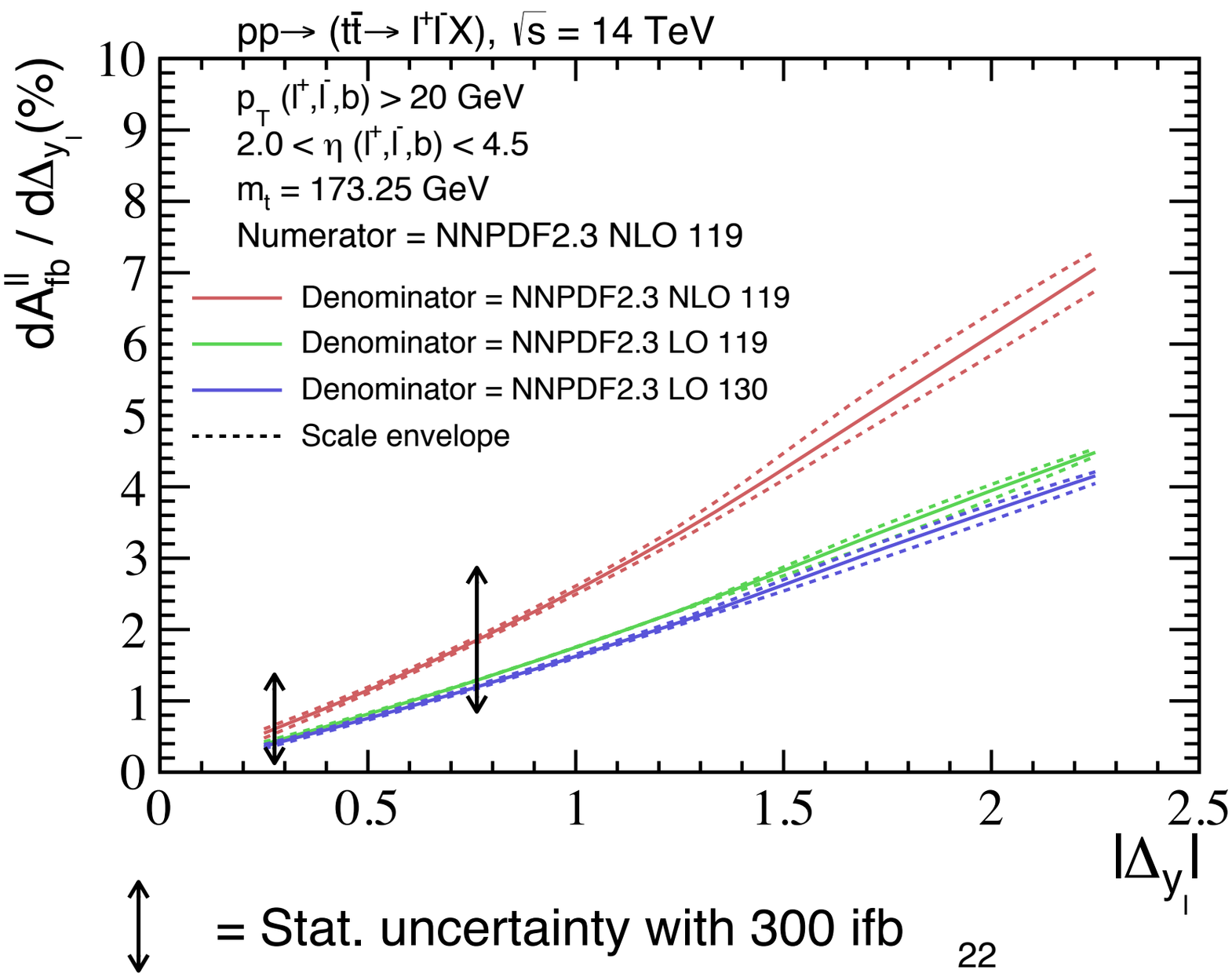
Multi channel fit to different (b)-jet multiplicity final states?

t-quark pairs (scenario 2)

Scenario 2 (RG: arXiv:1409.8631)

