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Heavy flavour production

Matteo Cacciari
LPTHE - Paris 6,7 and CNRS

Foreword

- Many elements of the theory of heavy flavour production are 20+ years old (and from the past century)
  - NLO corrections (rates) from the end of the Eighties
  - NLL resummation (inclusive distributions at large transverse momentum) from the mid-Nineties

- This is finally about to change
  - NNLO calculation completed recently
    - Only available for top total cross section for the time being
    - Differential distributions are work in progress
    - Application to charm and bottom should then become straightforward

Outline

- **Production of Charm, Bottom, Top**

  Selected topics from all three heavy quarks

- **Theoretical state of the art**

  What do we know?

  - pQCD provides normalisations and rates for bare heavy quarks
  - Branching fractions, electroweak decays and non-perturbative information are taken from data

  - **Tools**

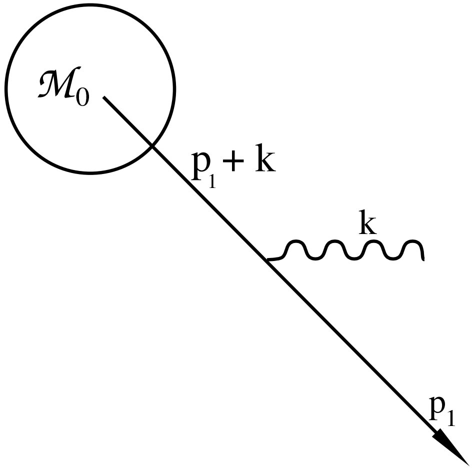
    How are predictions implemented? What can we run to calculate them?
    Appearance of automated NLO tools with matching to exclusive MC

- **Theory-Experiment comparisons**

  (mainly with recent measurements from LHC)

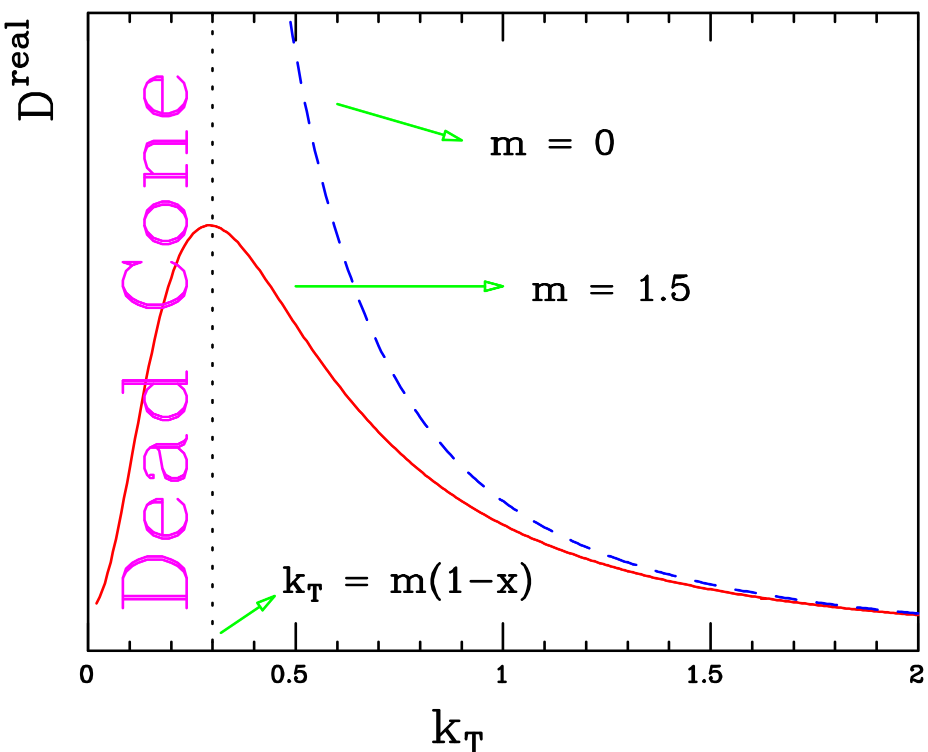
Heavy flavours are special

- Experimentally
  - Taggable (e.g. displaced vertices in decays)
- Theoretically
  - (Partially) calculable ($m > \Lambda_{QCD}$)



Gluon emission off a heavy quark

$$D^{\rm real}(x,k_T^2,m^2) = \frac{C_F\alpha_s}{2\pi}\left[\frac{1+x^2}{1-x}\,\frac{1}{k_T^2+(1-x)^2m^2} - x(1-x)\,\frac{2m^2}{(k_T^2+(1-x)^2m^2)^2}\right]$$



Emission probability **not divergent** at small transverse momentum

Calculability in pQCD

Factorization theorem

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

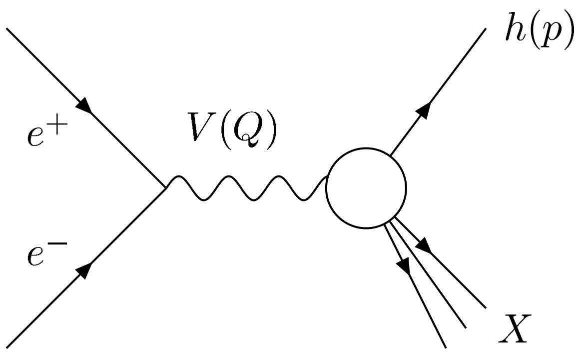
$$\sigma_Q(S,m^2) = \sum_{i,j\in L} \int dx_1 dx_2 \hat{\sigma}_{ij\to QX}(x_1x_2S, m^2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) F_{i/A}(x_1,\mu_F) F_{j/B}(x_2,\mu_F) + O\left(\frac{\Lambda}{m}\right)^p$$

Light flavours only

- Calculability in pQCD translates into:
  - power suppressed corrections to factorisation theorem for ***heavy quarks total cross sections***
  - possibility to define ***'perturbative' parton distribution functions for heavy quarks***, to be used ot resum certain classes of logarithms in the so-called 'n_{lf}+1 schemes'

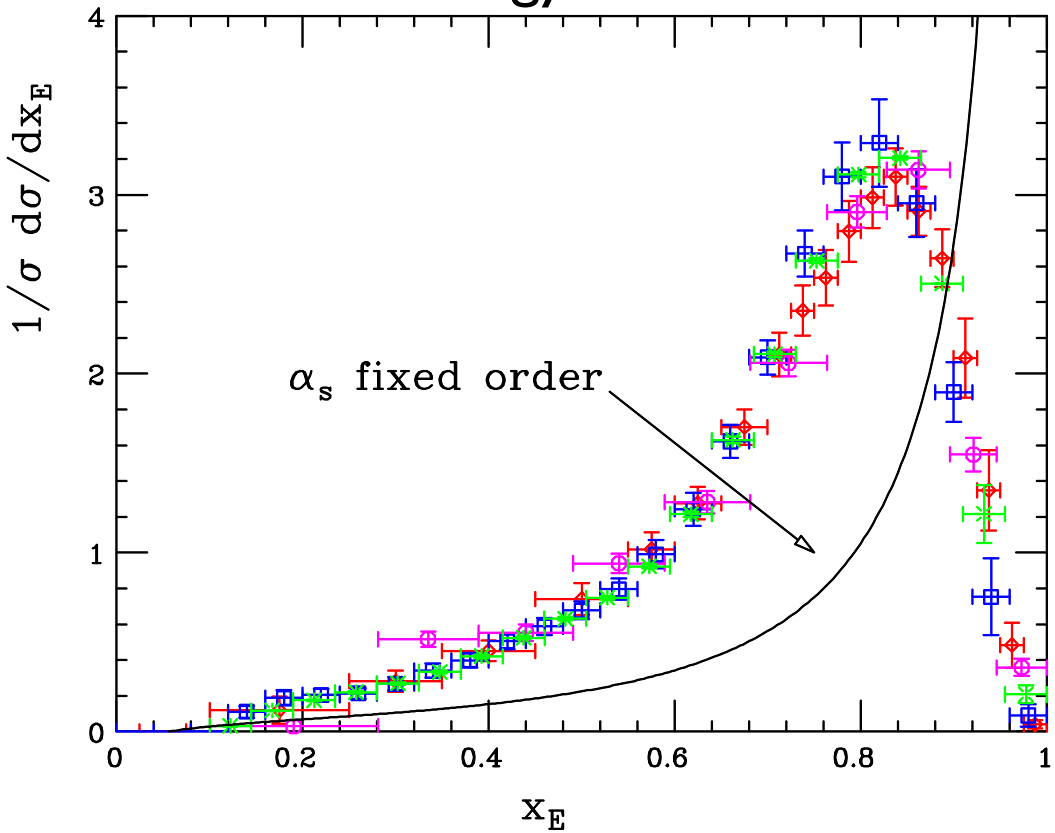
Calculable ≠ accurate

$e^+e^- \rightarrow B + X$



$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \delta(1-x)+\frac{\alpha_s(Q^2)}{2\pi}\left\{C_F+C_F\left[\ln\frac{Q^2}{m^2}\left(\frac{1+x^2}{1-x}\right)_+\right.\right.$$
$$+\; 2\frac{1+x^2}{1-x}\log x-\left(\frac{\ln(1-x)}{1-x}\right)_+(1+x^2)+\frac{1}{2}\left(\frac{1}{1-x}\right)_+(x^2-6x-2)$$
$$\left.\left.+\;\left(\frac{2}{3}\pi^2-\frac{5}{2}\right)\delta(1-x)\right]\right\} + \mathcal{O}\left(\frac{m}{Q}\right)$$

B hadrons energy distribution at LEP



Bad description from pQCD. What is missing?

Higher perturbative orders and non-perturbative effects

The prototype

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

measured cross section

Perturbative calculation

This can be at various accuracies, Monte Carlo, pQCD, LO, LO+LL, NLO+NLL, with or without collinear or soft resummation, etc)

non-perturbative fragmentation
(usually modeled and/or extracted from e+e- data)

Matteo Cacciari

Perturbative corrections

(N)LO + Logs (without double-counting)

- PYTHIA
- HERWIG
- FONLL — MC, Greco '94, MC, Greco, Nason '98
- GM-VFN — Kniehl, Kramer, Schienbein, Spiesberger, '05
- MC@NLO — Frixione, Webber '02
- POWHEG — Nason, '04
- aMC@NLO — Alwall et al, '14

+ others for DIS, photoproduction or implementing specific models

In all cases, matching between a (N)LO fixed order calculation (Nason, Dawson, Ellis, '88) and the resummation of large logs, either semi-numerically (e.g. FONLL, NLL accuracy) or via a parton shower Montecarlo (LL accuracy)

Non-perturbative fragmentation

What do we know about it?

