PDFs in the LHC Era

… a new perspective

Earth, as viewed from GGI

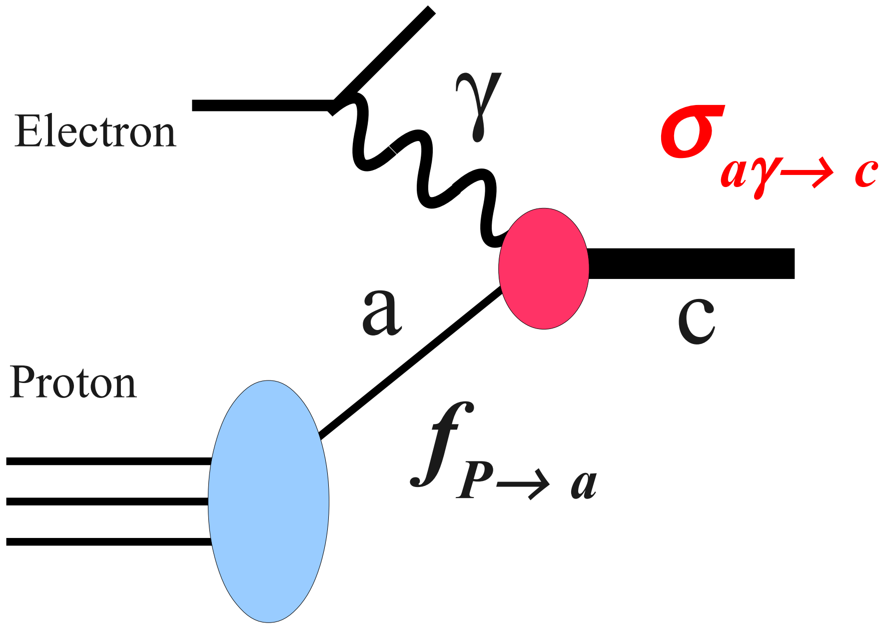
Fred Olness

SMU

GGI

16 September 2011

The Parton Model and Factorization



Parton Distribution Functions

(PDFs) $f_{P\to a}$

are the key to calculations

involving hadrons!!!

$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

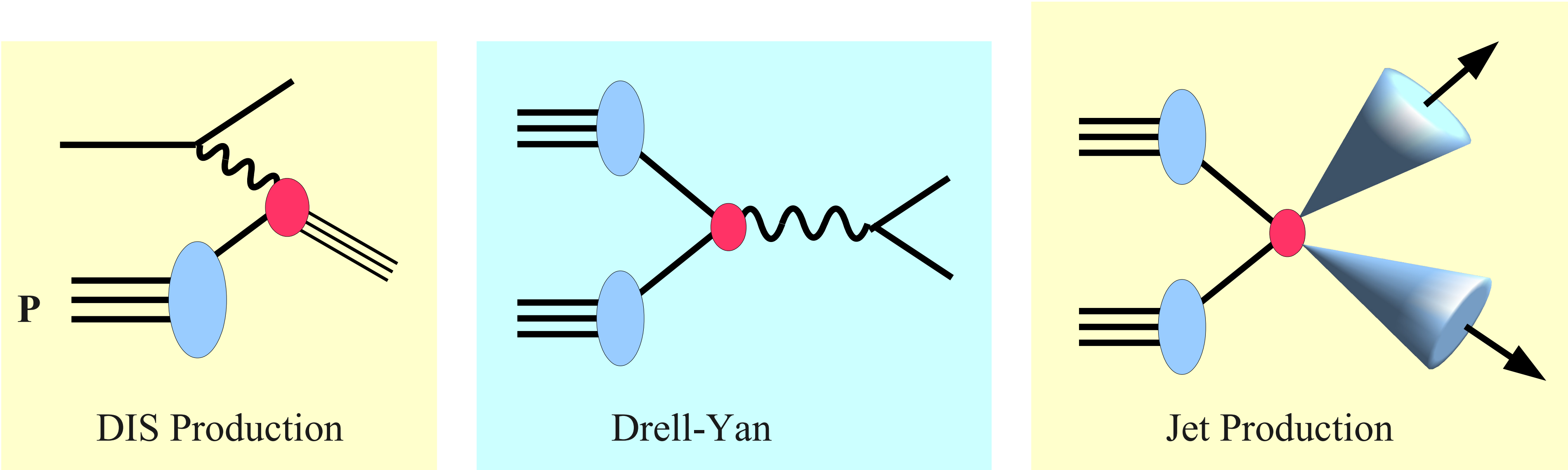
Corrections of order (Λ^2/Q^2)

must extract from experiment

calculable from theoretical model

Cross section is product of independent probabilities!!! *(Homework Assignment)*

PDF extraction requires a variety of measurements



$$F_2^{\nu} \sim [d + s + \bar{u} + \bar{c}]$$

$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$F_3^{\nu} = 2[d + s - \bar{u} - \bar{c}]$$

$$F_3^{\bar{\nu}} = 2[u + c - \bar{d} - \bar{s}]$$

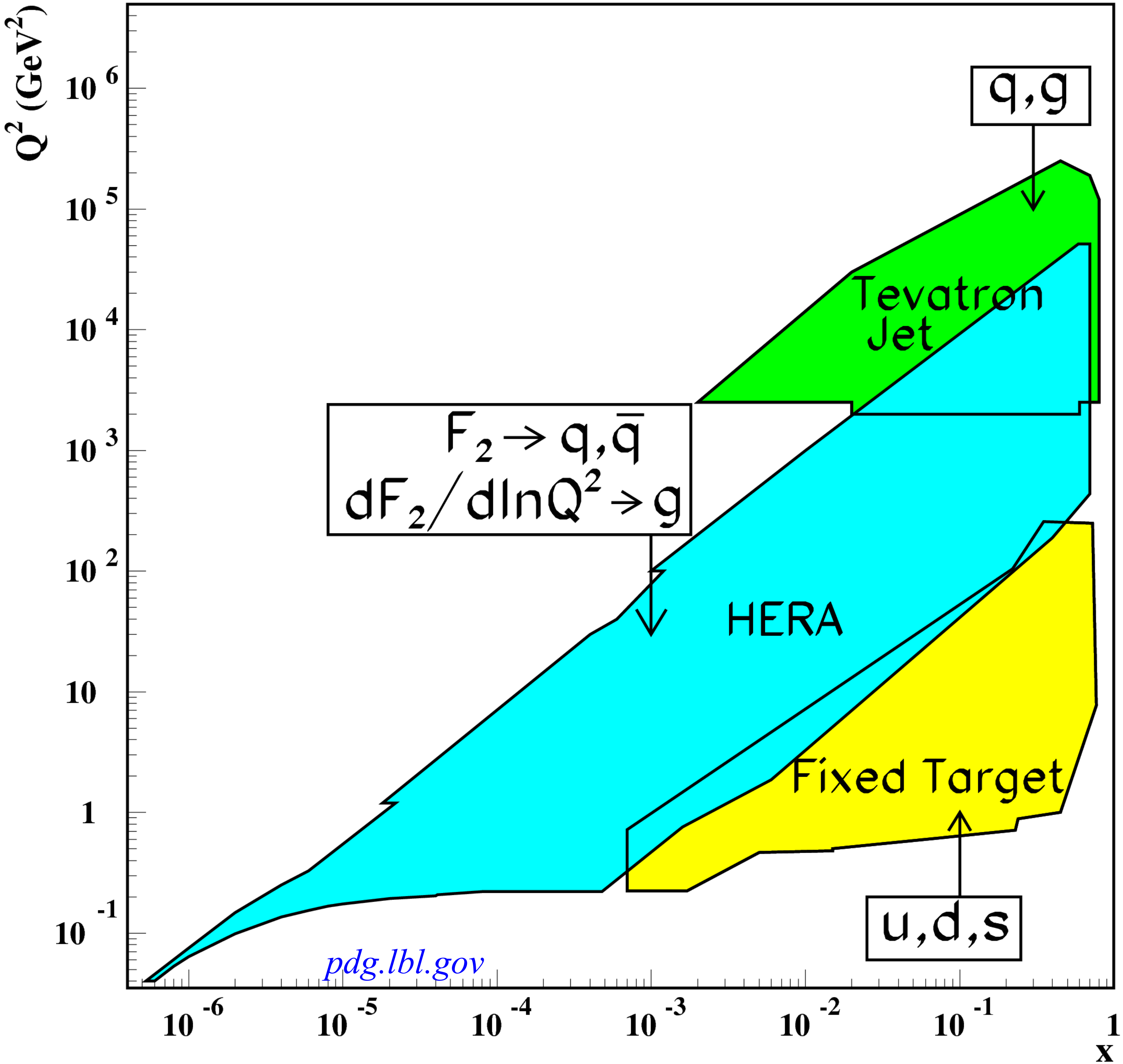
$$F_2^{\ell^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d + s] + \left(\tfrac{2}{3}\right)^2 [u + c]$$

In particular, the DIS combinations have historically been particularly useful

<u>Different</u> linear combinations – key for flavor differentiation

The ν-DIS data typically use heavy targets, and this requires the application of ***<u>nuclear corrections</u>***