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

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



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

$$\delta A_{fb}^{ll} \simeq 0.5\%$$

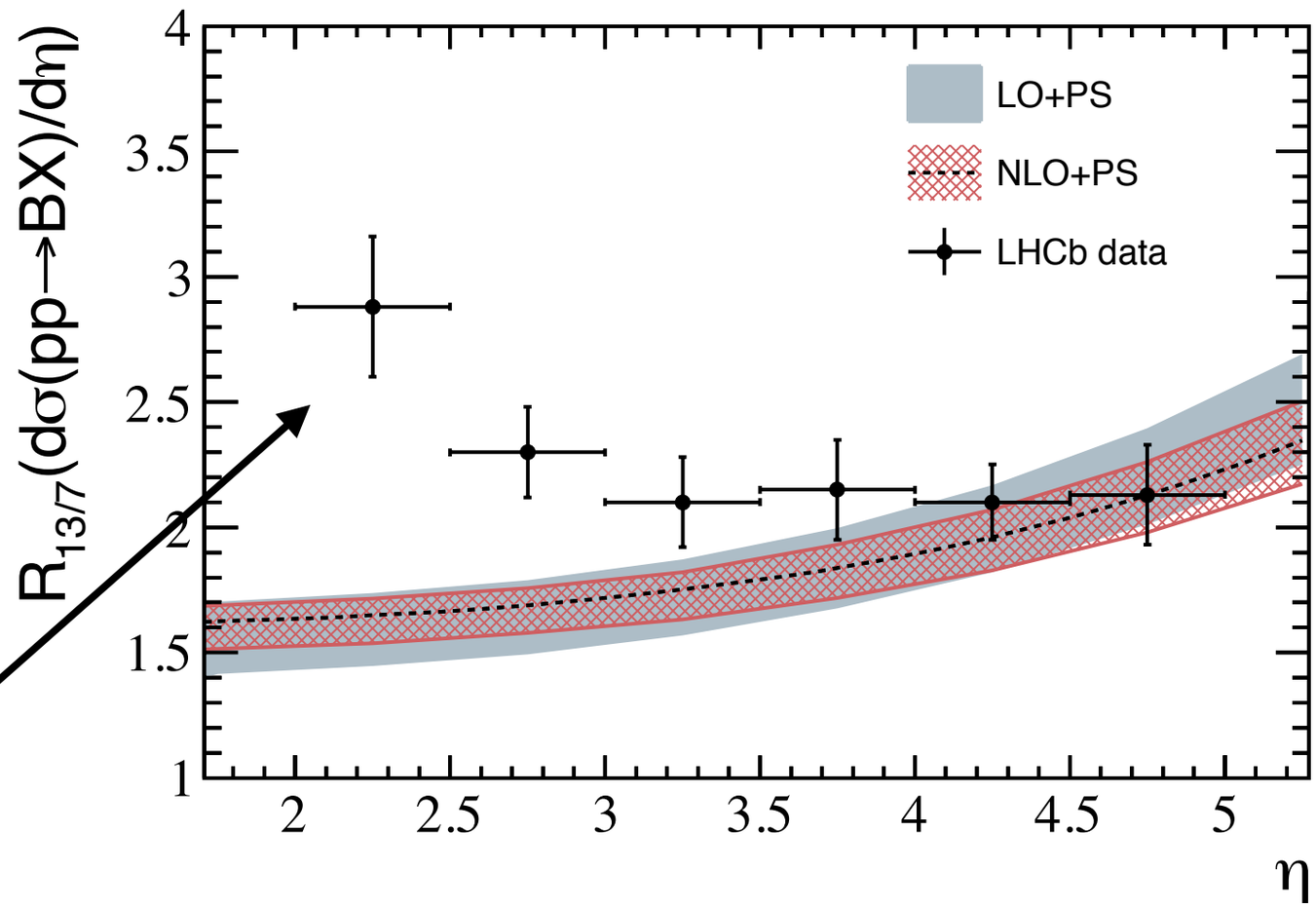
stat. 300 ifb

summary 1

- **c/b-jet pair cross section and asymmetries - 13/14 TeV**
  - ★Perform differentially in MQQ bins (Z-pole, and 100-150, 150-200 ,..etc.)
  - ★Also provide the symmetric cross section (not just asymmetry)!
  - ★Measurements of sigma_bb/sigma_cc at different working points
    - Important validation of jet flavour tagging > 100 GeV

- **top measurements - 13/14 TeV**
  - ★13 TeV: cross section measurement (lb,lbj,lbb, l+l-b,..etc.) feed into PDFs
  - ★13 TeV: precision measurement of forward rate of t vs tbar?
    - Probably challenging to fit multi-backgrounds (Wb,Wj,..etc.)
  - ★14 TeV: asymmetry measurement for l+l-b final state (stats limited)

Anomalies in inclusive B production?