- If the quark is light, not much.
  - It's a process-independent artificial (i.e. non-physical) object (factorisation theorem) that we must extract from data (e.g. pion fragmentation functions)
- If the quark is heavy
  - Its fragmentation function is still artificial (and needs to be extracted from data), but it can be implemented as a ***(parametrically) small effect*** when full use of pQCD calculability is made

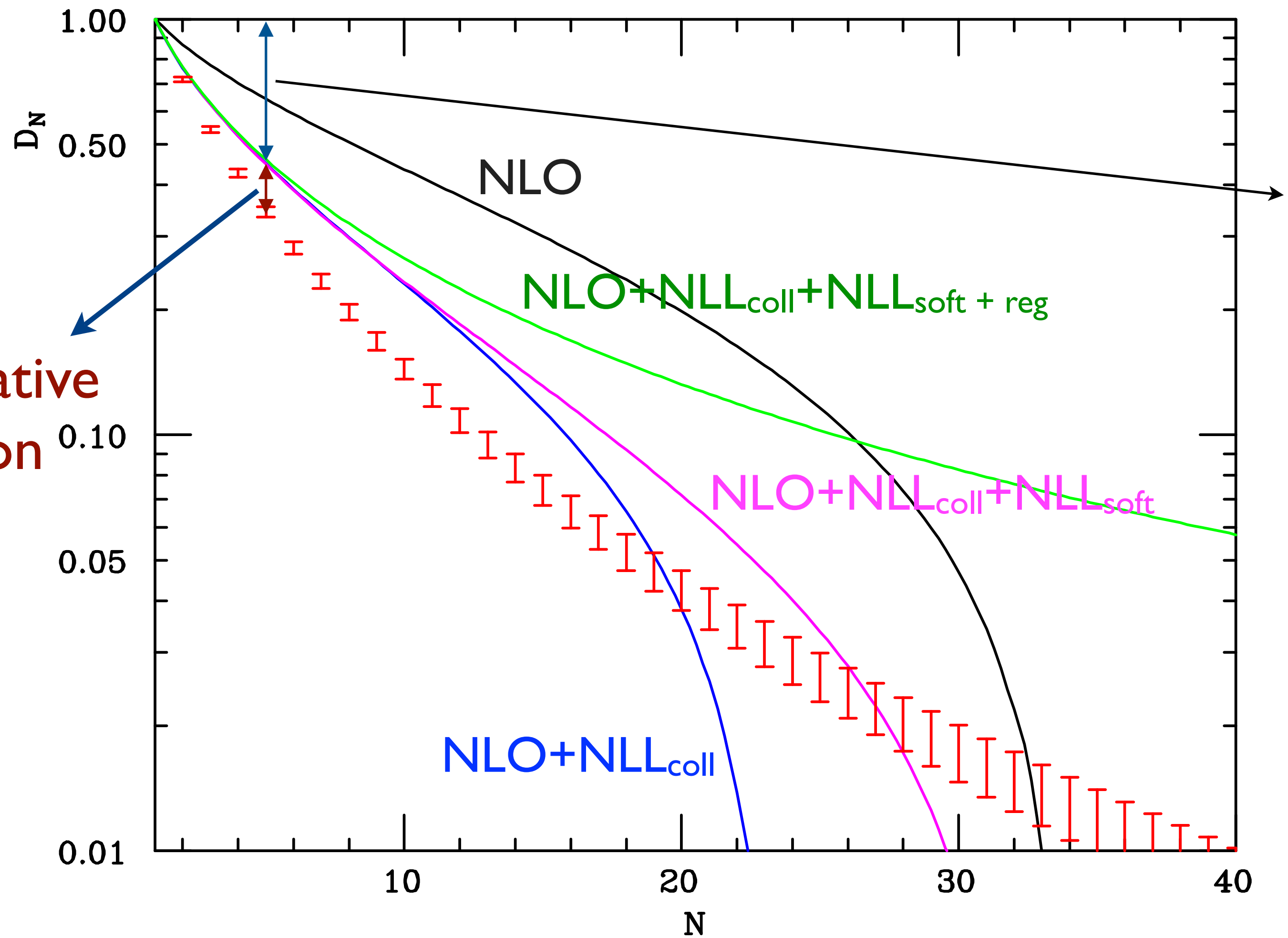
Non-perturbative fragmentation

LEP B meson data translated to Mellin space

$$f_N \equiv \int_0^1 x^{N-1} f(x)\, dx = \langle x^{N-1} \rangle$$

In this space **convolutions become products**

$$\langle x \rangle_{expt} = \langle x \rangle_{pQCD} \langle x \rangle_{np}$$



This gap: non-perturbative contribution for N=5

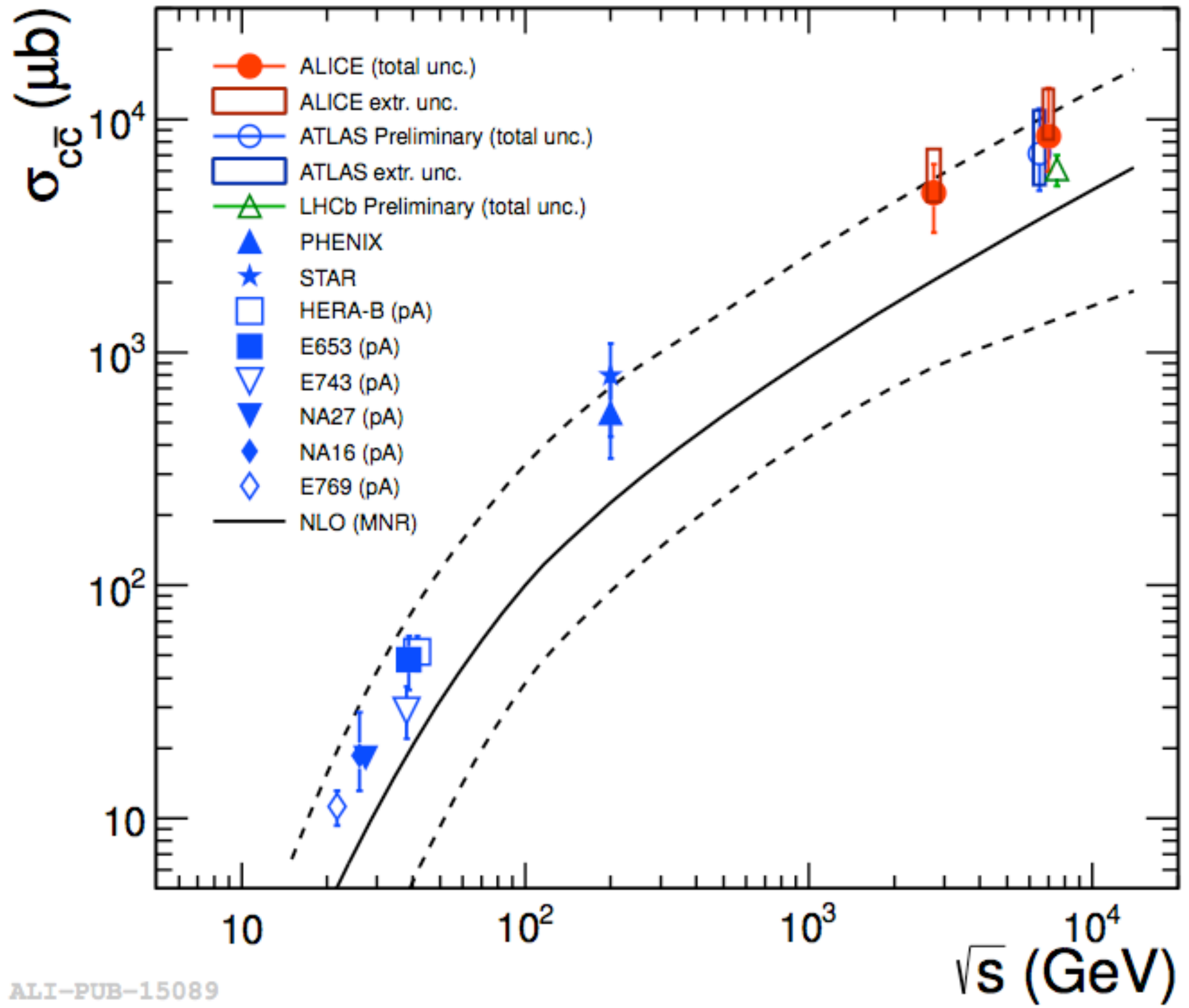
resummed pQCD

Successive approximations improve the perturbative prediction and approach the data

Charm

(and charmonium)

Total charm cross section



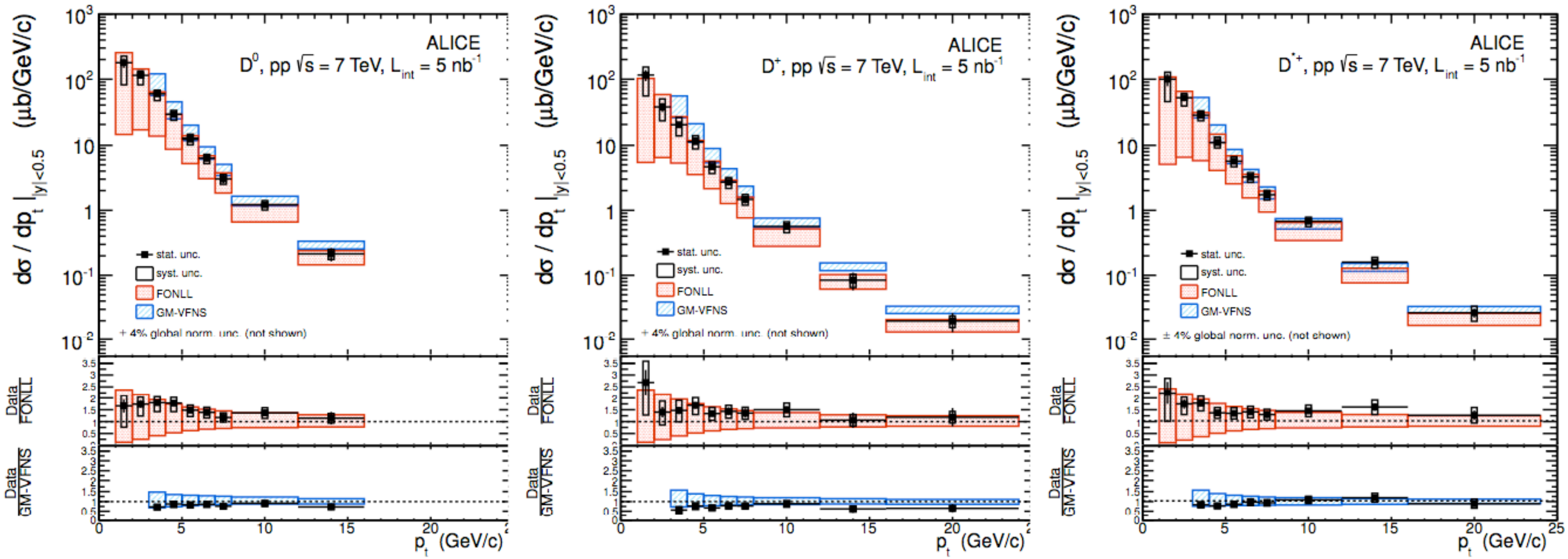
Agreement, but huge theoretical uncertainty