Global PDF analyses combine Hadron-Hadron w/ other sets



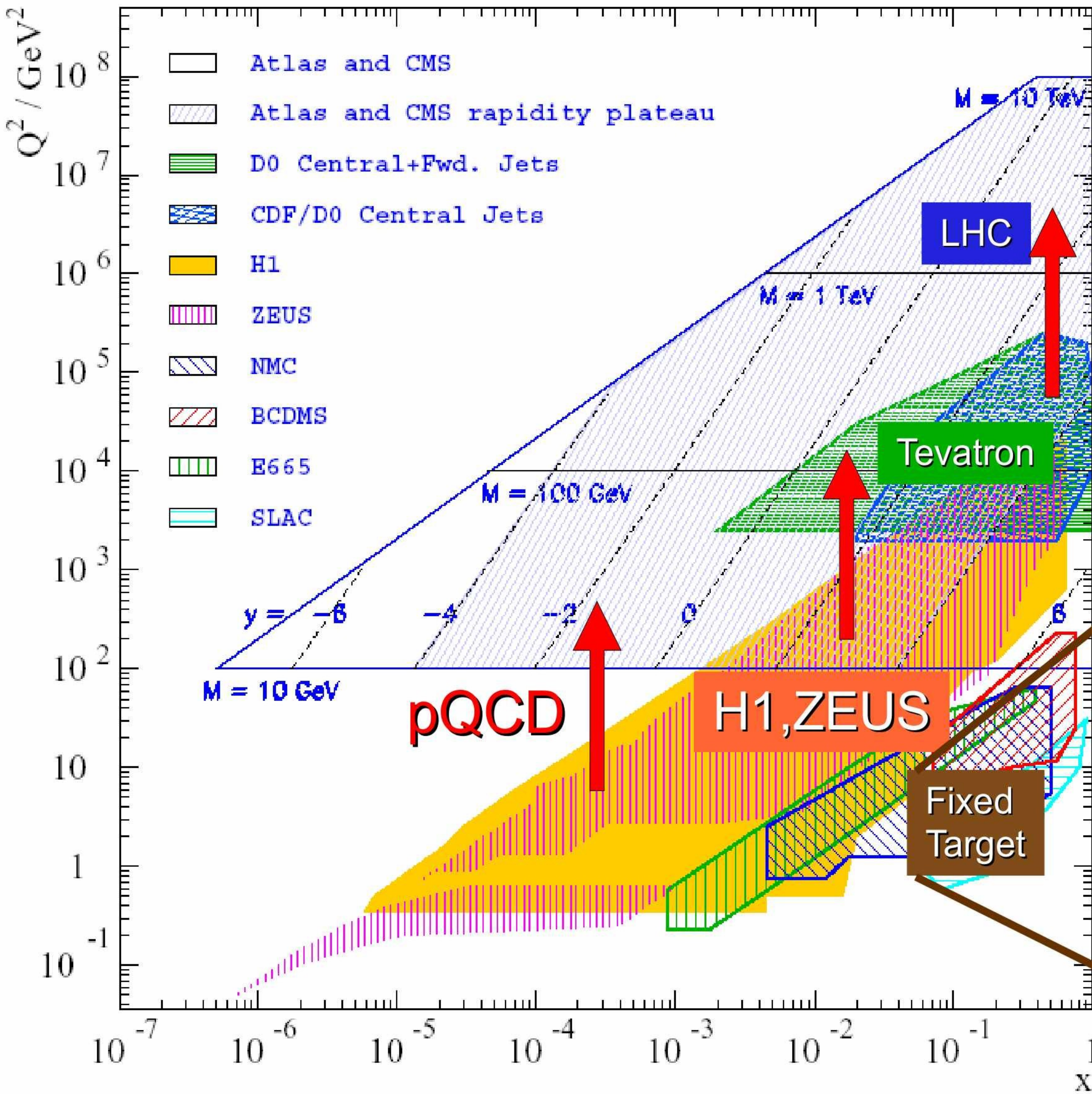
Fixed Target:
DIS charged lepton
DIS neutrino
DY
Direct Photon

HERA (ep)

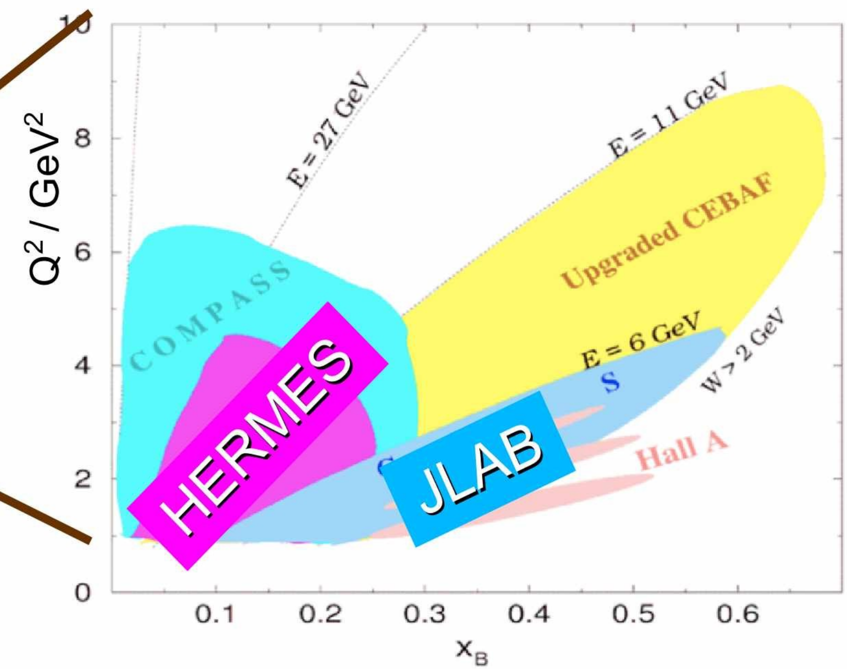
Tevatron:
Jets
W Asymmetry

LHC DATA
just now being included

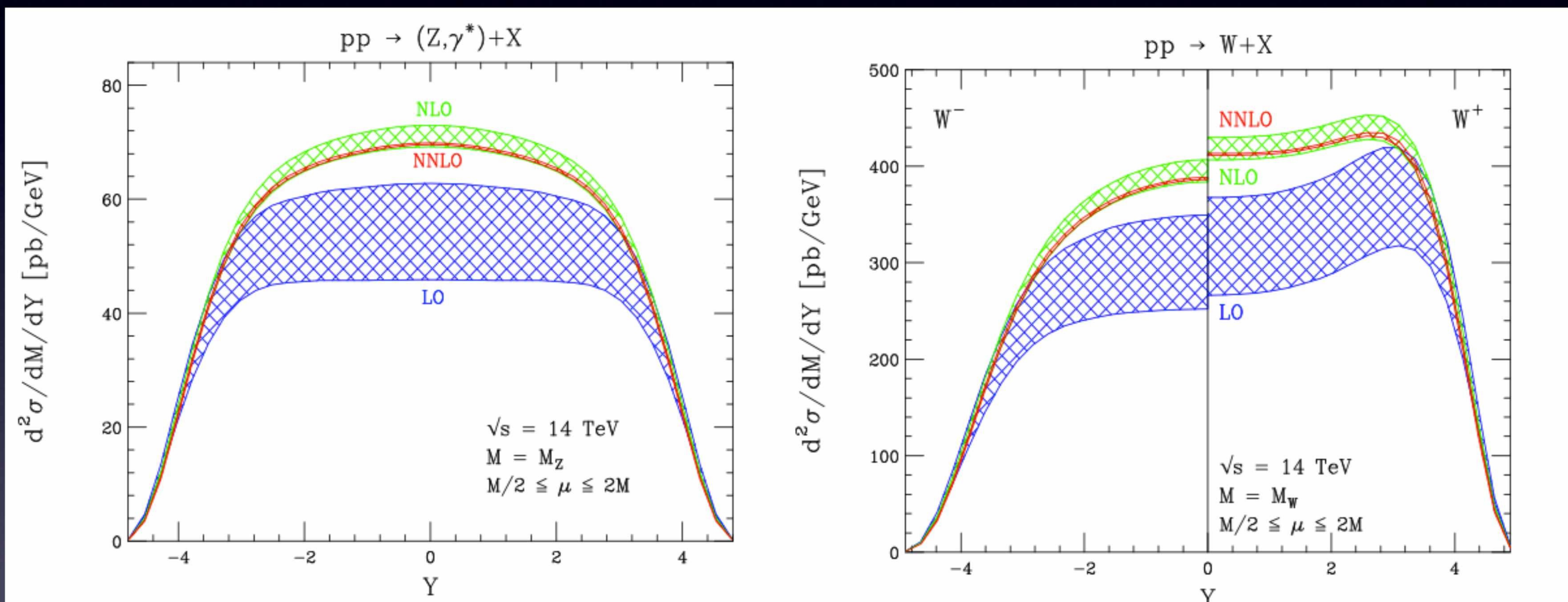
Kinematics



- H1, ZEUS: large coverage in x und Q^2
- HERMES, JLAB: access to large x and low Q^2
- pQCD (DGLAP) predicts Q^2 dependence