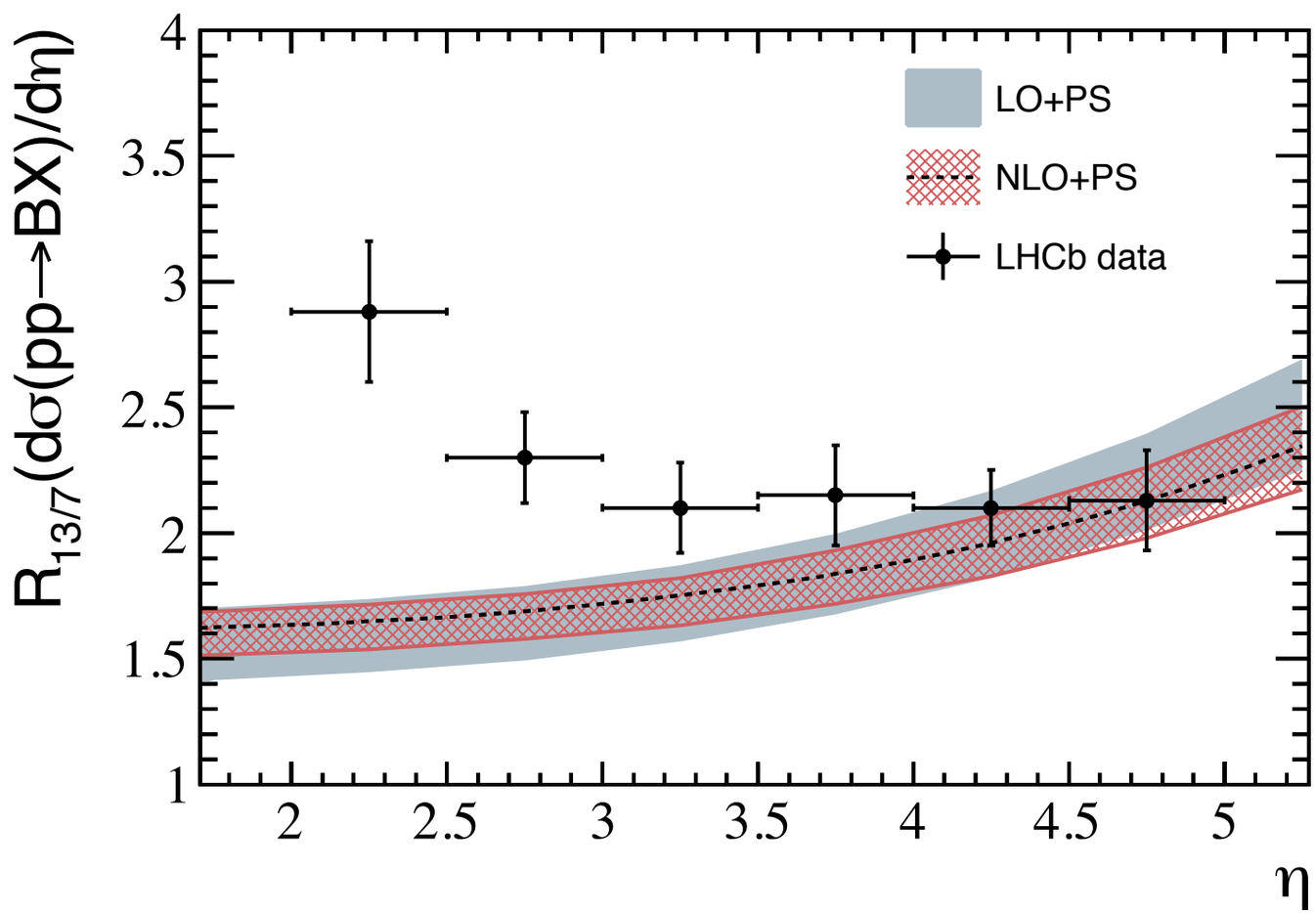
My guess of data

LHCb-Paper-201(6?)-013 - Preliminary

$b \to sll =$ Old News

Anomalies in inclusive B production?

$\hat{P}$



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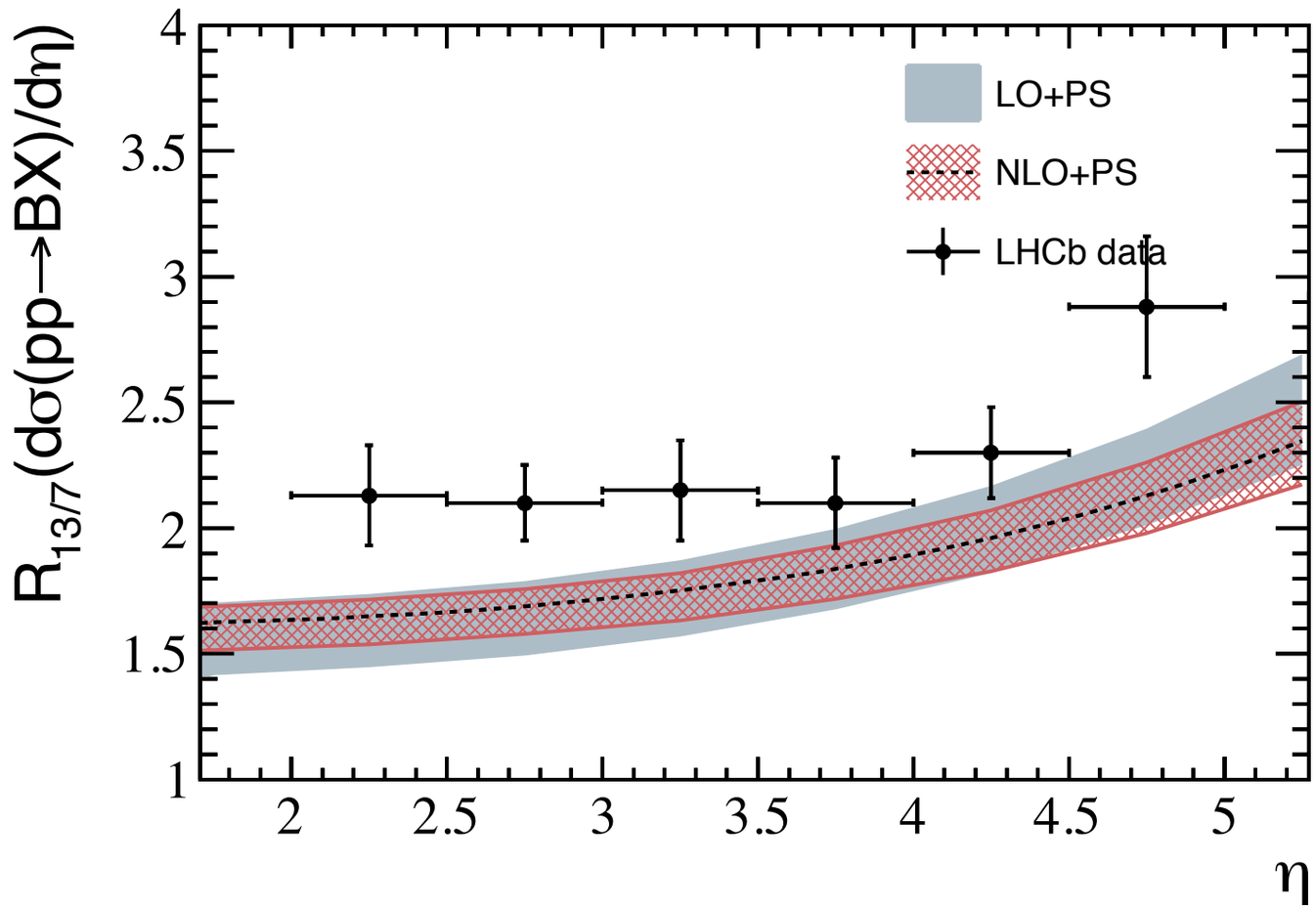
Anomalies in inclusive B production?