Charm total cross section is more an opinion than a prediction

(also, measurements usually include non-negligible extrapolation factors based on theory)

Charm mesons

Transverse momentum distributions of
reconstructed D mesons in central rapidity region



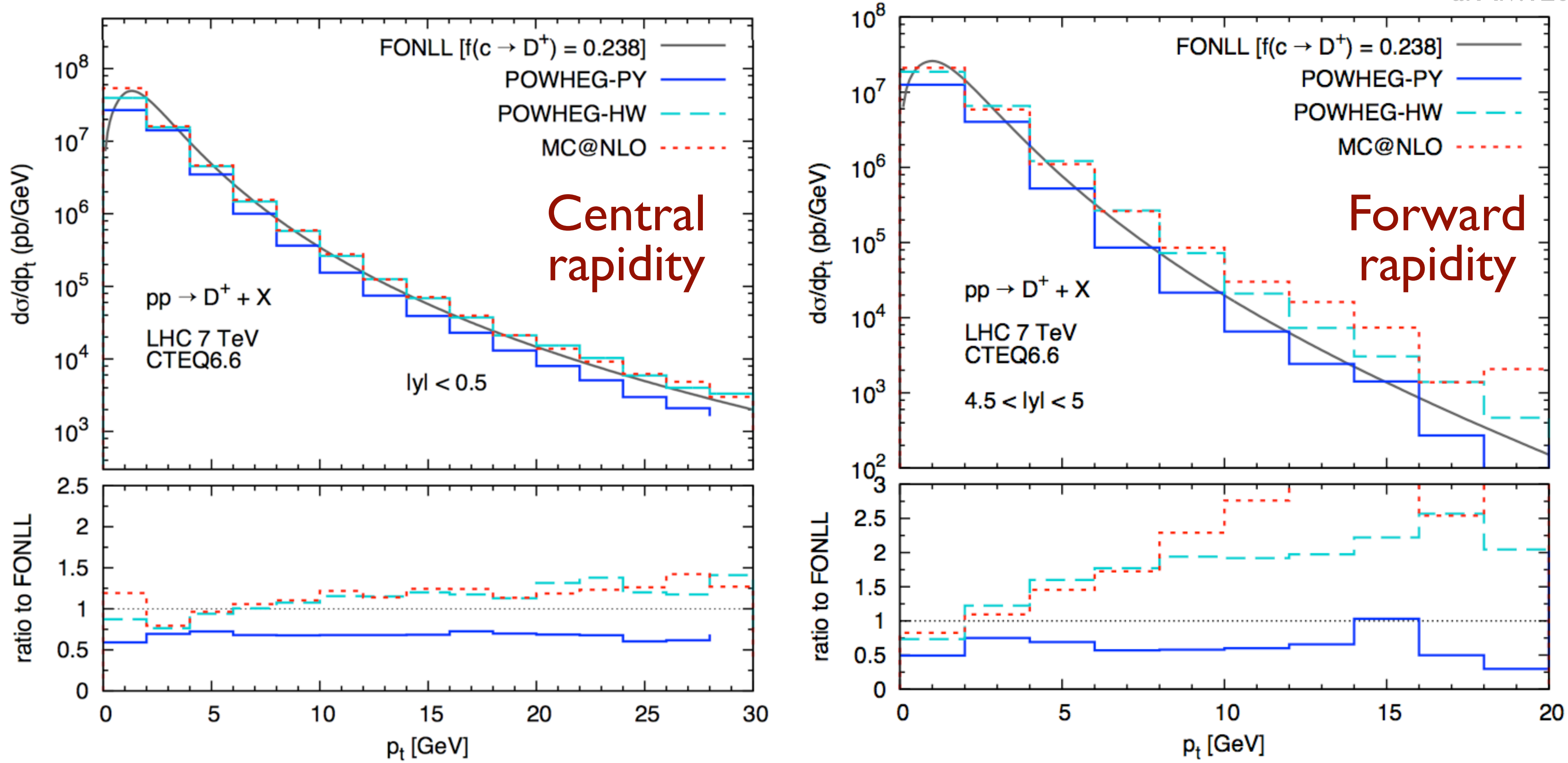
Situation similar to Tevatron:
agreement with upper side of theoretical bands

Worth noting: measurement down to very low $p_T \approx 1$ GeV

D mesons: theory tools comparisons

Comparison of FONLL, PYTHIA, HERWIG (via MC@NLO and POWHEG)

arXiv:1205.6344

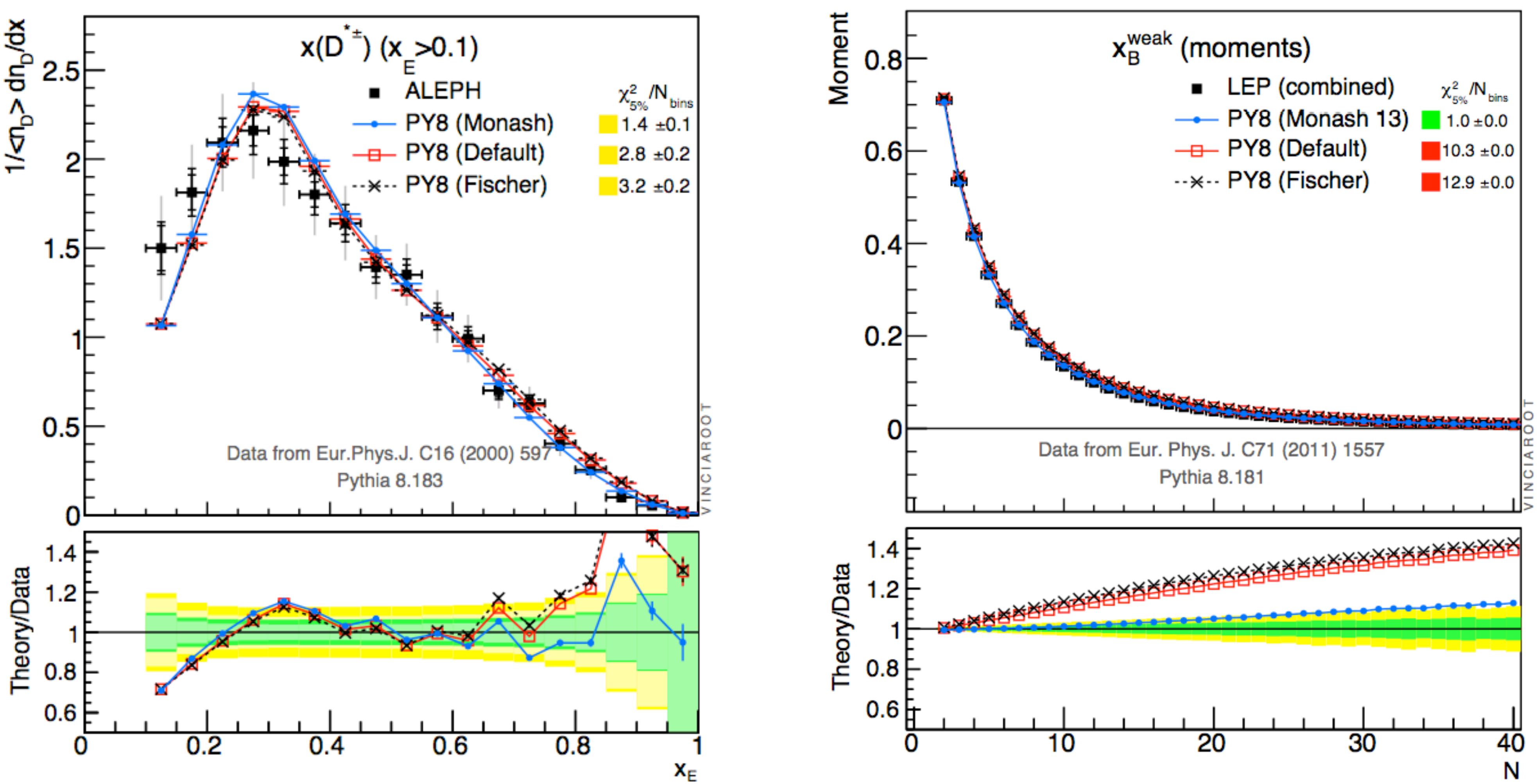


Disagreement can exist already at central rapidity,
becomes quite large at large rapidity

Some ingredients of some tools (e.g. non-perturbative fragmentation, MC tune) may need to be properly adjusted