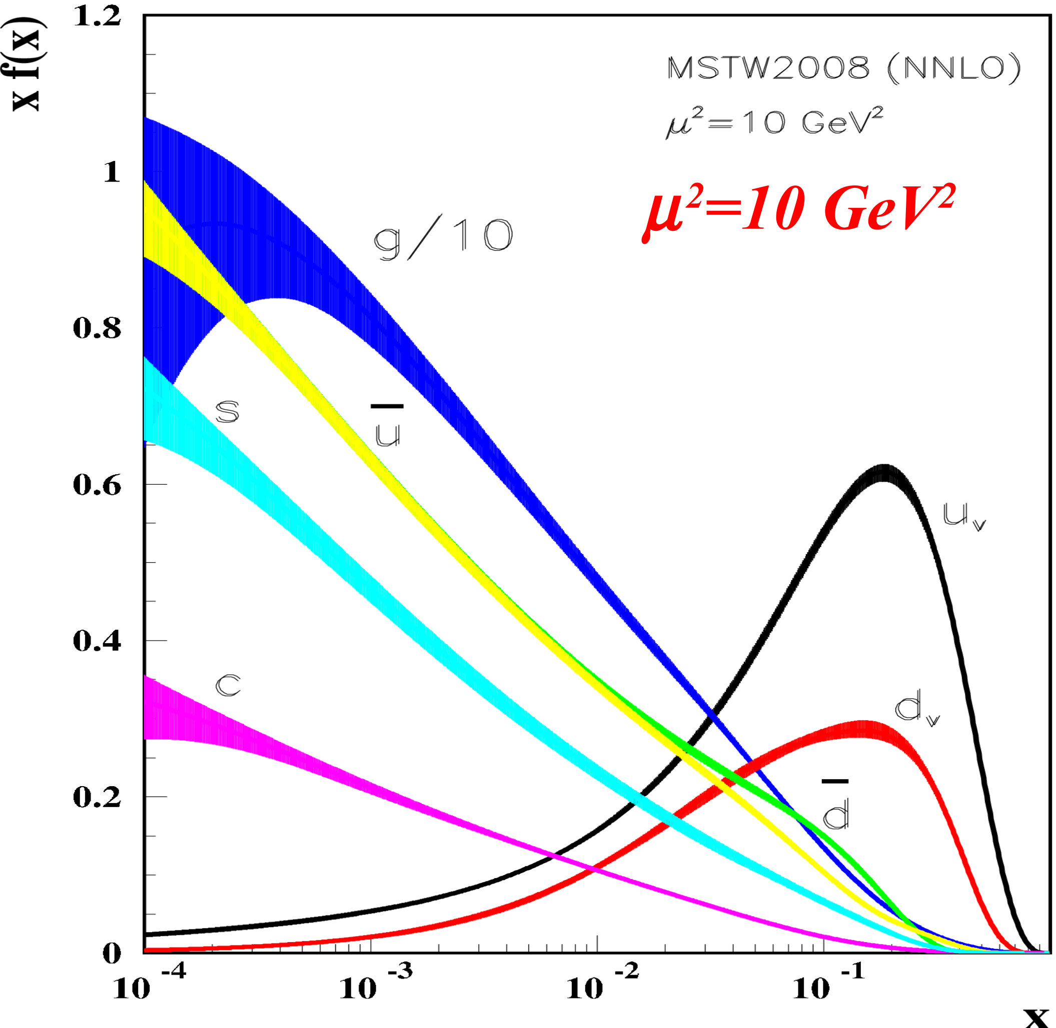
Rapidity distributions



Anastasiou, Dixon, Melnikov, Petriello '03, '05; Melnikov, Petriello '06

☛ *LHC: perturbative accuracy of the order of 1%. This is absolutely unique.*

PDFs are certainly one of the foundations that our search for "new physics" is built upon



LHC results

LHC is ideal for certain measurements

For full picture, we need to combine with other measurements

These measurements are interdependent
and part of the foundation we use
to calibrate the search for “new physics”

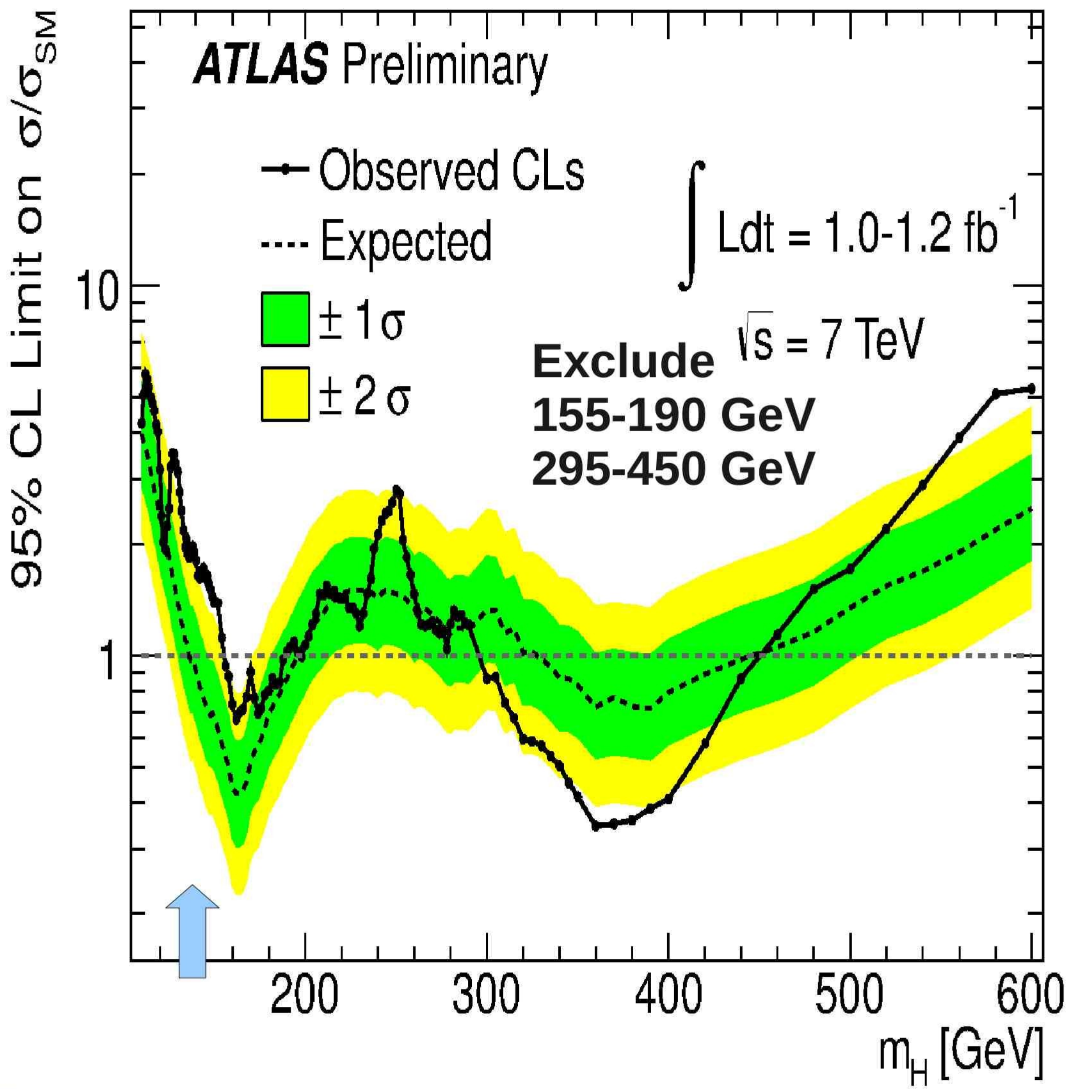
I will look at some select examples

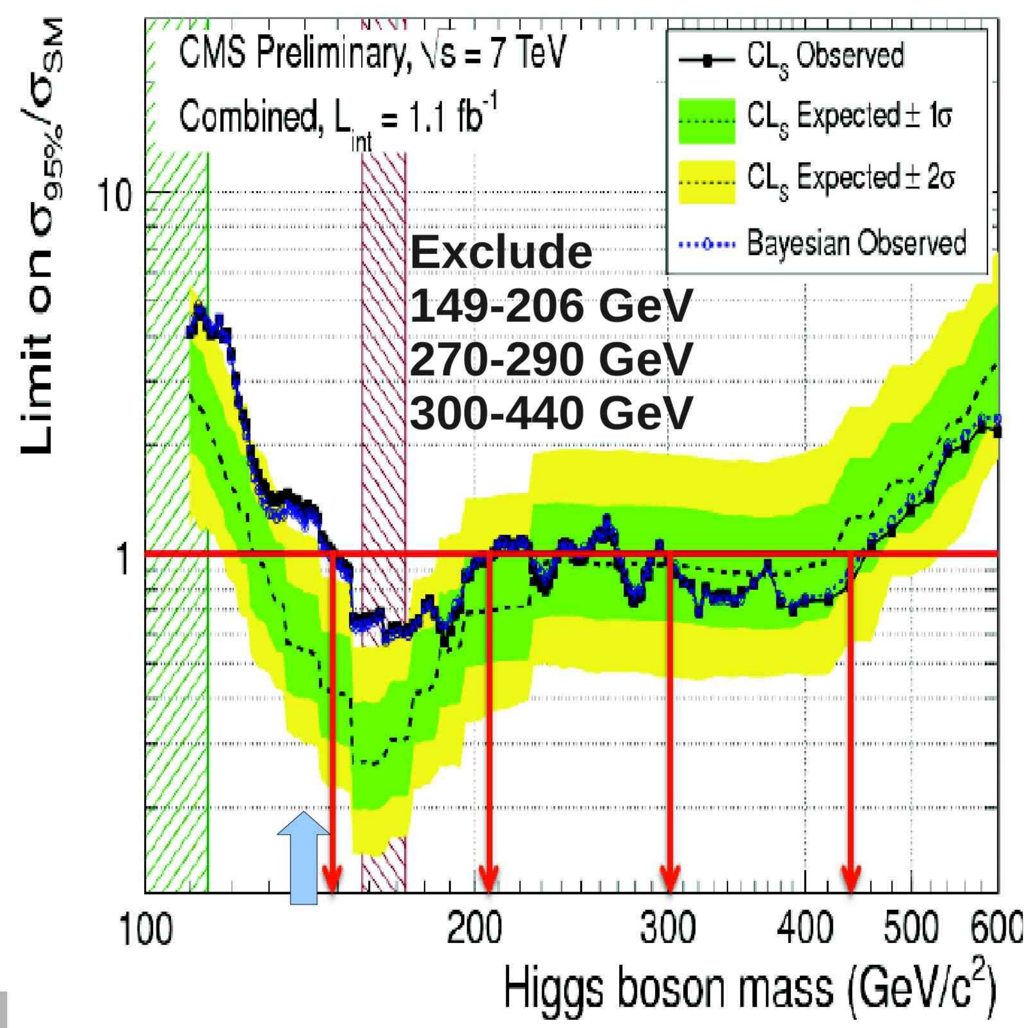
Higgs Production

. . .