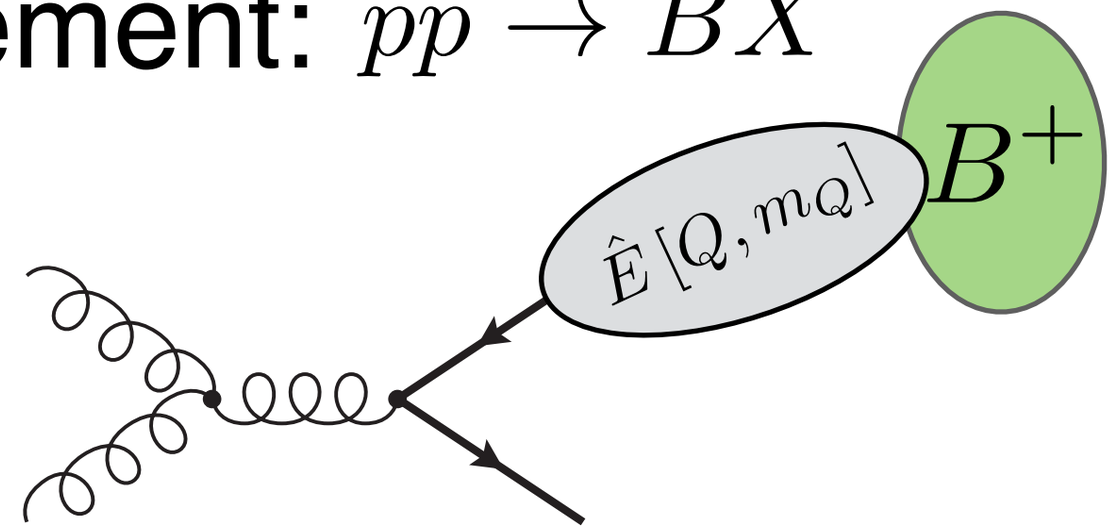


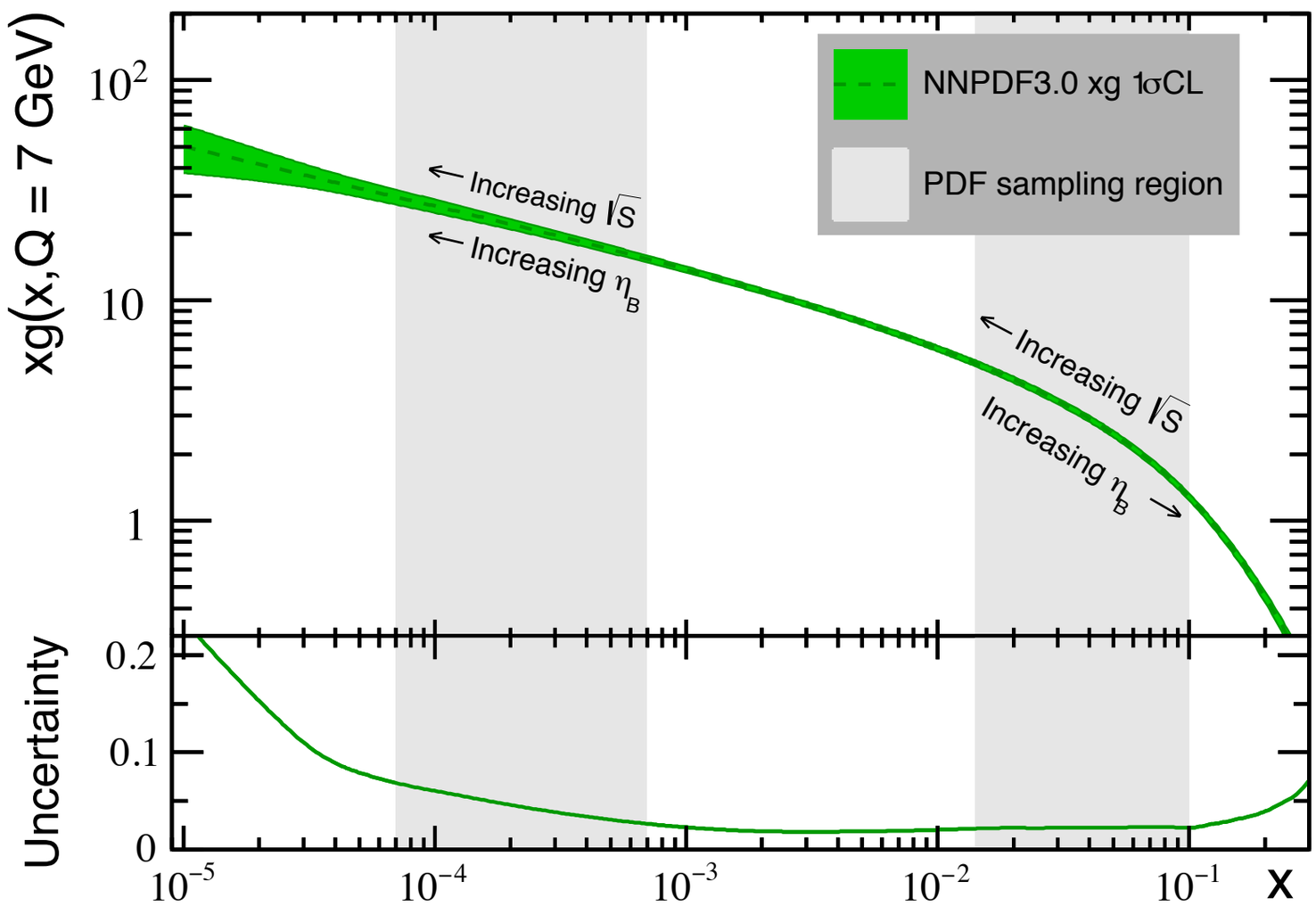
LHCb-Paper-201(6?)-013 - Preliminary

$b \to sll =$ Old News

Inclusive measurement: $pp \to BX$