New ‘Monash 2013’ tune in Pythia8

Skands, Carrazza, Rojo, arXiv:1404.5630

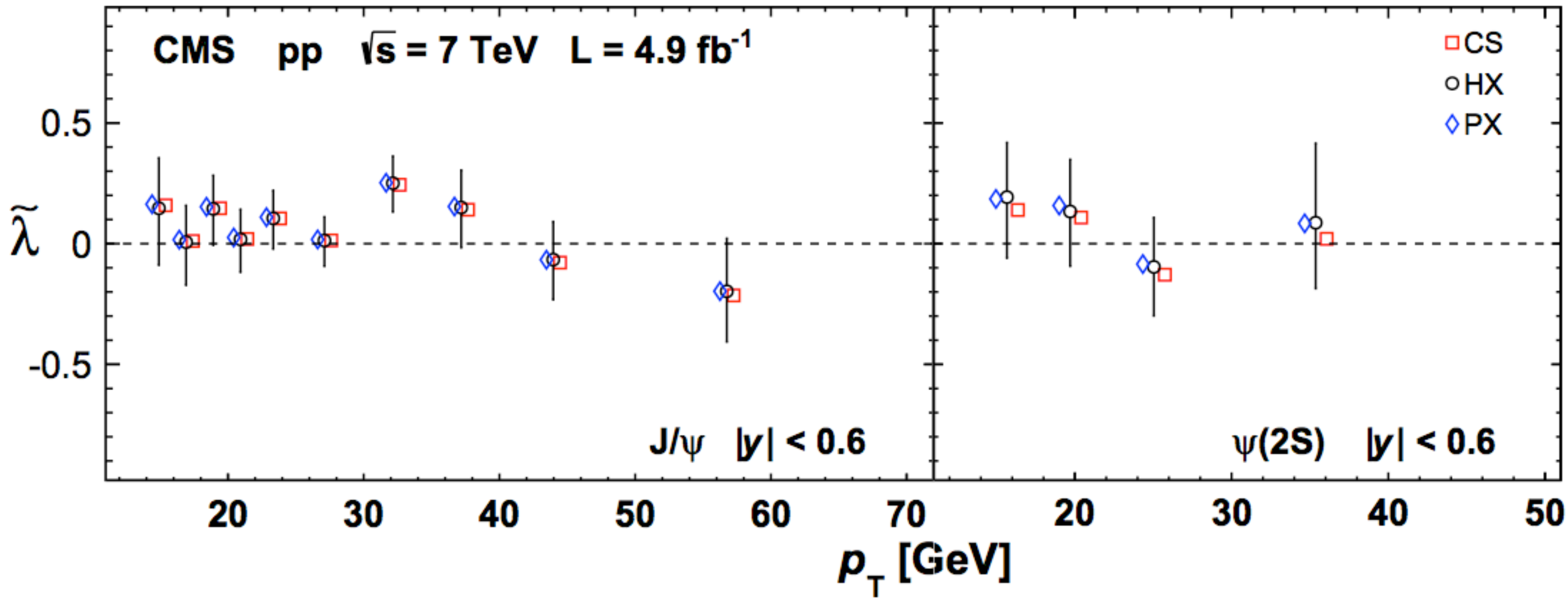


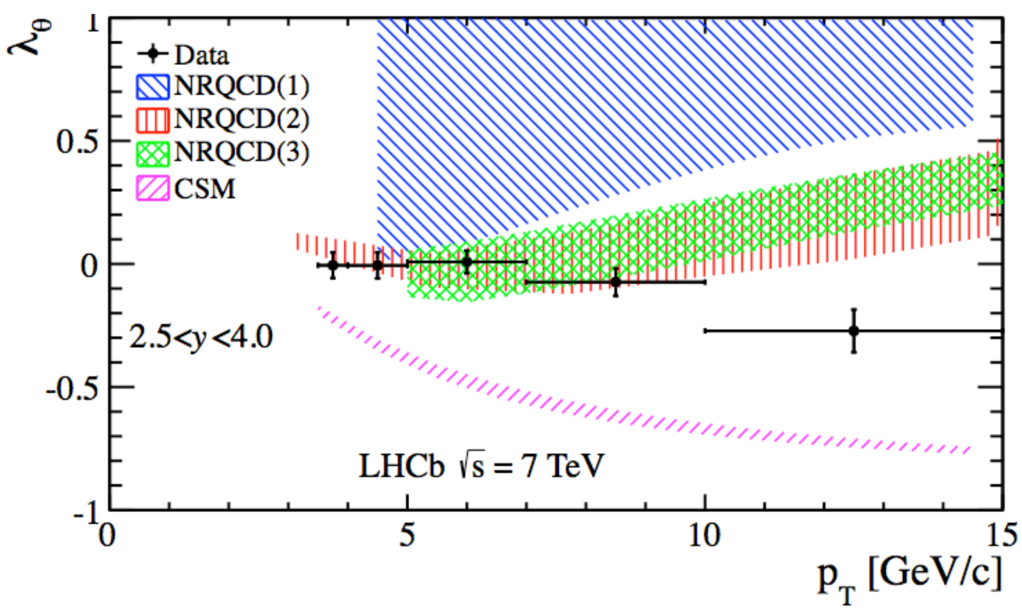
D and B softer in Pythia8

- Effect on hadroproduction?

Charmonium polarization

CMS 1307.6070, ALICE 1111.1630, LHCb 1307.6379 1403.1339

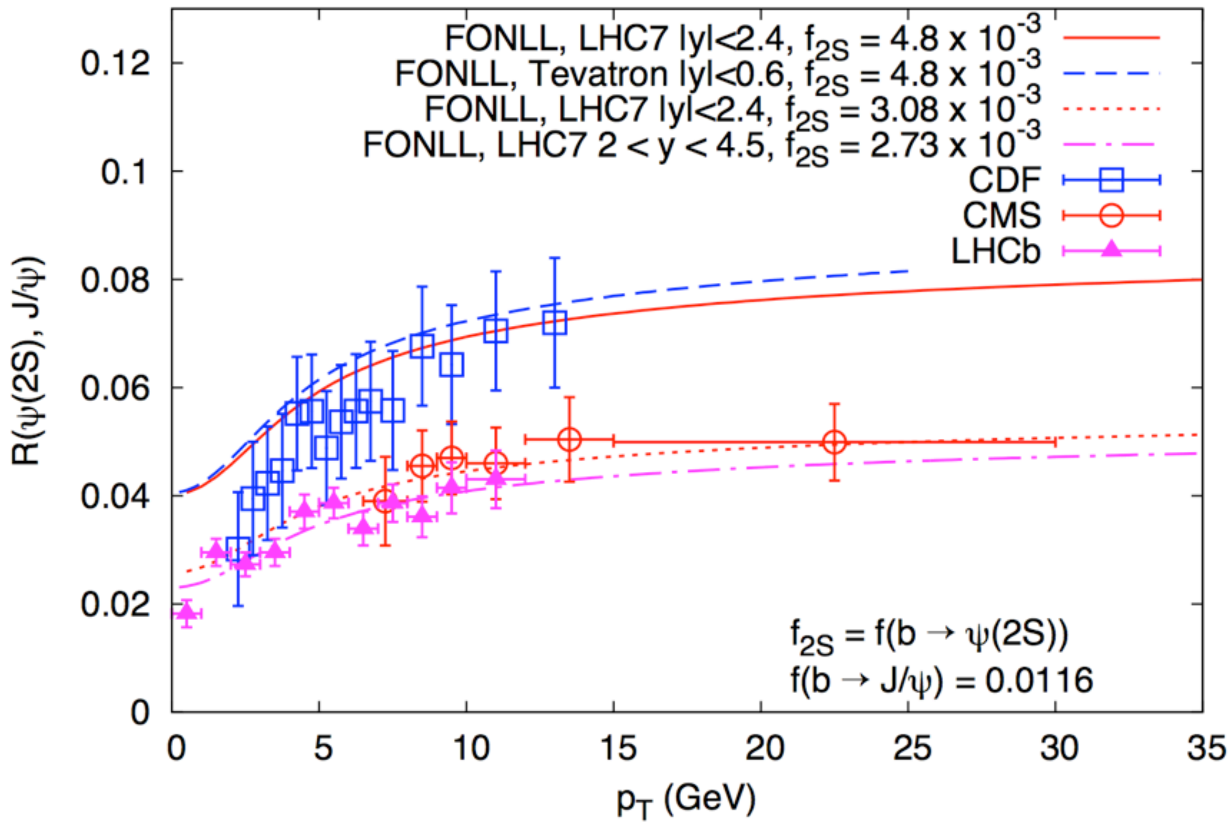




Both J/ψ and ψ(2S) are found to be produced ***unpolarized***, at odds with NRQCD predictions at large transverse momentum

Charmonium from bottom: J/ψ / ψ(2S) ratio

arXiv:1205.6344



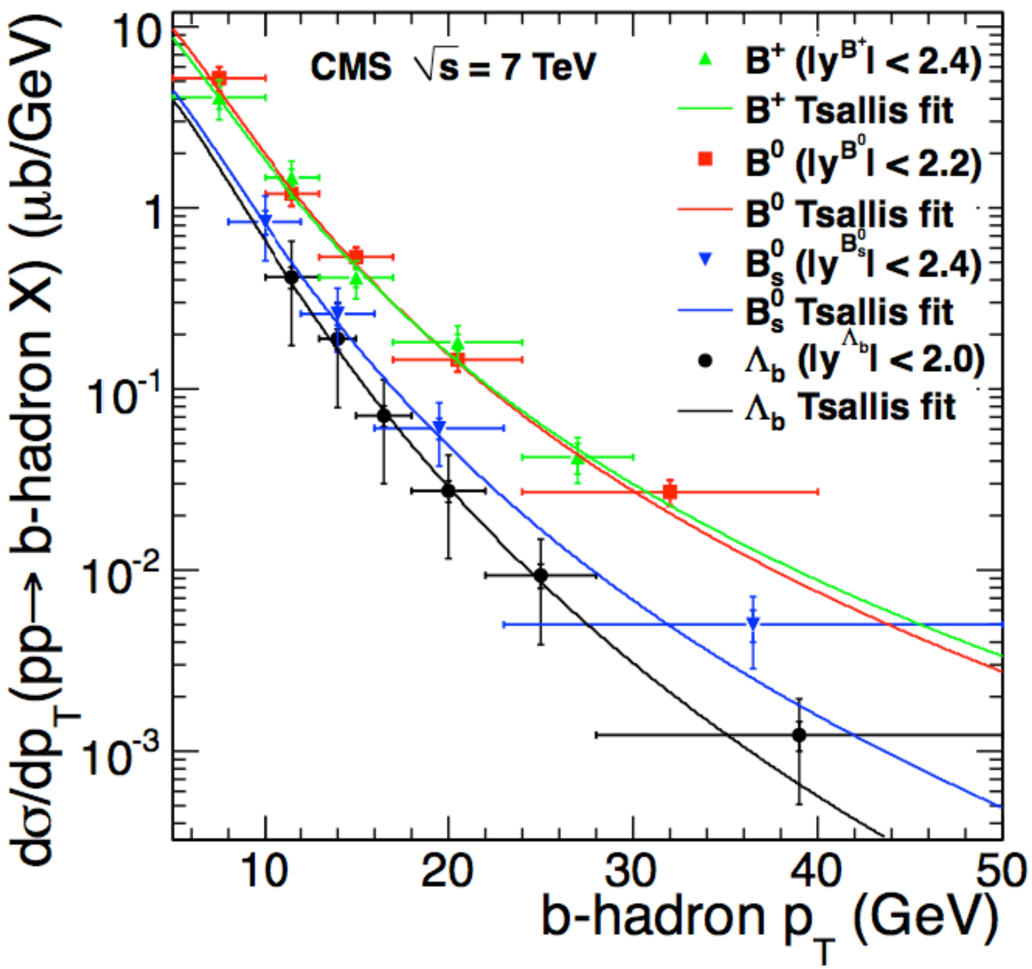
CMS and LHCb in good agreement, **new b→ψ(2S) branching ratios** agree within themselves and with old one from PDG within its large error (4.8 ± 2.4)