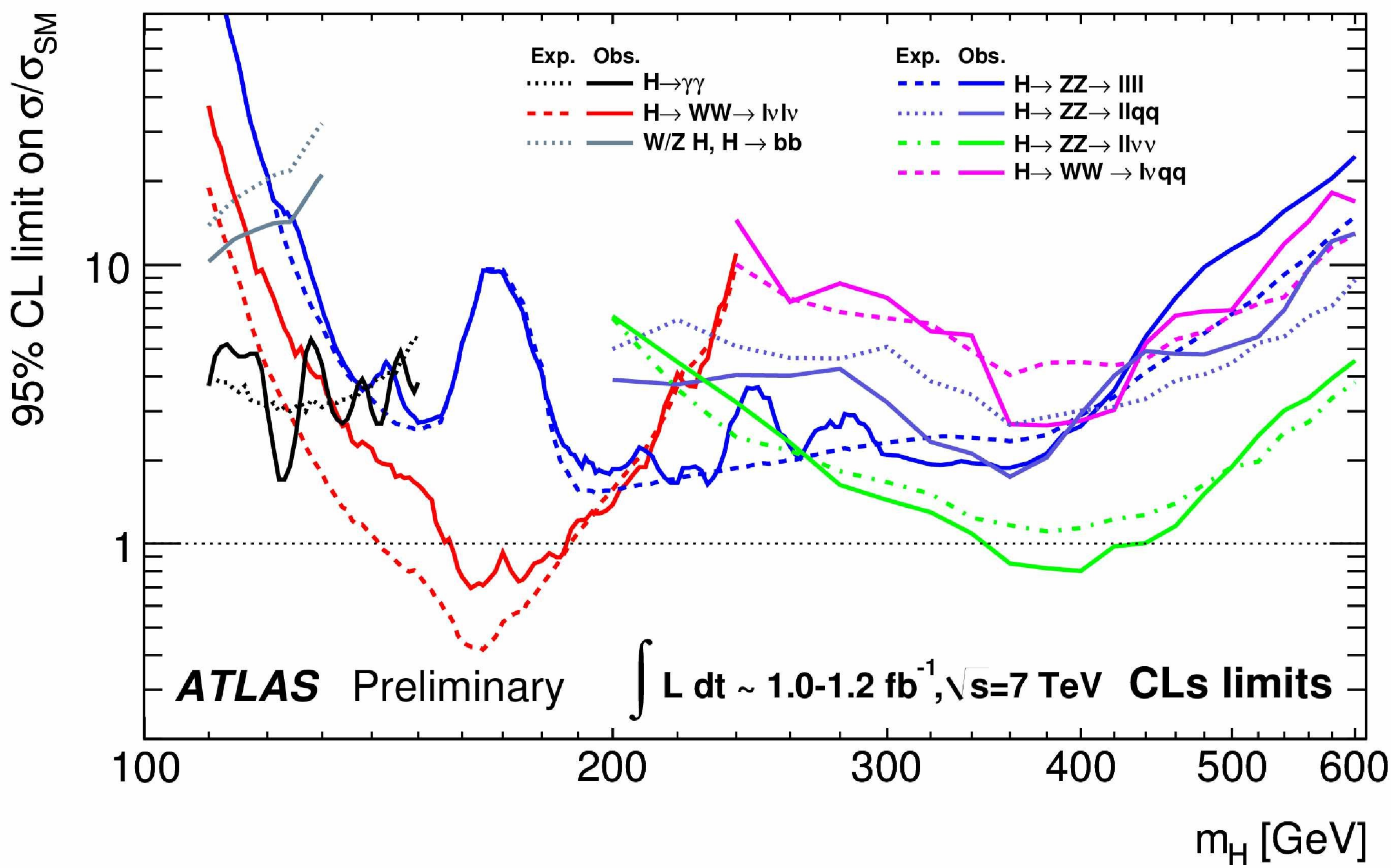
ATLAS & CMS limits

Sensitivities differ in detail
But on average similar





Channels reviewed (ATLAS)



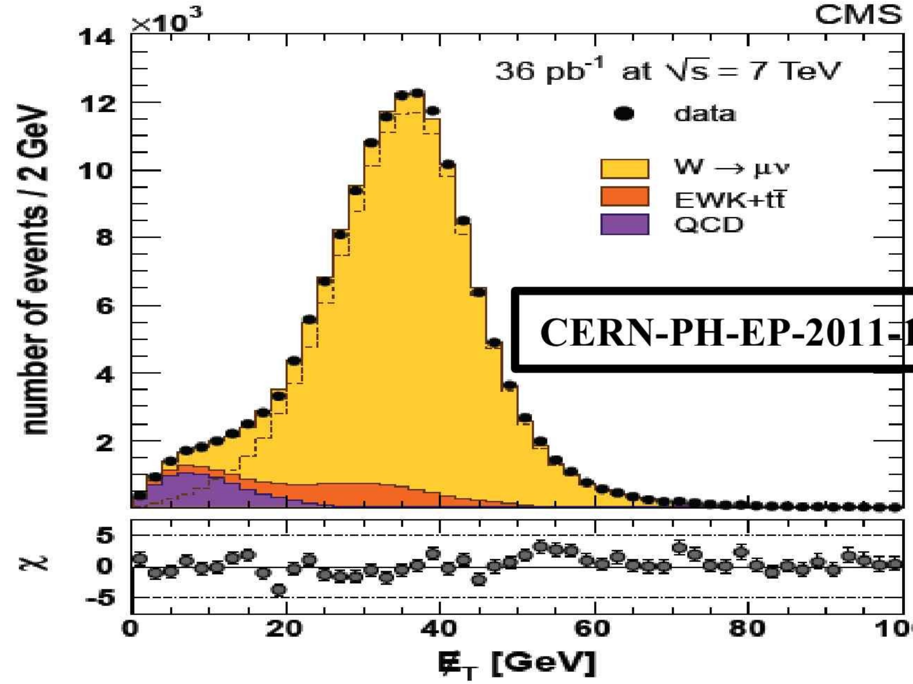
W/Z Production

“Benchmark Calculations”

W and Z selection (muons/electrons)

W selection:

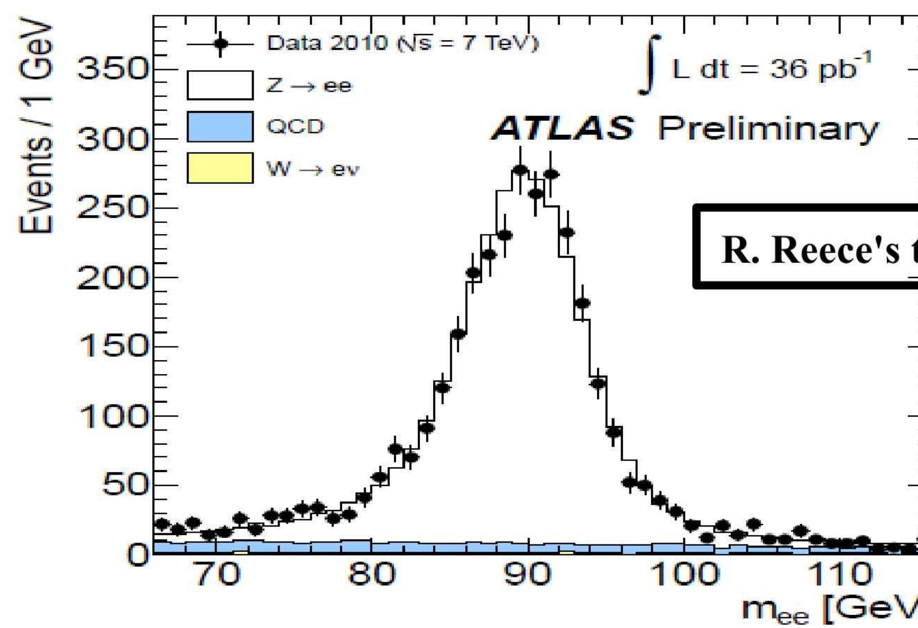
- High-p_T lepton (p_T>20-25 GeV)
- Well Isolated from hadronic activity
- Loose cut on missing transverse energy (or not cut at all (CMS))
- Efficiencies, resolutions, signal and background shapes studied / extracted from data.



CERN-PH-EP-2011-107

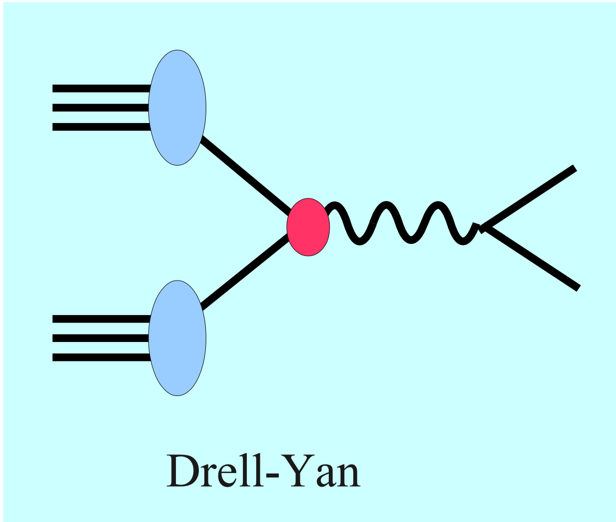
Z selection:

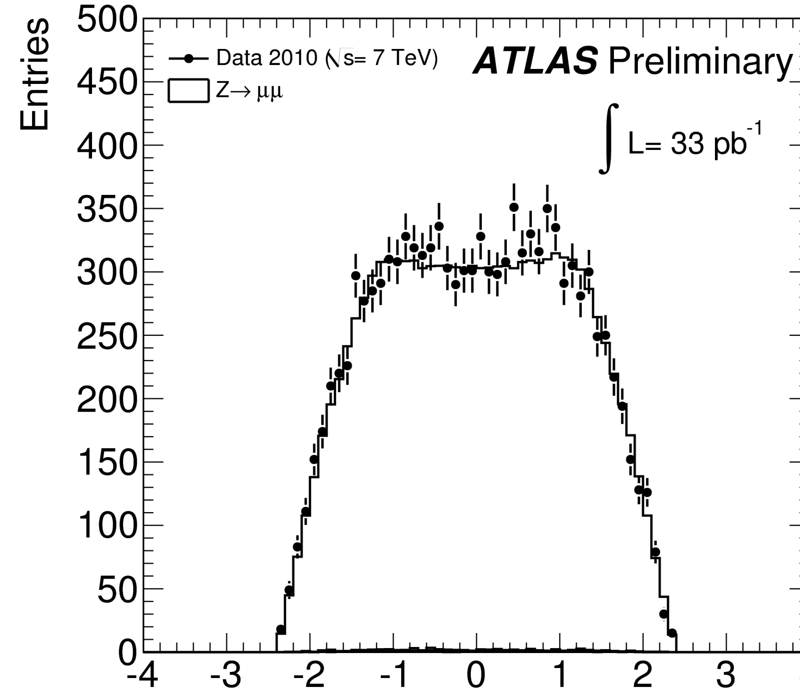
- Two high- p_T leptons (p_T>20-25 GeV), also isolated
- Dilepton mass consistent with a Z
- Efficiencies, resolutions studied / extracted from data.
- Almost background free