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



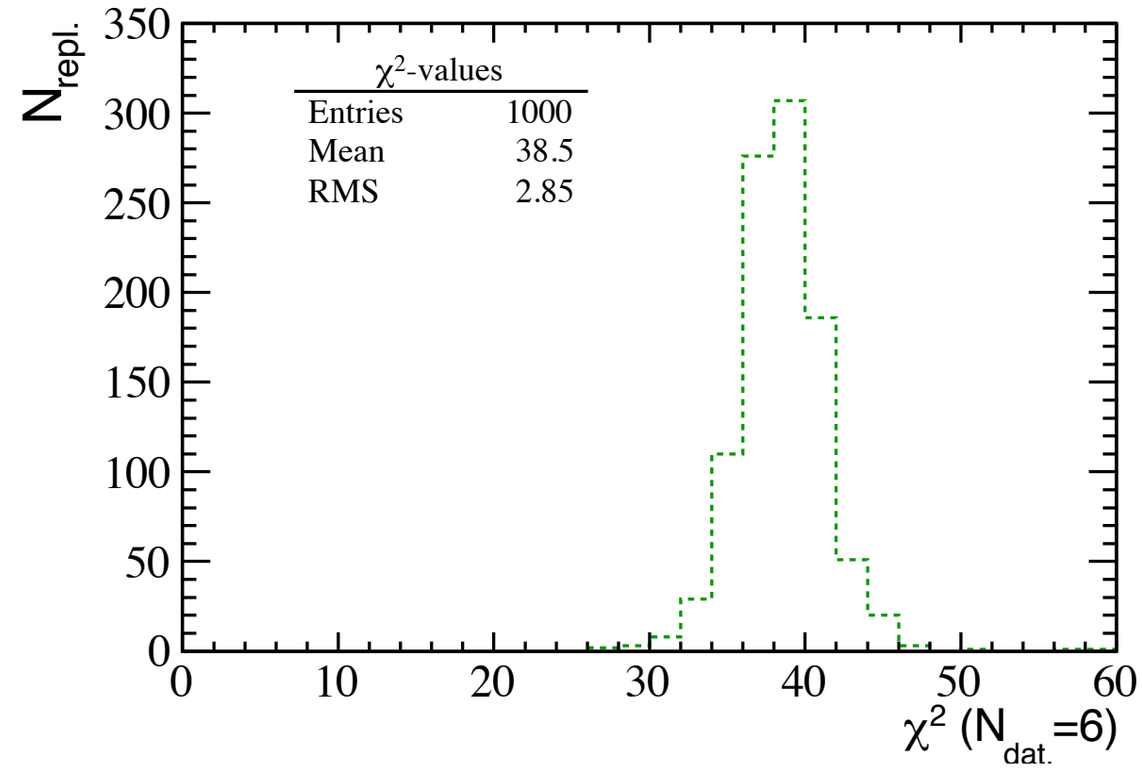


Impact of this data on input PDFs?

$$\chi^2/N_{\rm dat} = 39/6$$

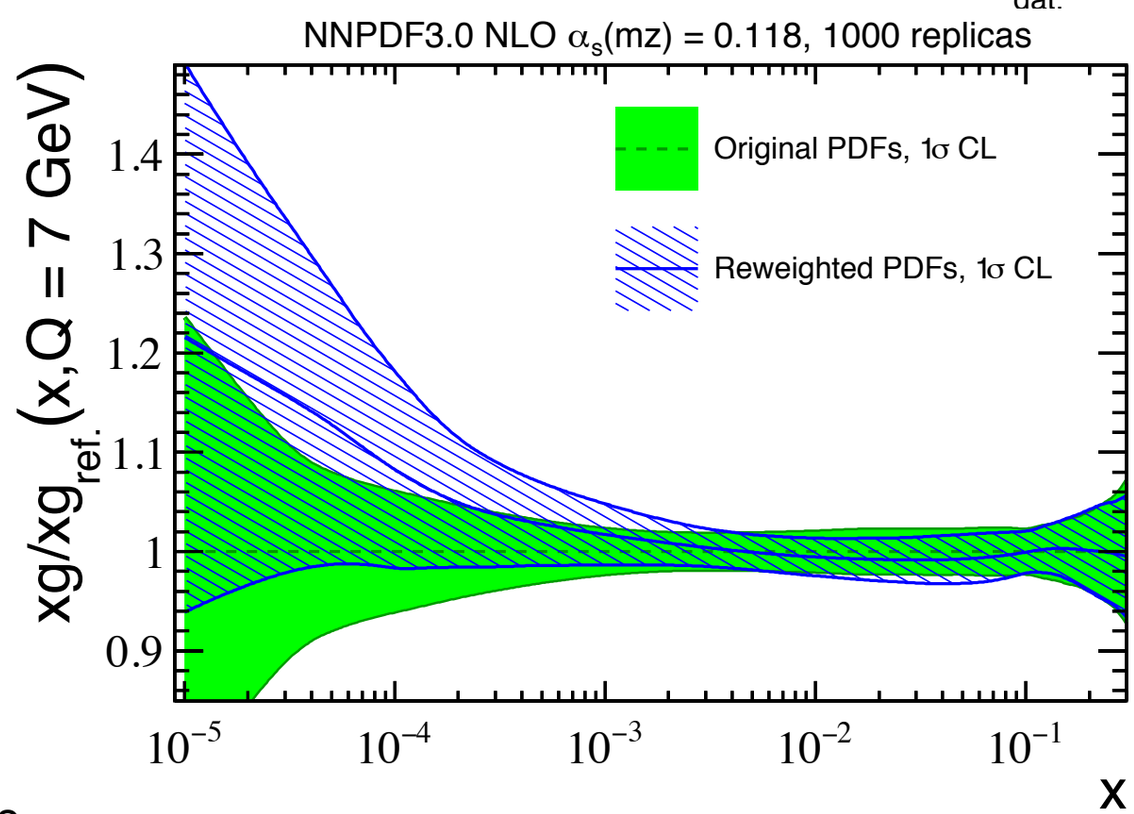
Fit to data very poor.