Instead, CDF data only marginally consistent, while theory predicts no significant difference

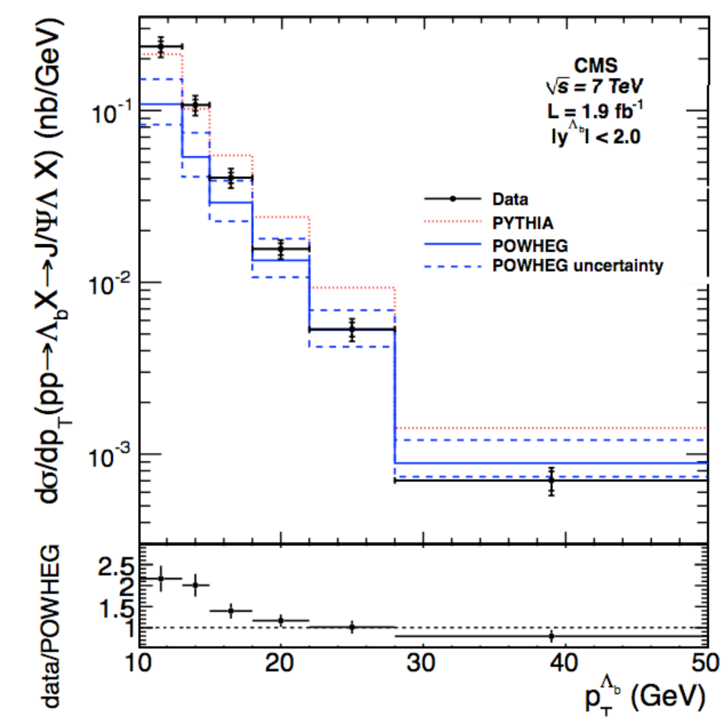
Bottom

b-hadrons

CMS 1205.0594

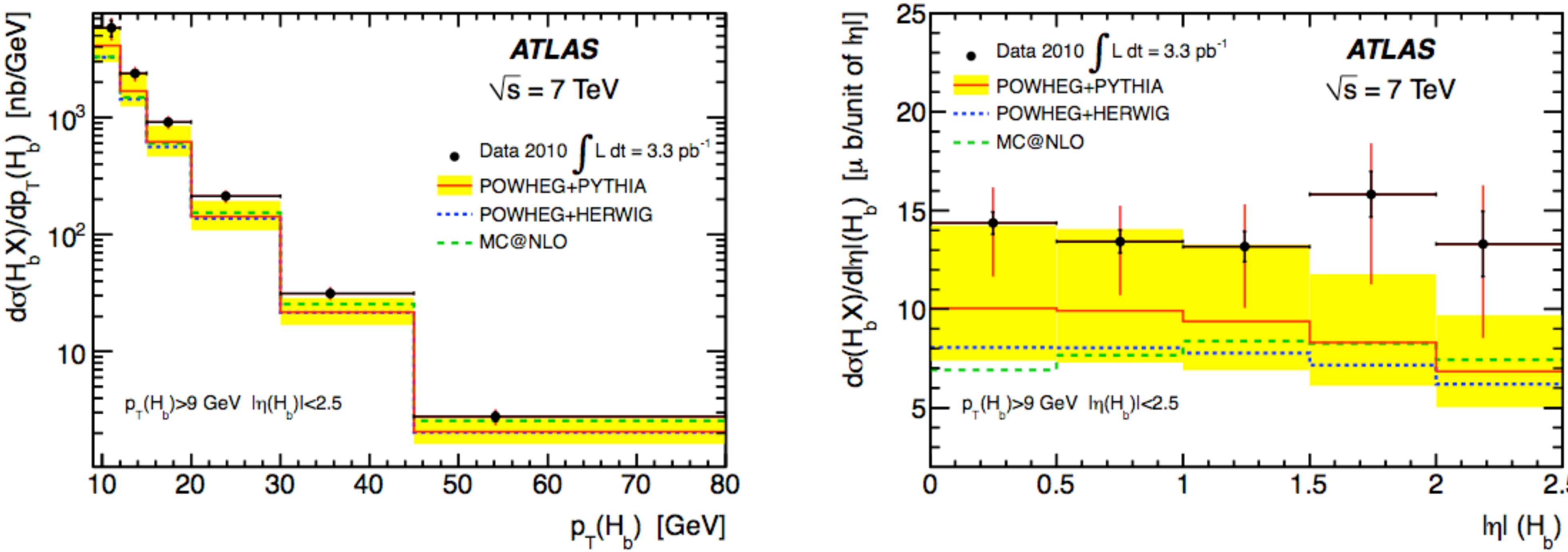


- Measurement by CMS of all four main b-hadrons
- B^0, B^+, B_s very similar (BR aside for Bs), Λ_b softer, as expected
- Λ_b a bit softer than POWHEG and PYTHIA predictions



ATLAS 1206.3122

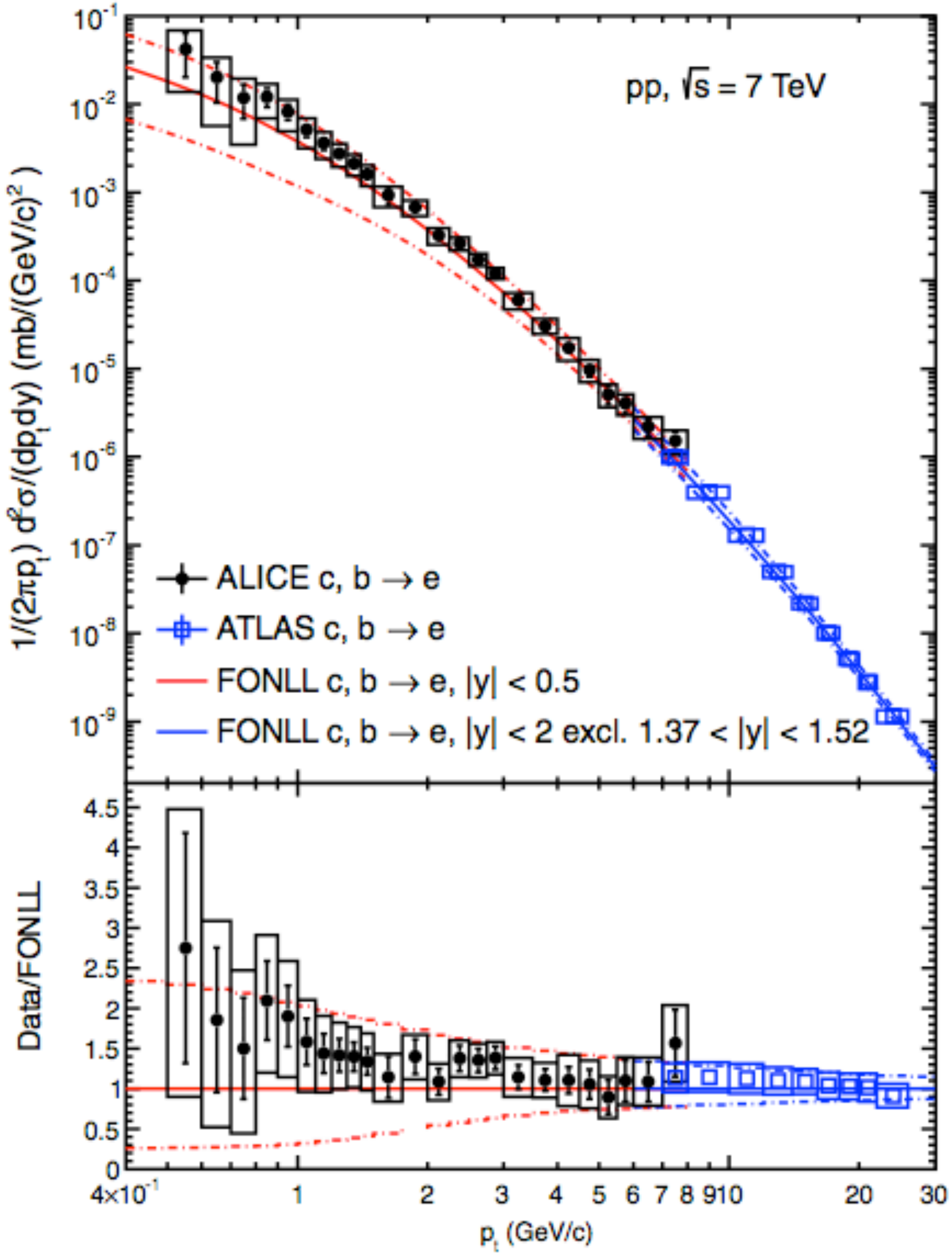
Measurement by ATLAS using partially reconstructed $H_b \to D^{*+}\mu^- X$