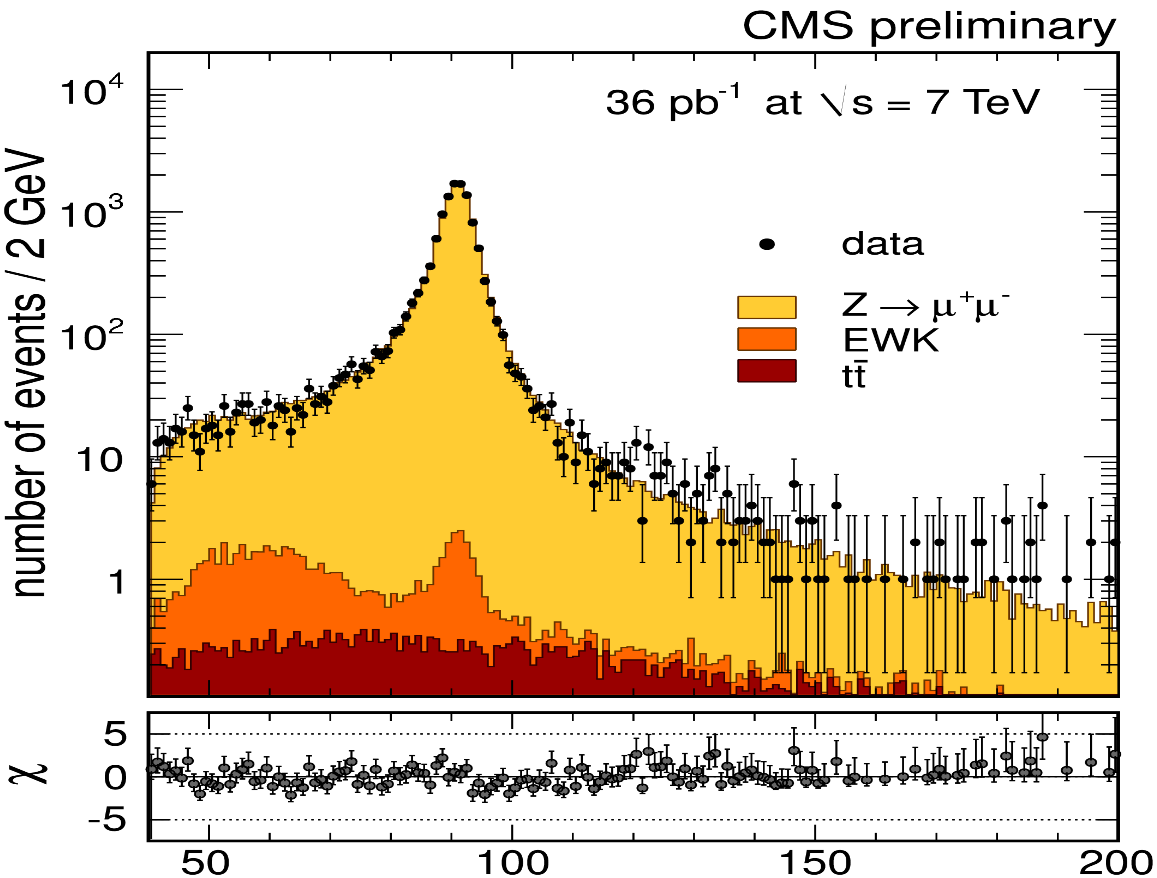
R. Reece's talk

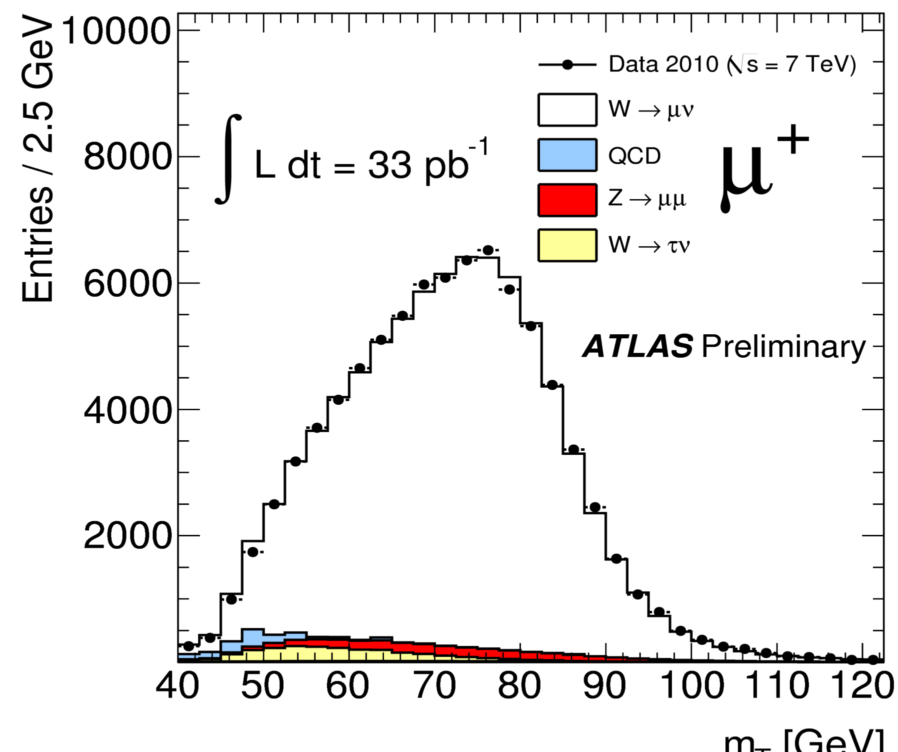
W/Z PRODUCTION





We'll see this again later





Great for searches

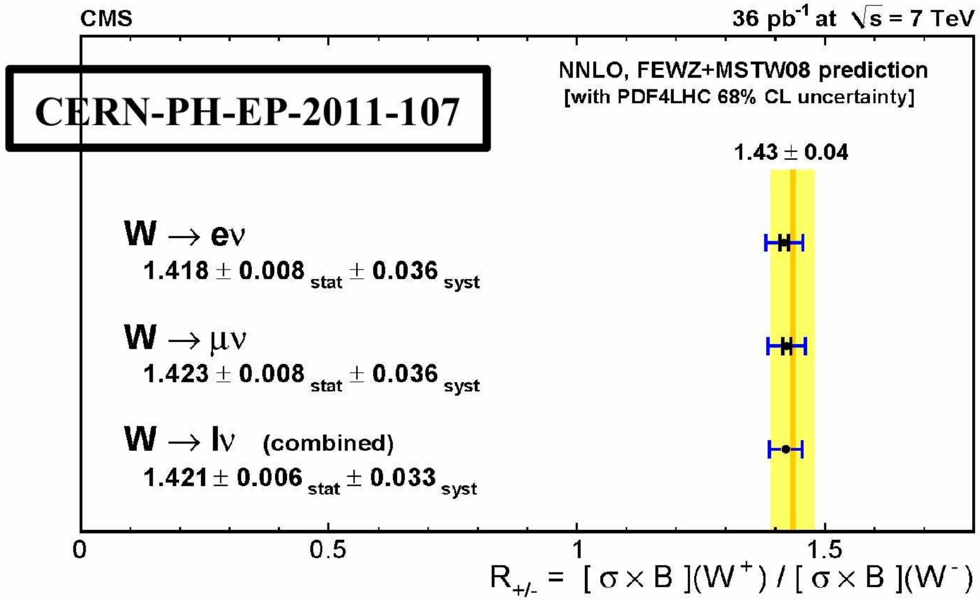
Systematic uncertainties (CMS)

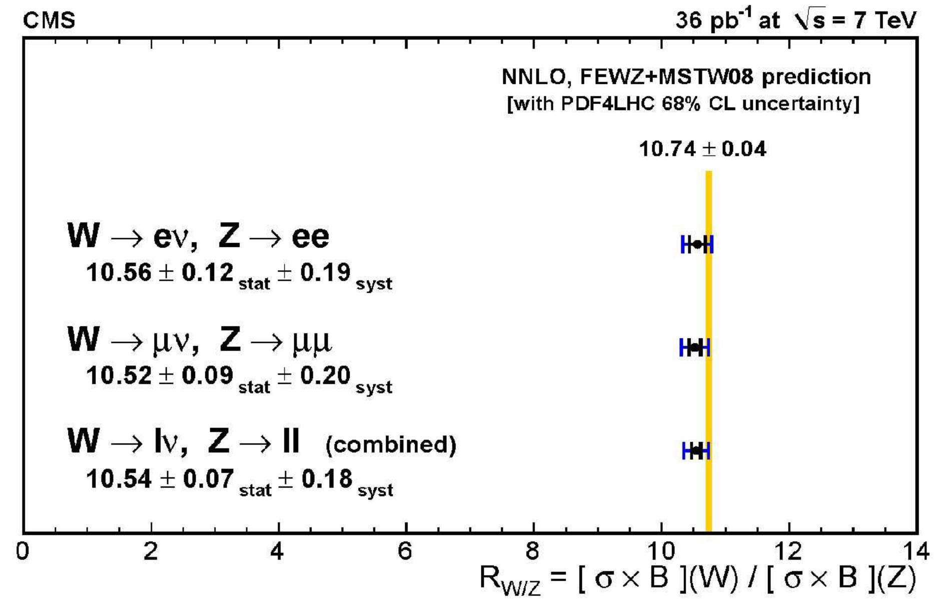
Source (%)	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.4	0.9	1.8	n/a
Trigger prefiring	n/a	0.5	n/a	0.5
Energy/momentum scale & resolution	0.5	0.22	0.12	0.35
$\not{E}_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	0.28
Trigger changes throughout 2010	n/a	n/a	n/a	0.1
Total experimental	1.6	1.1	1.8	0.7
PDF uncertainty for acceptance	0.6	0.8	0.9	1.1
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	0.9	1.1	1.6	1.9
Total (excluding luminosity)	1.8	1.6	2.4	2.0