Tried fitting with 1000 replica input PDF set



Impact on PDFs actually rather small

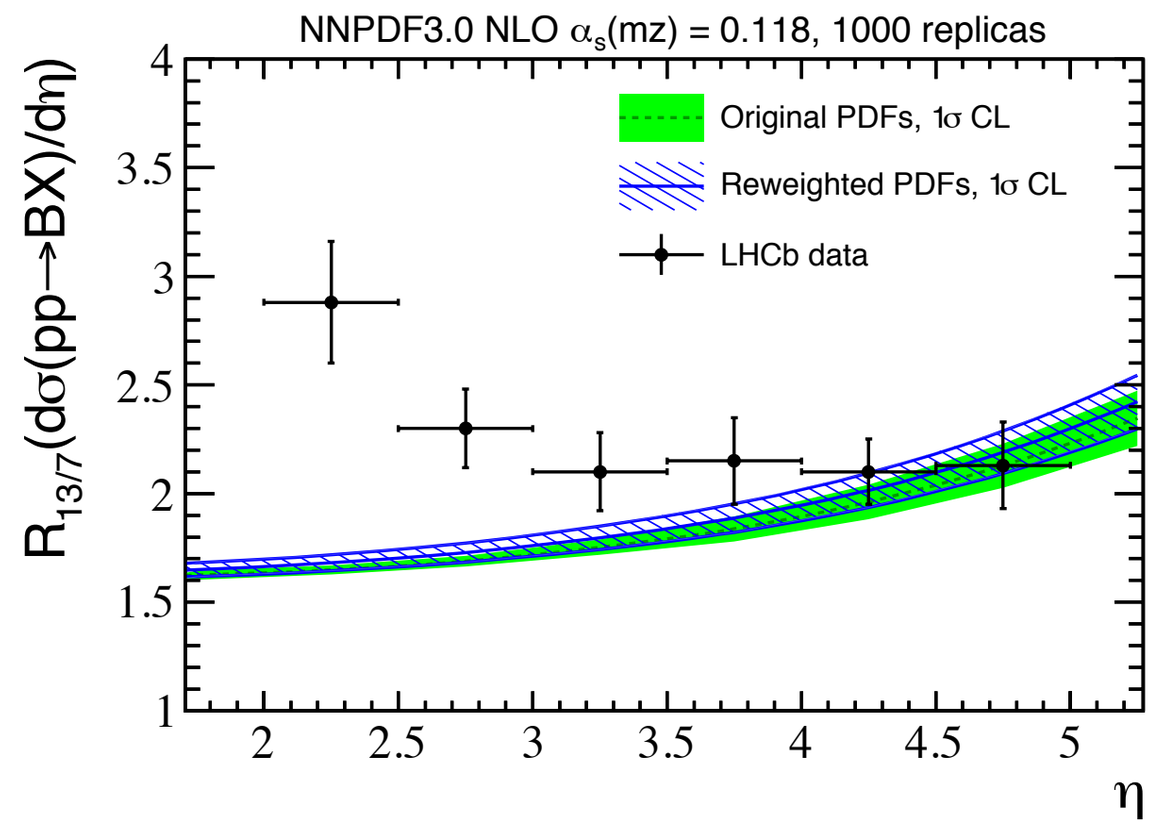
Low-x data already constrained by low-Q2 low-x HERA Charm data



Impact of this data on input PDFs?