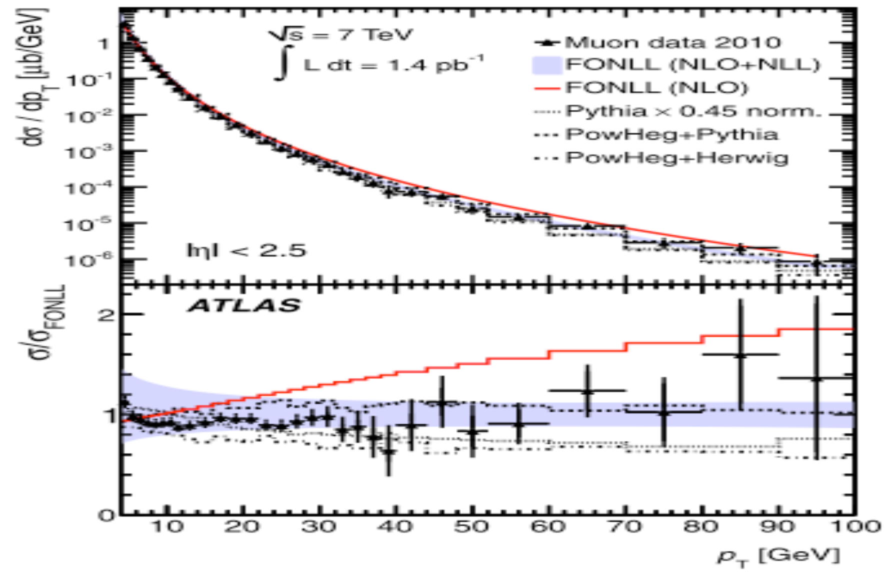
Fair agreement with MC@NLO and POWHEG (PY or HW)

b-hadrons through lepton decays

ALICE 1205.5423



ATLAS 1109.0525

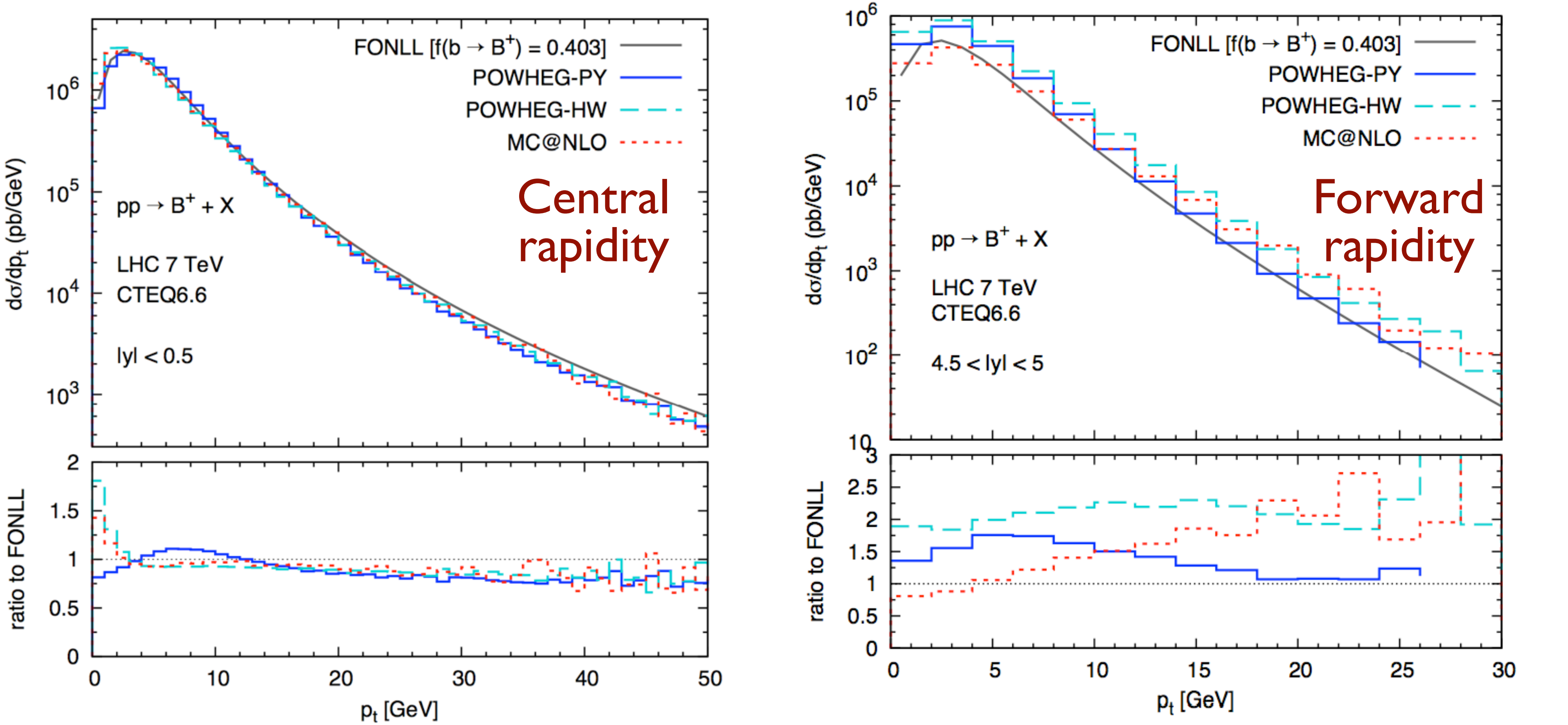


- Measurements by ALICE, ATLAS, CMS cover a wide range in p_t, from <1 GeV to > 100 GeV
- Good agreement with predictions employing
  - NLO+NLL pQCD
  - NP fragmentation (fitted from LEP)
  - modeling of decay to leptons
- POWHEG (PY or HW) a bit too soft?

B mesons: theory tools comparisons

Comparison of FONLL, PYTHIA, HERWIG (via MC@NLO and POWHEG)

arXiv:1205.6344



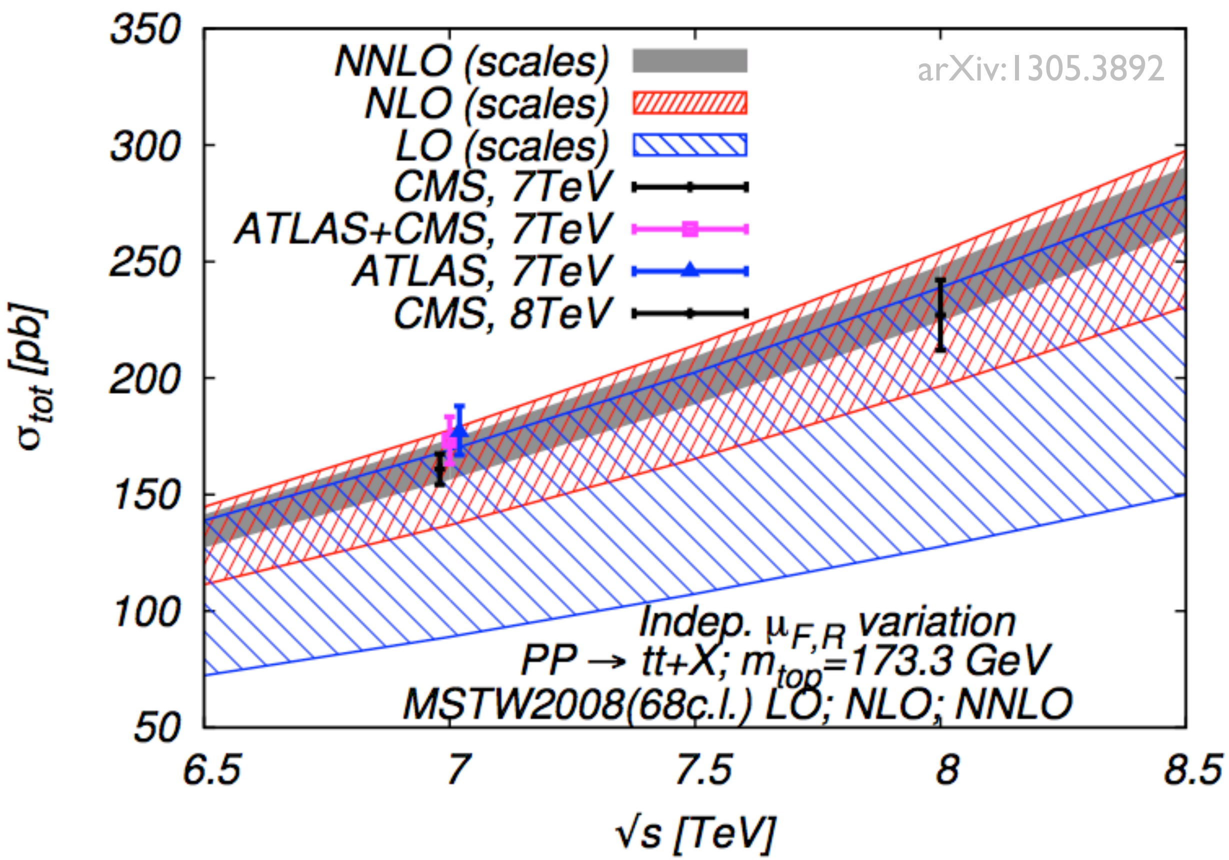
Situation similar to D mesons case:
fair agreement (even better here) for central rapidities,
significant disagreements in forward region