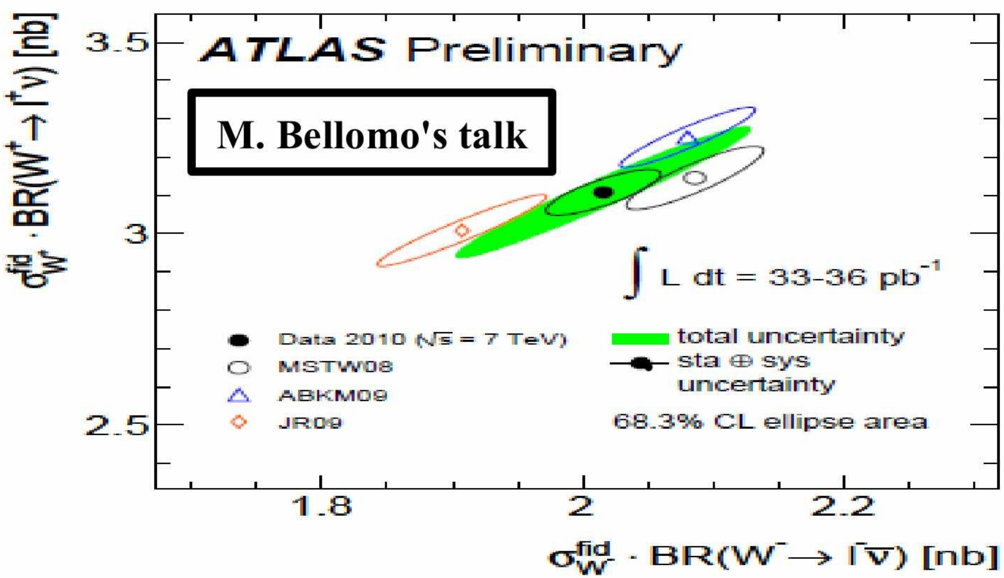
- These are the final 2010 results from CMS (already submitted for publication)
- Experimental uncertainties are significantly reduced thanks to the extensive use of data-driven methods to control efficiencies, backgrounds and signal shapes
- Theoretical and experimental uncertainties have similar sizes
- Measurements in fiducial volume are also provided (smaller theory uncertainty)