Predictions containing the information from B ratio

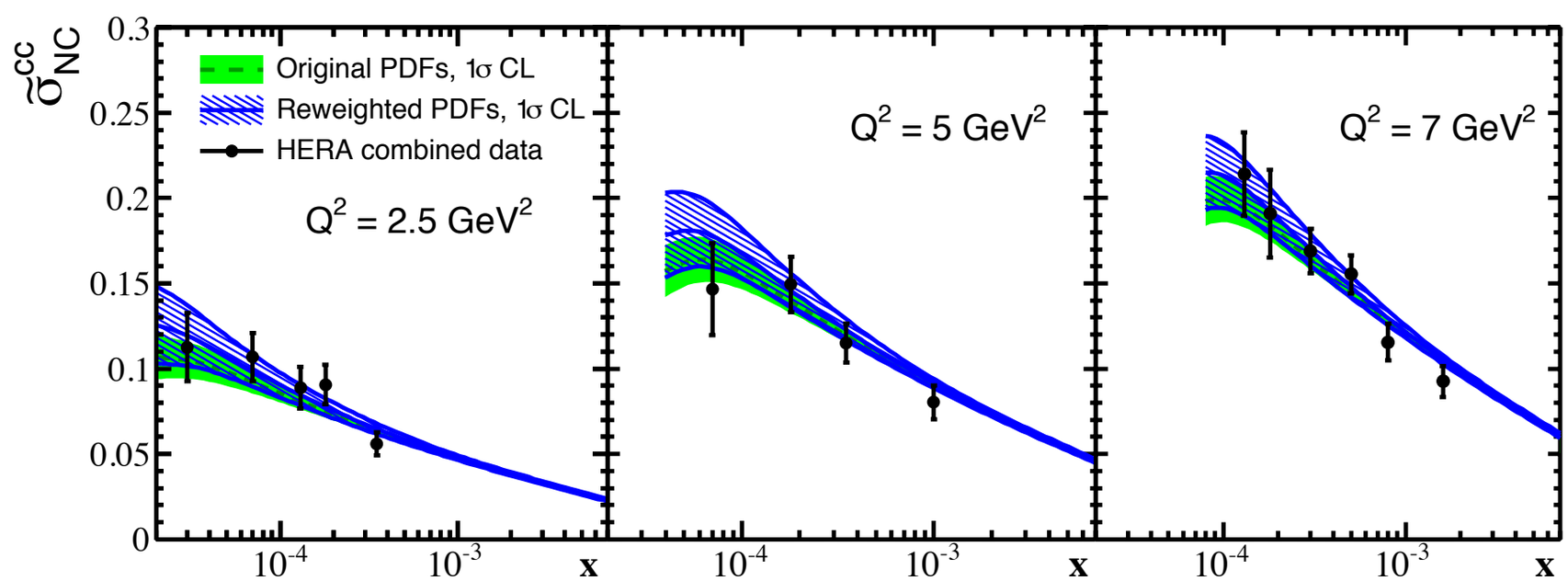
Small shift in right direction



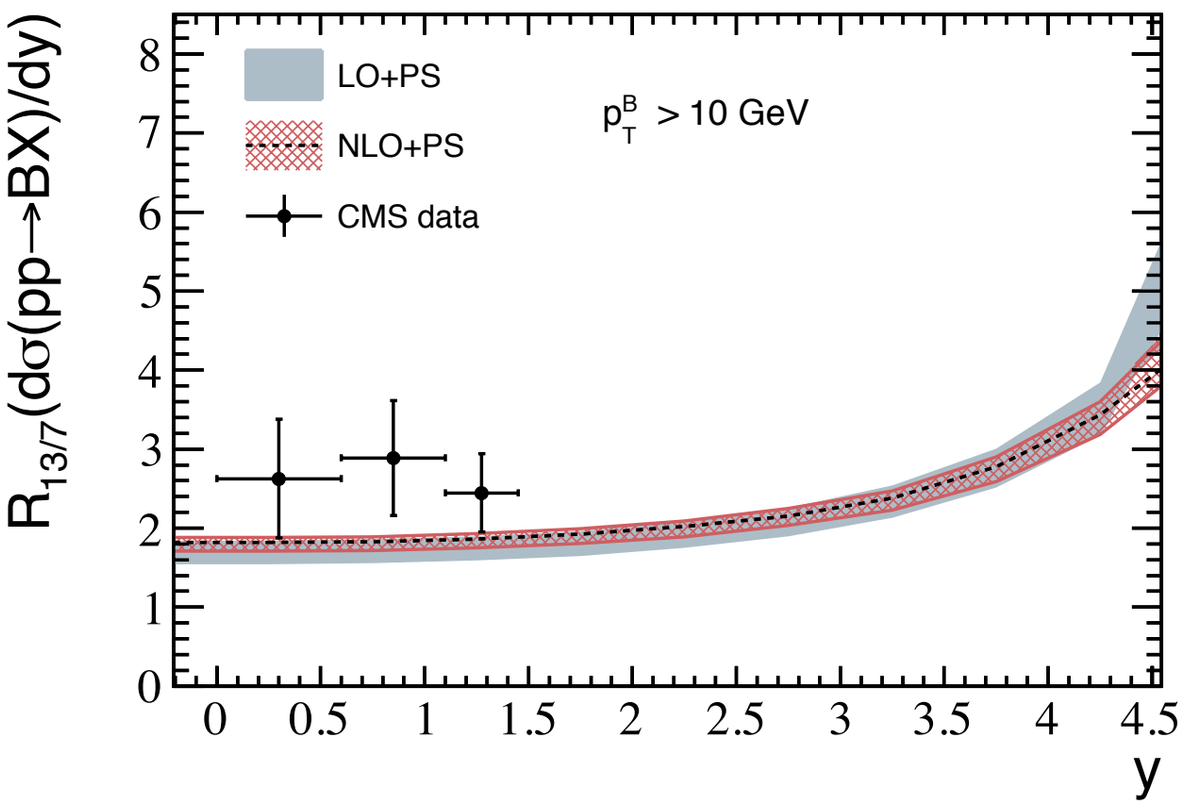
Reduced cross section

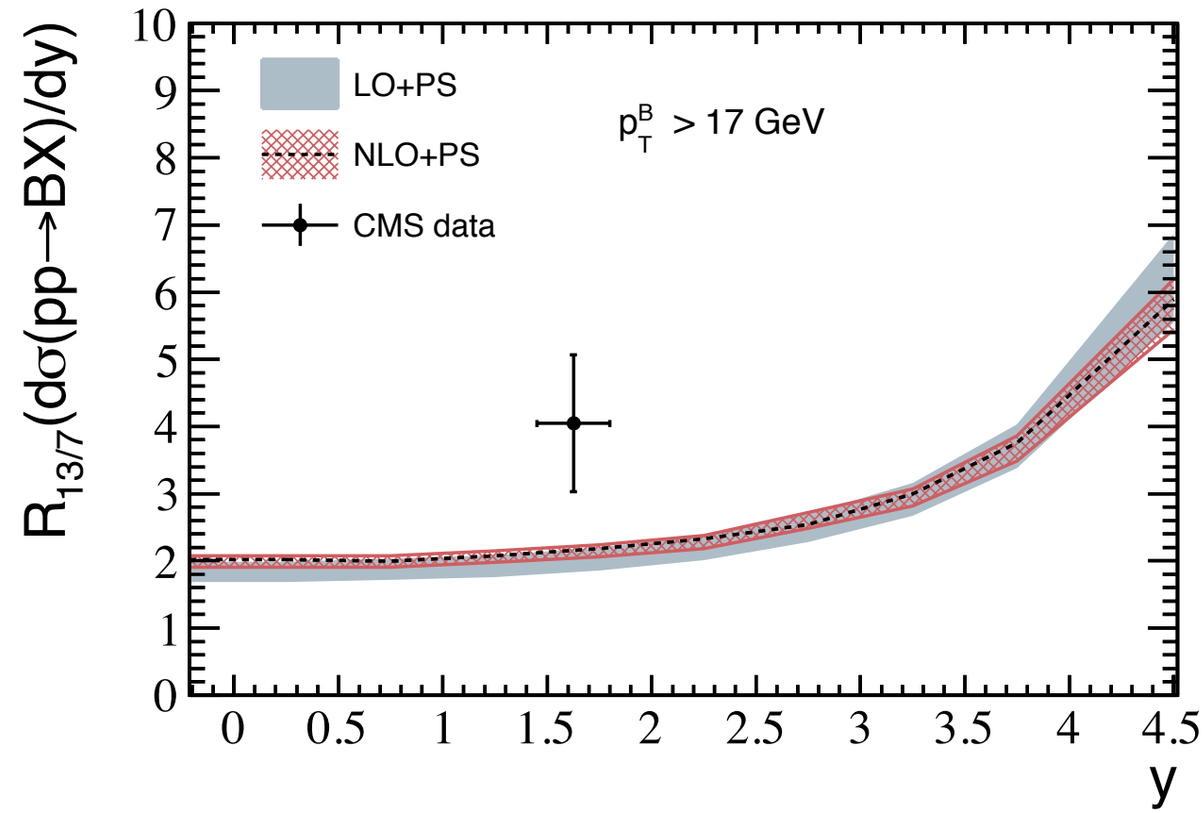
Constraining Charm data from HERA

arXiv: 1211.1182



Comparison with CMS data



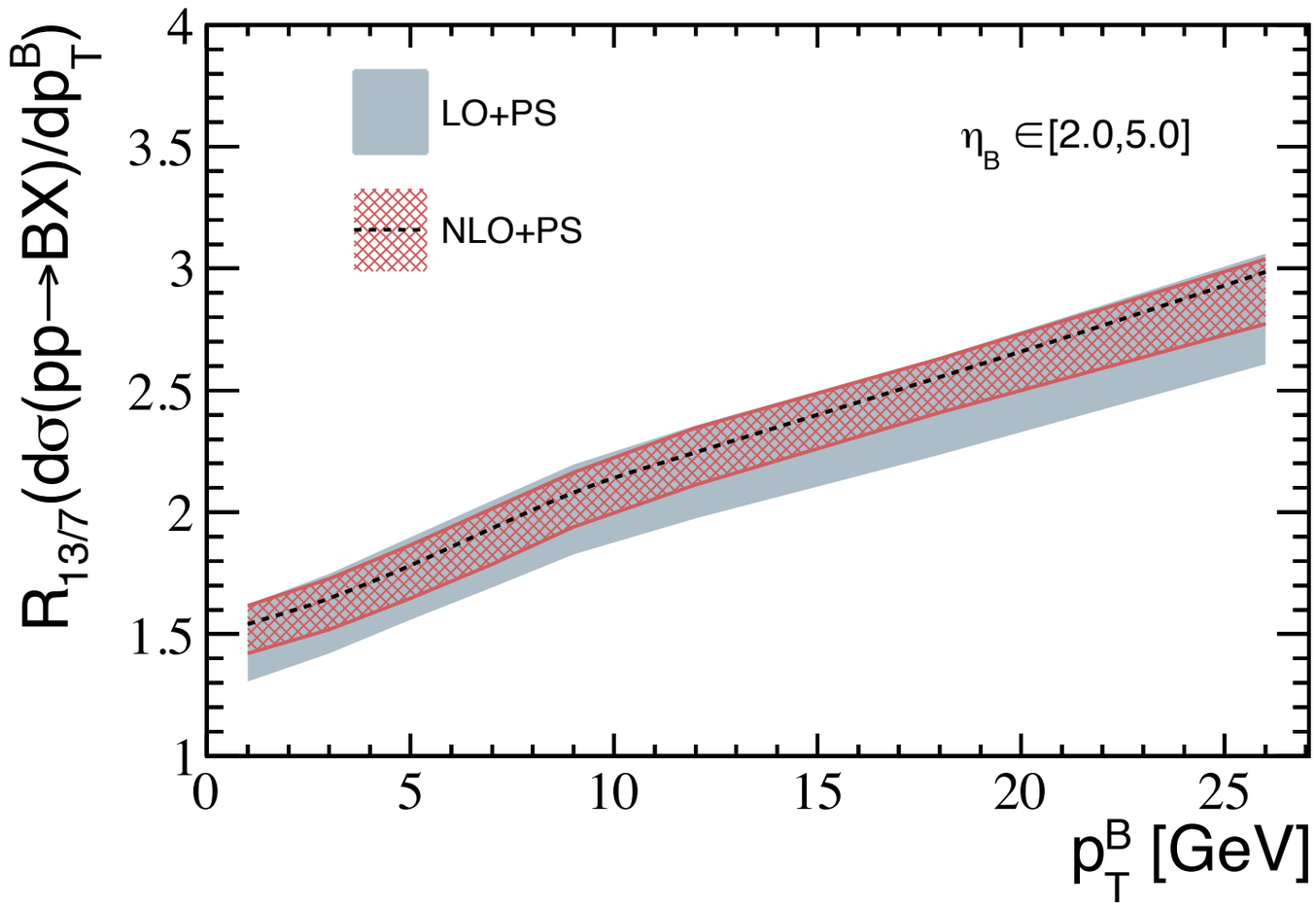


Extract ratio from CMS measurement arXiv: 1609.00873

Big difference: minimum pT cut, lower rapidity

Could perform similar measurements in LHCb acceptance

Differentially in p_T



Already have enough stats for this measurement

summary 2

- **c/b-jet pair cross section and asymmetries - 13/14 TeV**
  - ★Perform differentially in MQQ bins (Z-pole, and 100-150, 150-200 ,..etc.)
  - ★Also provide the symmetric cross section (not just asymmetry)!
  - ★Measurements of sigma_bb/sigma_cc at different working points
    - Important validation of jet flavour tagging > 100 GeV

- **top measurements - 13/14 TeV**
  - ★13 TeV: cross section measurement (lb,lbj,lbb, l+l-b,..etc.) feed into PDFs
  - ★13 TeV: precision measurement of forward rate of t vs tbar?
    - Probably challenging to fit multi-backgrounds (Wb,Wj,..etc.)
  - ★14 TeV: asymmetry measurement for l+l-b final state (stats limited)

- **Inclusive B production**
  - ★Could perform ratio differentially in pT, or with cuts to compare to CMS
  - ★Include bin-by-bin correlations, and can compute normalised cross section