Top

ttbar total cross section

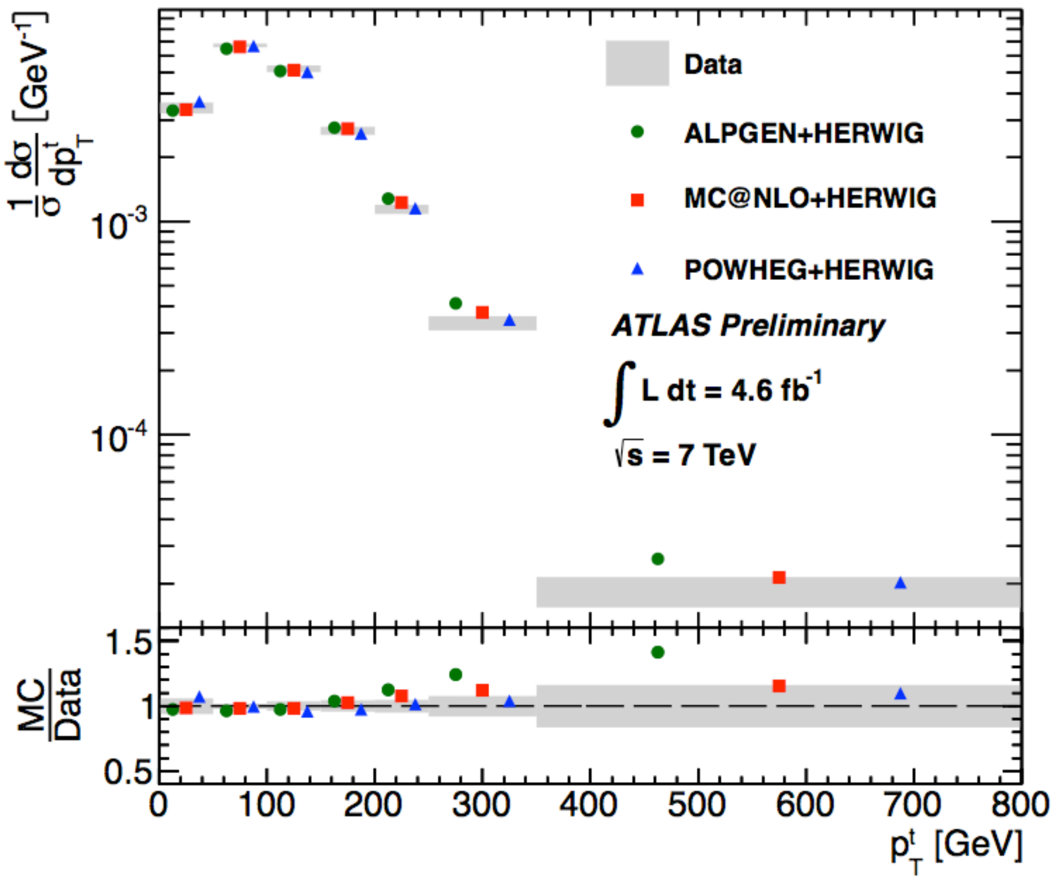
Theory state of the art: NNLO+NNLL

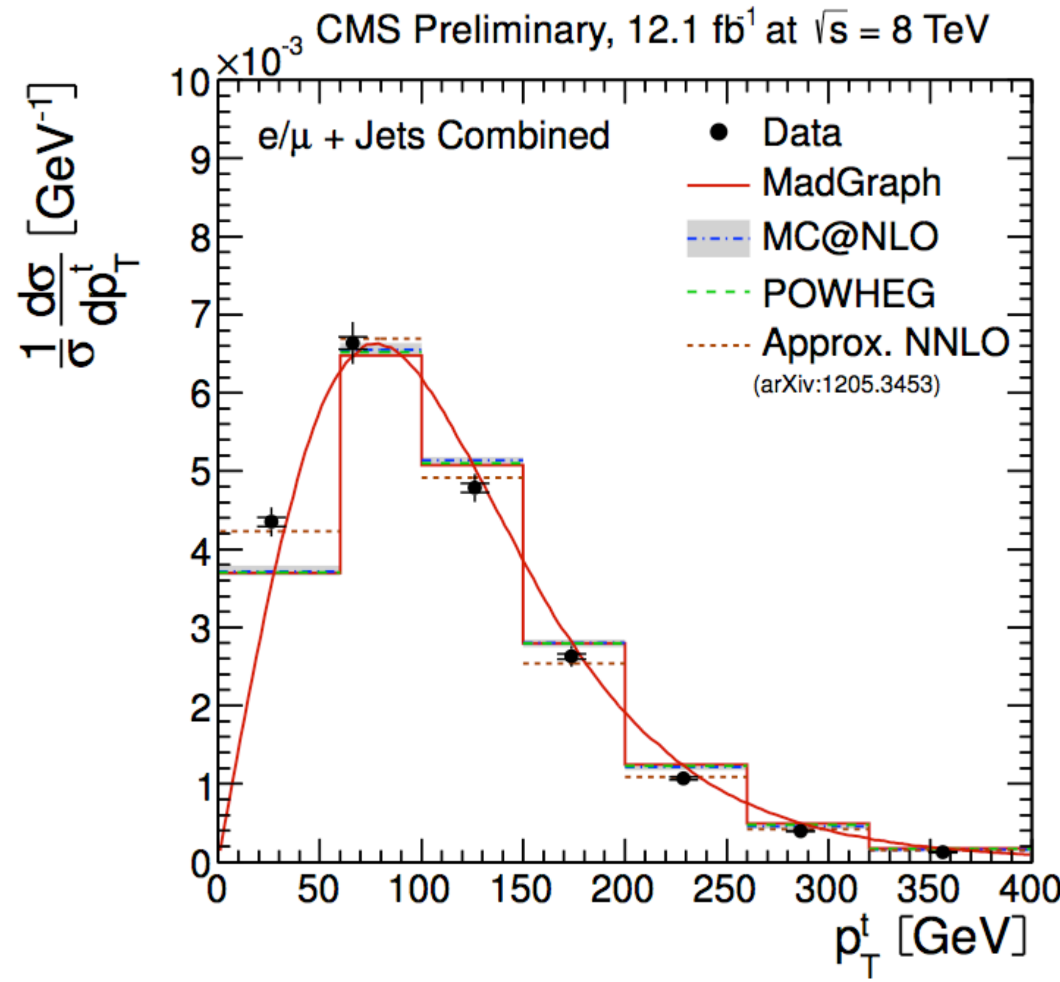
Czakon, Mitov et al. 1303.6254, 1303.7215



- Good convergence of perturbation theory
- Confirmed good agreement with data
- Theoretical uncertainty at LHC reduced from ±10% to ±3%

Top p_t distributions

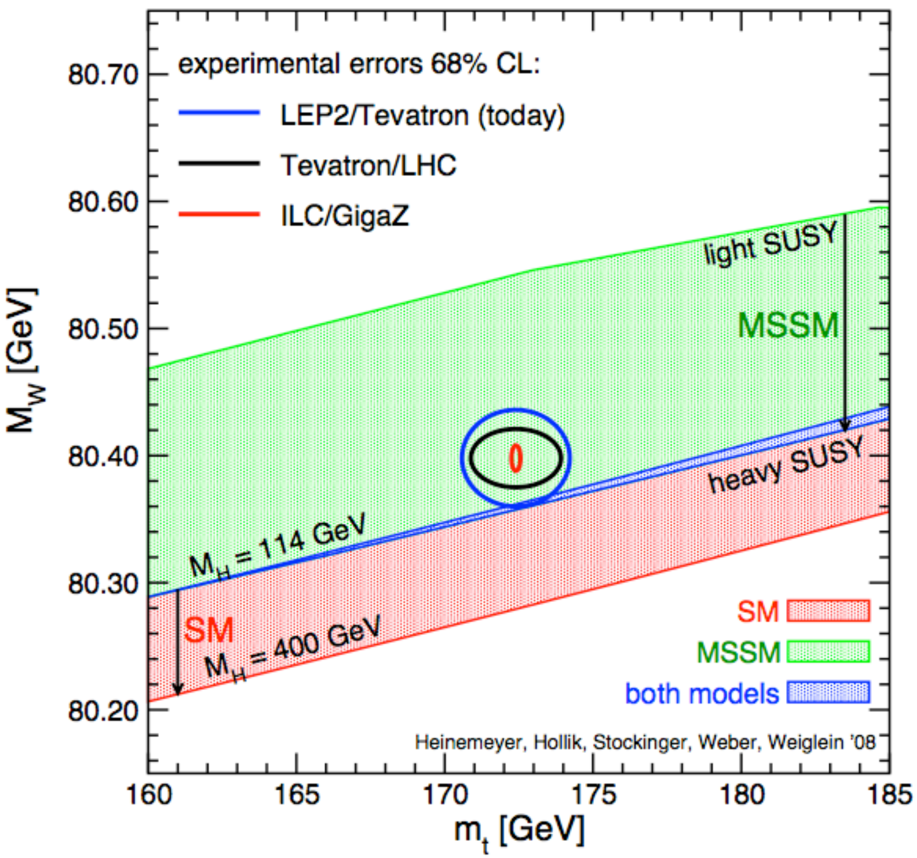


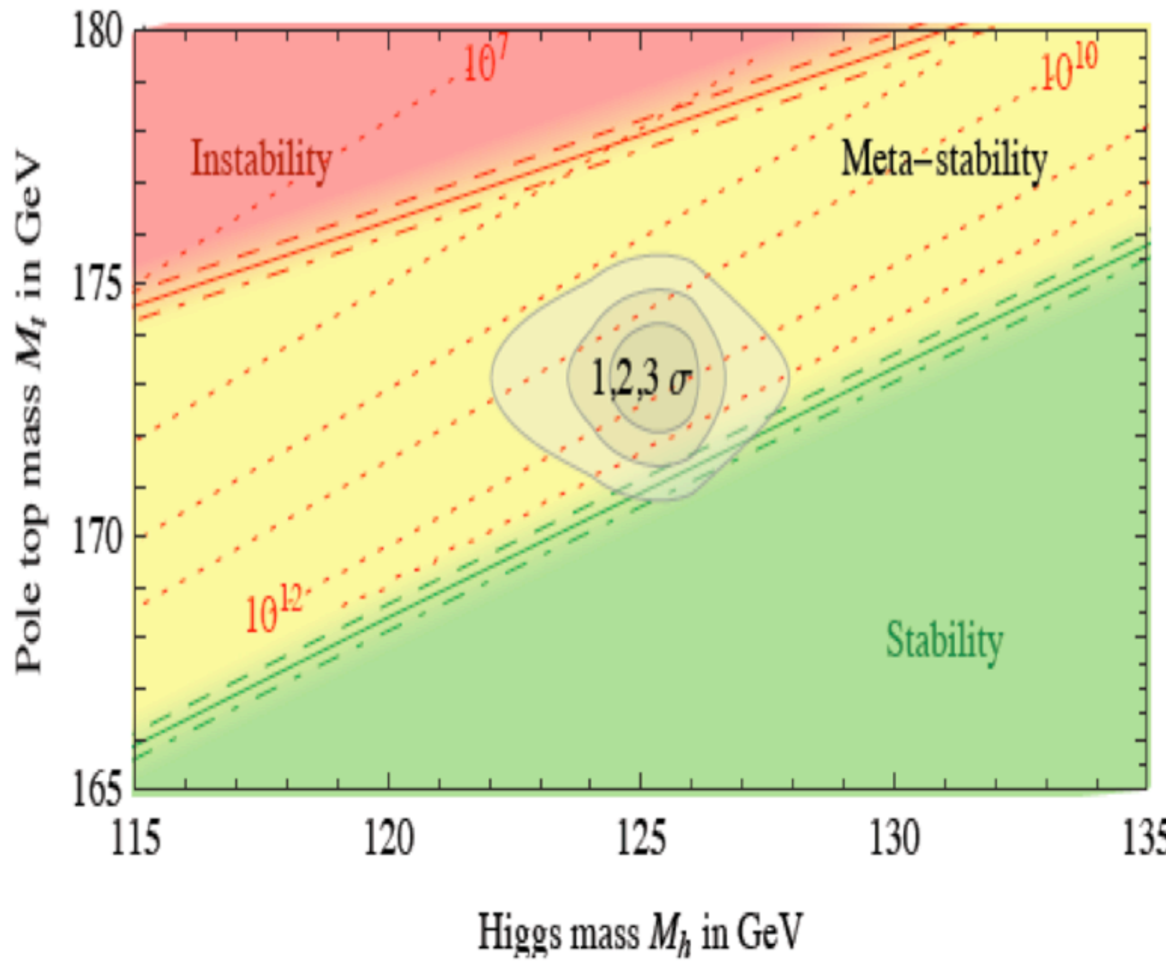


Theory up to NLO accuracy (or just a little better), good agreement with experiment, no surprises