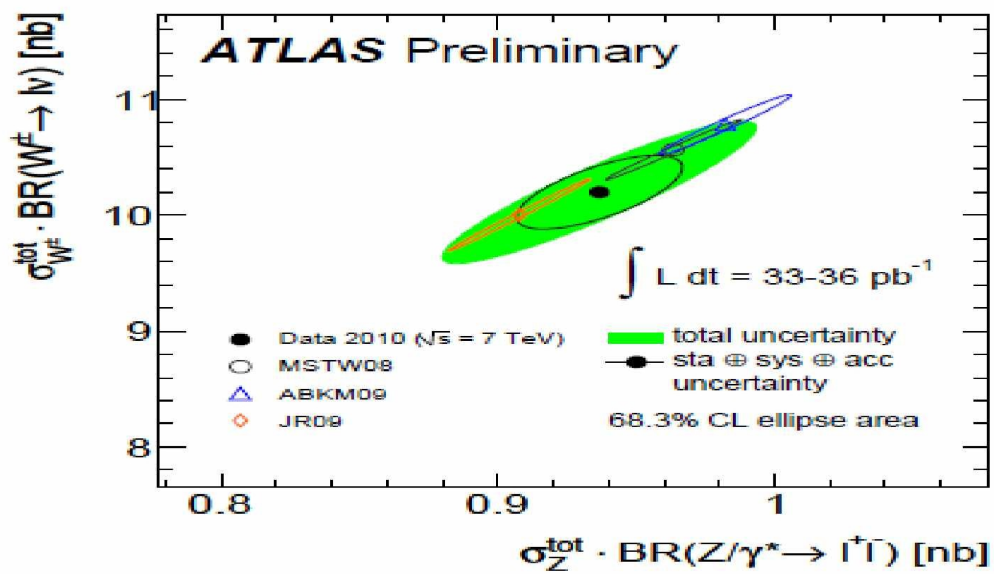
W/Z
Ratios

LHC W+/W- and W/Z ratios





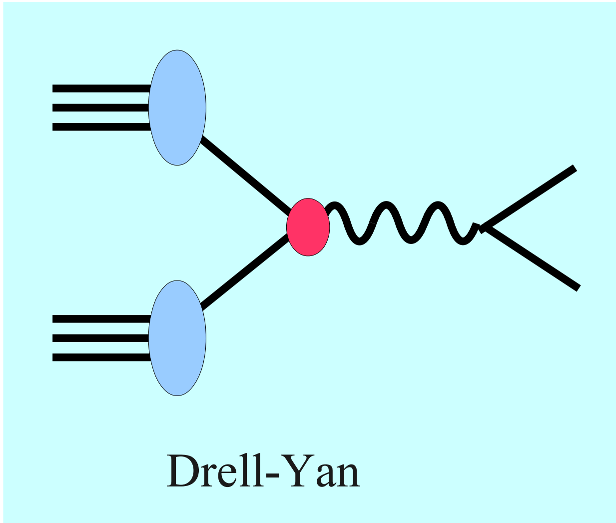


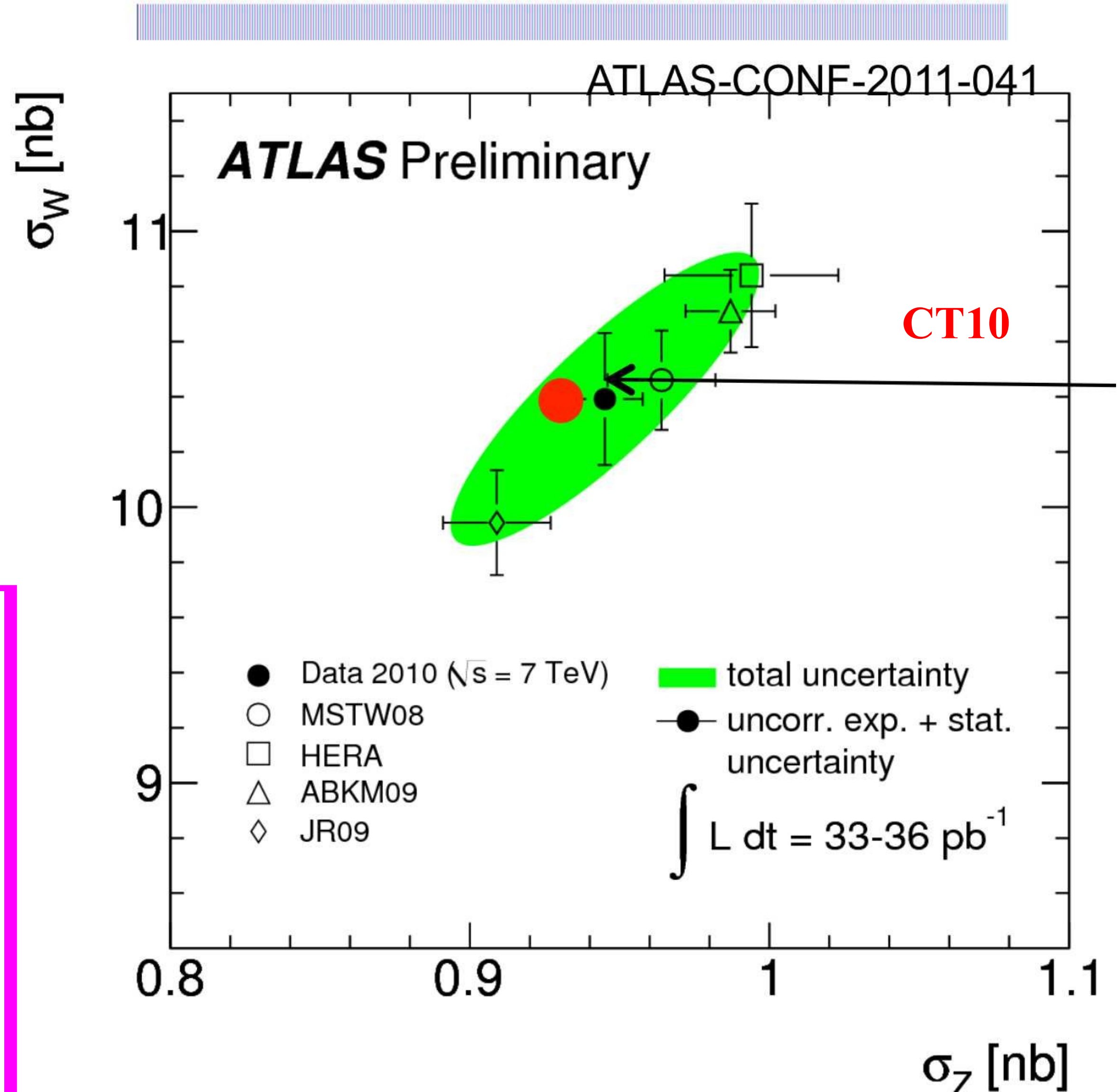


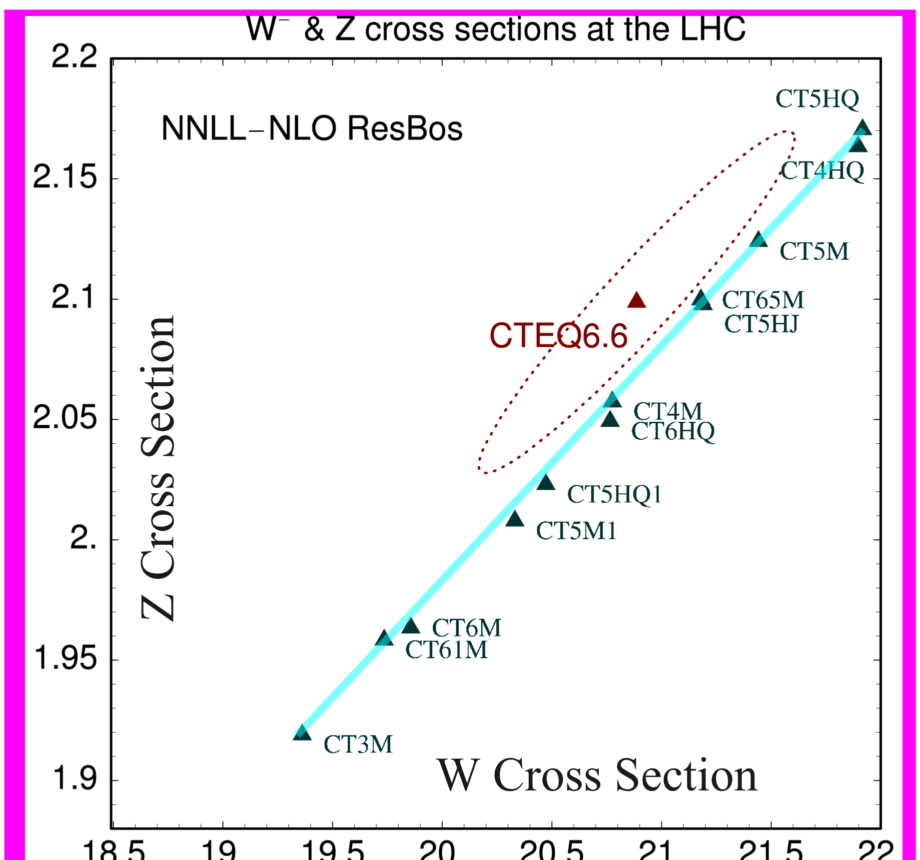
W+/W-: potential to constrain PDF uncertainties

W/Z: stringent test of theoretical expectations

W/Z PRODUCTION





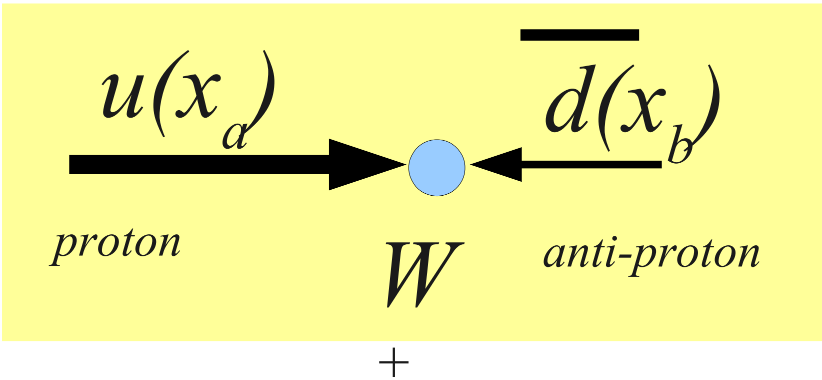


ATLAS W/Z cross section ratio in good agreement with NNLO predictions from the PDF groups shown

W
Asymmetry
@ LHC

W Asymmetry

A bit of calculation



$$A(y) = \frac{\frac{d\sigma}{dy}(W^+) - \frac{d\sigma}{dy}(W^-)}{\frac{d\sigma}{dy}(W^+) + \frac{d\sigma}{dy}(W^-)}$$

With the previous approximation,

$$A \approx \frac{u(x_a)d(x_b) - d(x_a)u(x_b)}{u(x_a)d(x_b) + d(x_a)u(x_b)} = \frac{R_{du}(x_b) - R_{du}(x_a)}{R_{du}(x_b) + R_{du}(x_a)}$$

where $\quad R_{du}(x) = \frac{d(x)}{u(x)}$

$$x_{1,2} = x_0 e^{\pm y} \simeq x_0(1 \pm y)$$

We can make Taylor expansions:

$$R_{du}(x_{1,2}) \approx R_{du}(x_0) \pm y\, x_0 R'_{du}(\sqrt{\tau})$$

Thus, the asymmetry is:

$$A(y) = -y\, x_0 \frac{R'_{du}(x_0)}{R_{du}(x_0)}$$

EXERCISE: Verify the above.

W lepton charge asymmetry

- A first natural extension of the W inclusive studies is the study of the W^+/W^- ratio, R_W, as a function of different kinematic variables.
- Experimentally, a clean way to do this study is to measure the charge asymmetry as a function of the lepton pseudo-rapidity

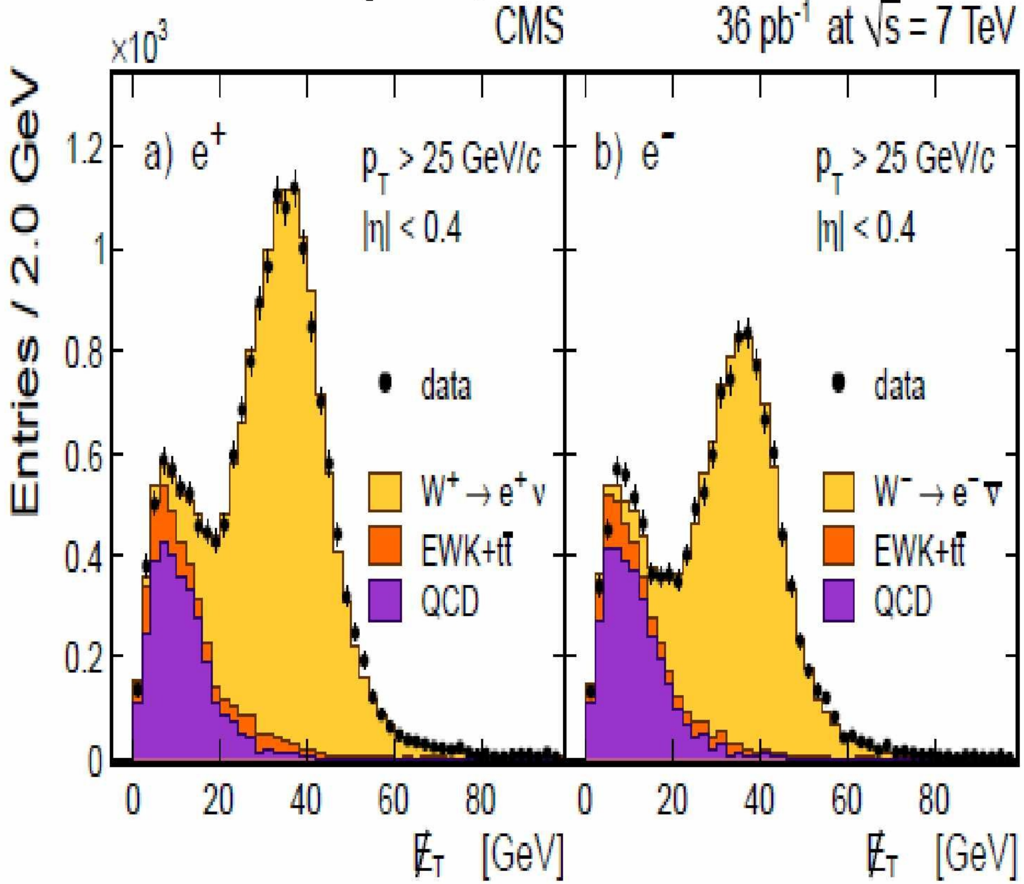
$$A(\eta)=\frac{\frac{d\sigma}{d\eta}(W^+\to l^+\nu)-\frac{d\sigma}{d\eta}(W^-\to l^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+\to l^+\nu)+\frac{d\sigma}{d\eta}(W^-\to l^-\bar{\nu})}$$

$$\left(A(\eta)\equiv\frac{R_W(\eta)-1}{R_W(\eta)+1}\right)$$

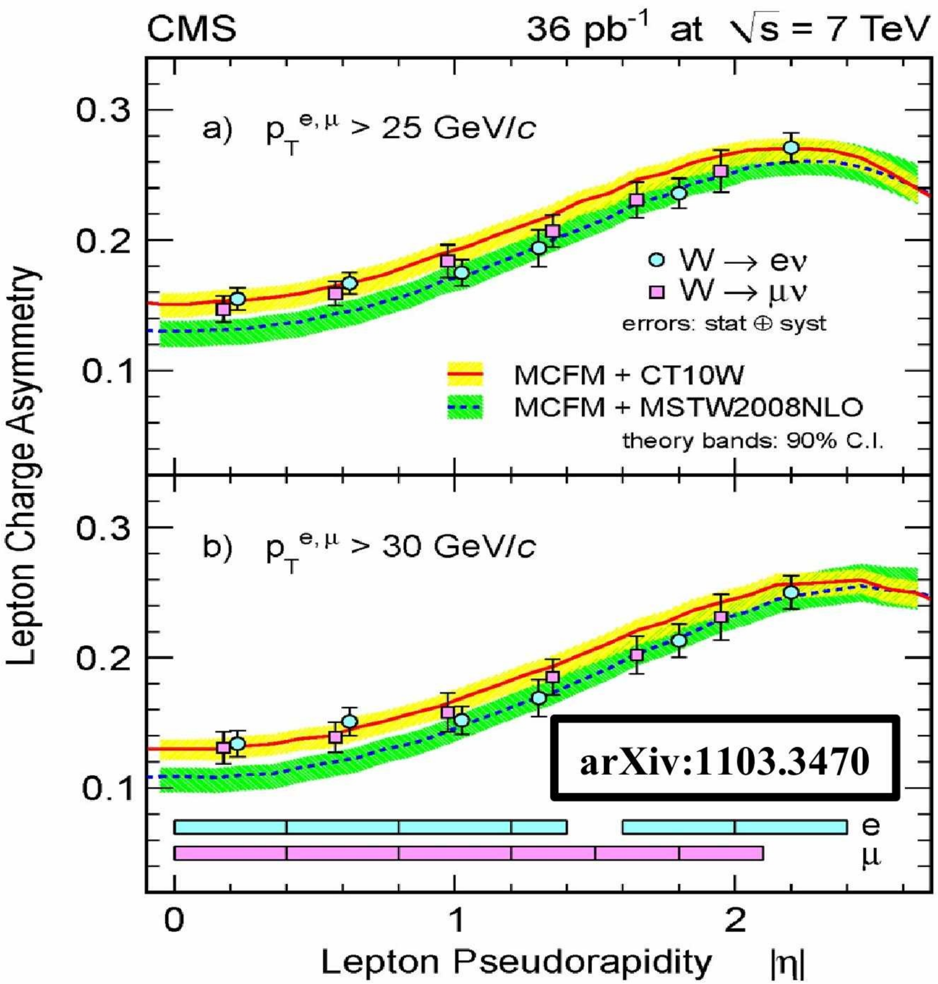
- This measurement is rather sensitive to PDFs because most systematic uncertainties cancel in the ratio
- Selections follow closely the criteria used in inclusive measurements.