Top mass

Precise knowledge is relevant for ***SM fits/BSM searches*** and understanding of ***stability of electroweak vacuum***

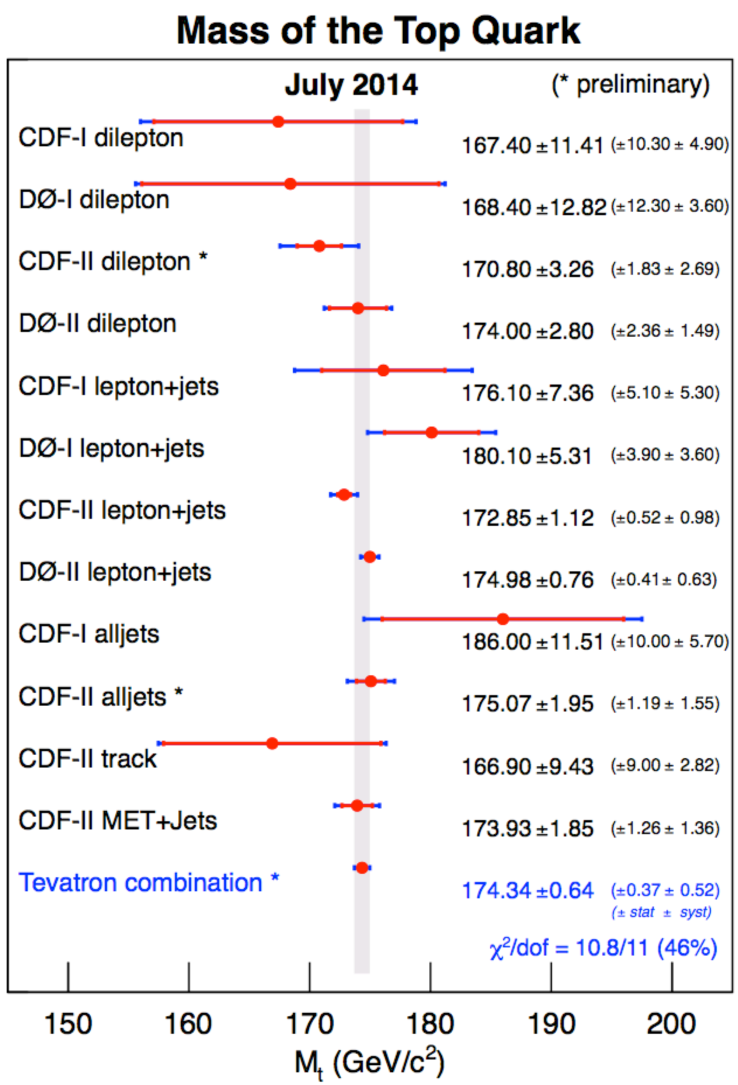




Knowing the top mass with < 1 GeV accuracy may matter

Top mass

CDF and D0 1407.2682



- Latest world average:

  $$m_t = 173.34 \pm 0.76\ \text{GeV}$$

- Latest combination from Tevatron:

  $$m_t = 174.34 \pm 0.64\ \text{GeV}$$

- LHC measurements also below ±1 GeV, sometimes largish discrepancies with averages observed, e.g. from CMS

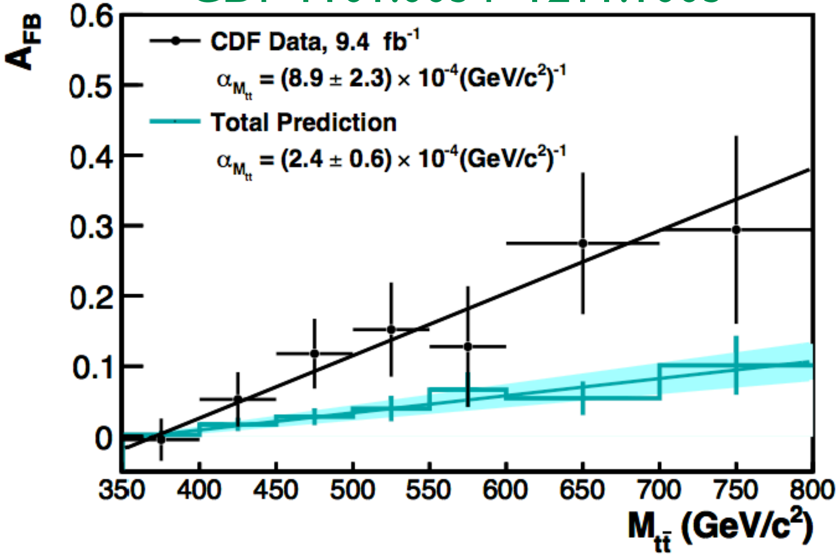
  $$m_t = 172.04 \pm 0.77\ \text{GeV}$$

- However the real issue is ***what*** exactly is being measured
  - measurement through decays products: pole mass value affected by hadronization effects (a few hundred MeV): each measurement may measure a slightly different object
  - measurement through total cross section: theoretically cleaner but lower precision
  - e^+e^- linear collider: allows for "clean" definition and high accuracy
  - Active research field, many proposals

Top forward-backward asymmetry

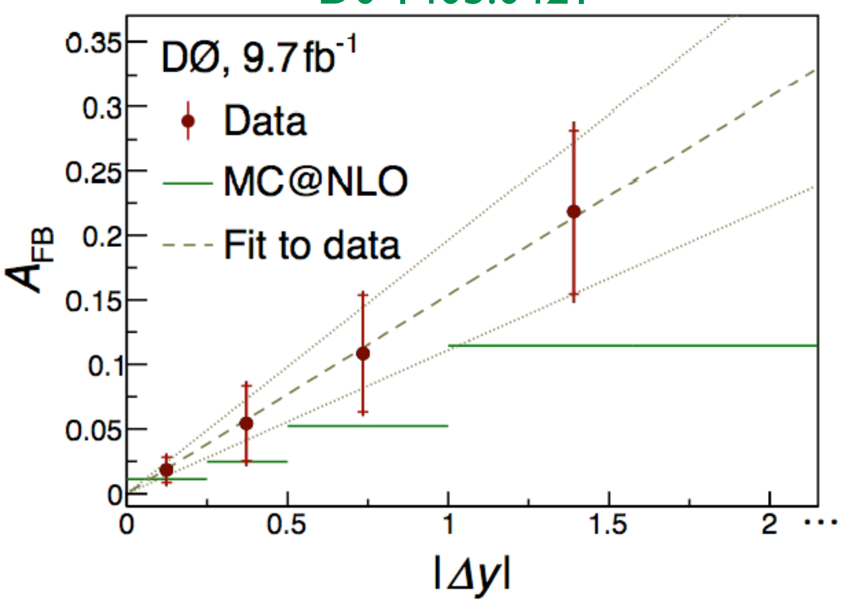
$$A^{t\bar{t}}(M_{t\bar{t},i}) = \frac{N(\Delta y > 0, M_{t\bar{t},i} - N(\Delta y < 0, M_{t\bar{t},i})}{N(\Delta y > 0, M_{t\bar{t},i}) + N(\Delta y < 0, M_{t\bar{t},i})}$$

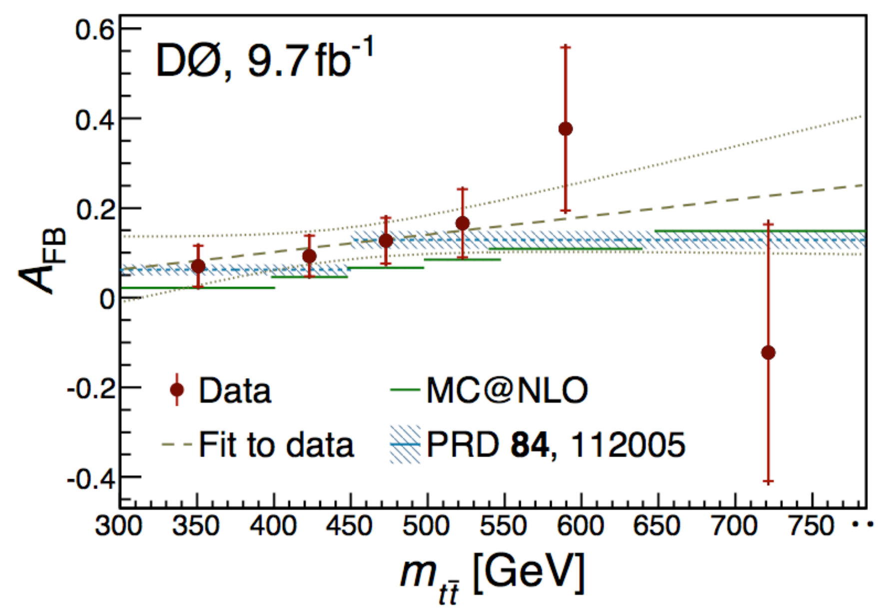
CDF 1101.0034 1211.1003



- It arises from interference at NLO in QCD, due to different content of light quark and antiquark in proton
- Measurement by CDF appeared in excess of QCD predictions
  - Has sparked a number of BSM interpretations
- LHC measures a related charge asymmetry and finds no discrepancies
- Recent measurement by D0 shows no discrepancy

D0 1405.0421





First lessons from LHC

- Picture successful at Tevatron and RHIC still working well

- No critical threshold apparently crossed going from Tevatron to LHC (e.g. no large small-x effects visible so far)

Summary

- NLO and resummations successfully matched in various frameworks
- Predictions successful in first LHC data
  - new (automated) NLO+PS codes POWHEG/(a)MC@NLO are now a valid alternative to semi-numerical predictions to NLO accuracy
  - Some Monte Carlo tunes will likely have to be updated (e.g. for non-perturbative fragmentation information)
- These first data can only test the NLO calculation plus some rough matching with NP physics
  - More refined tests, e.g. of the NLL resummation and matching to NP fragmentation, will need more data at larger transverse momentum