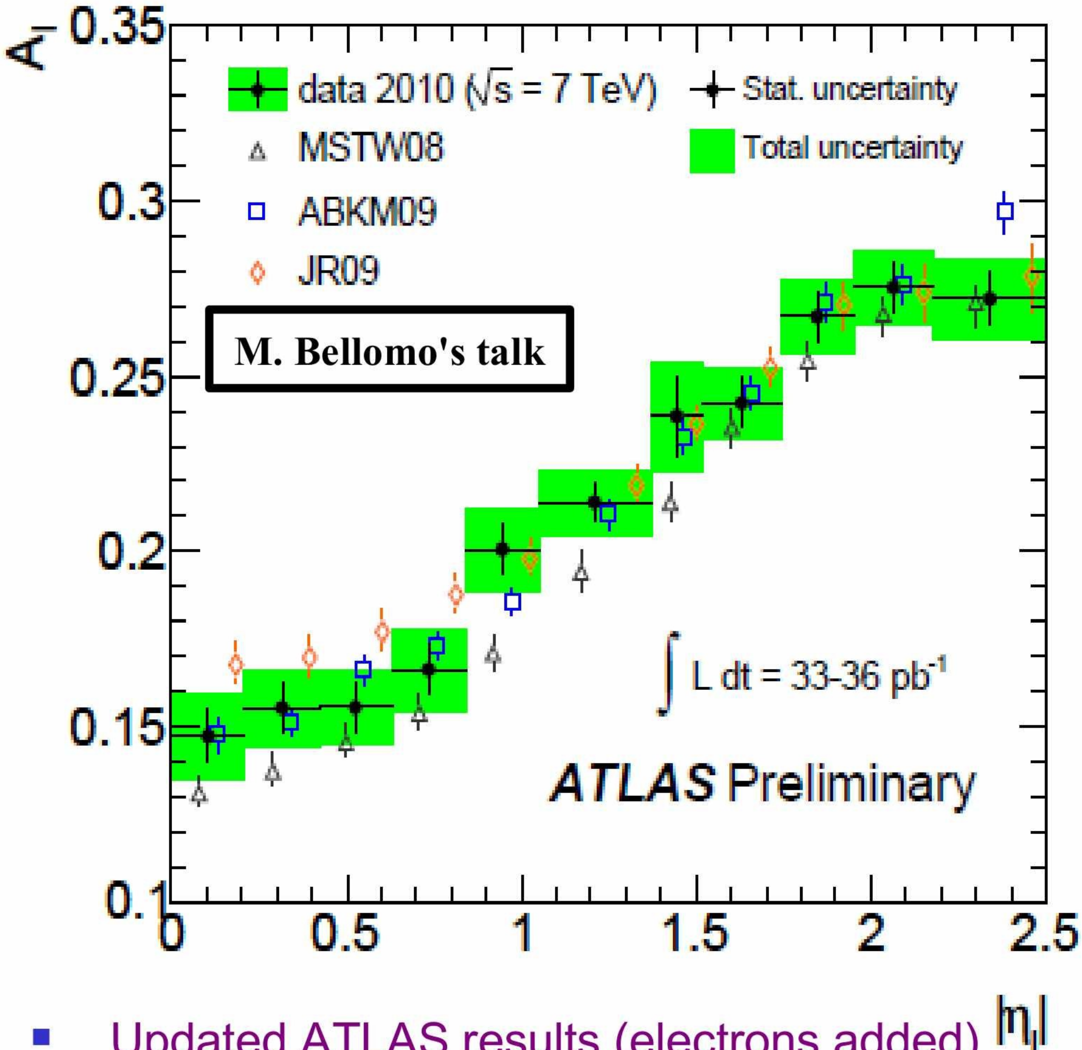
arXiv:1103.3470

First η bin, electron channel



W lepton charge asymmetry

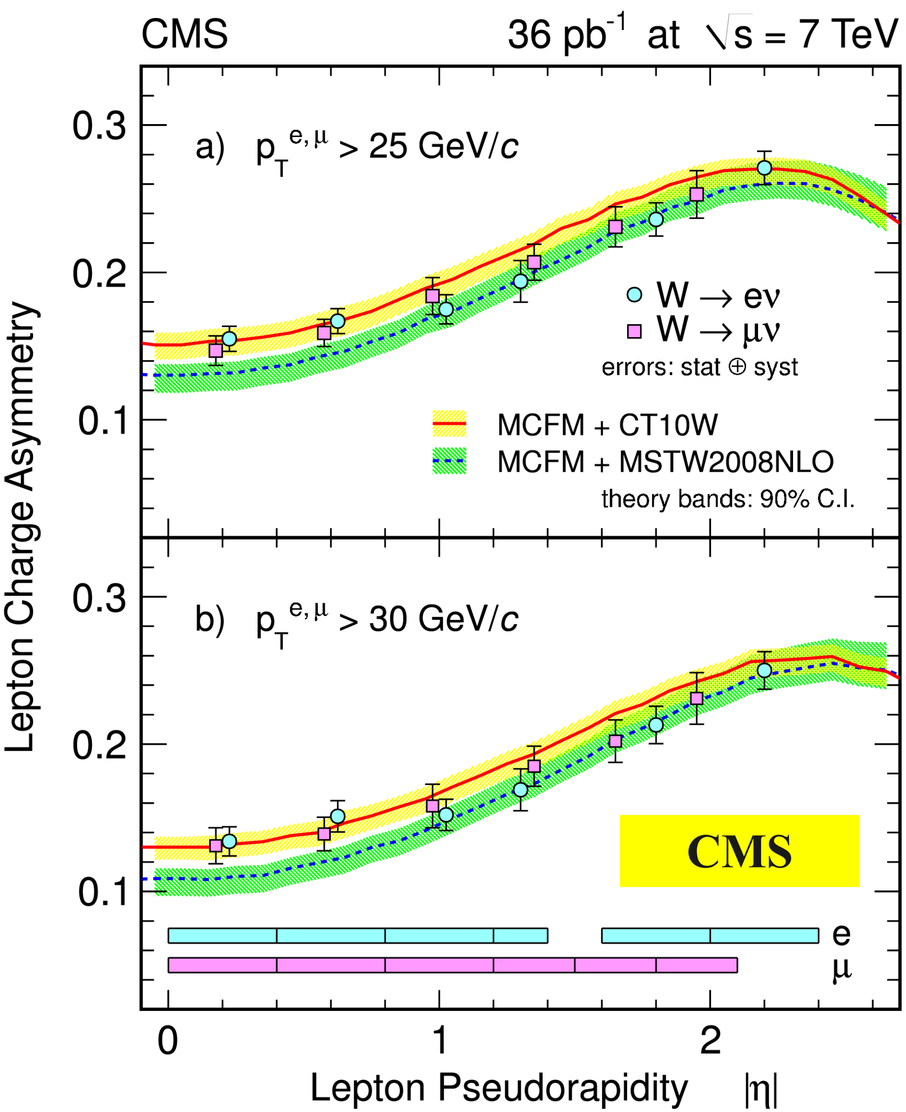


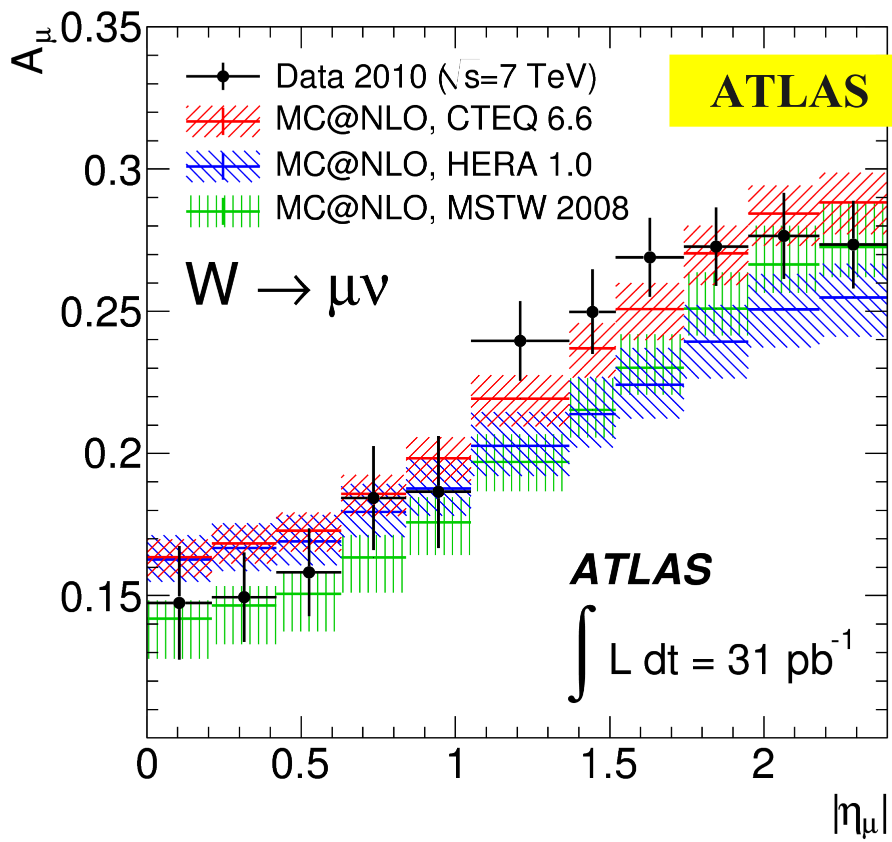


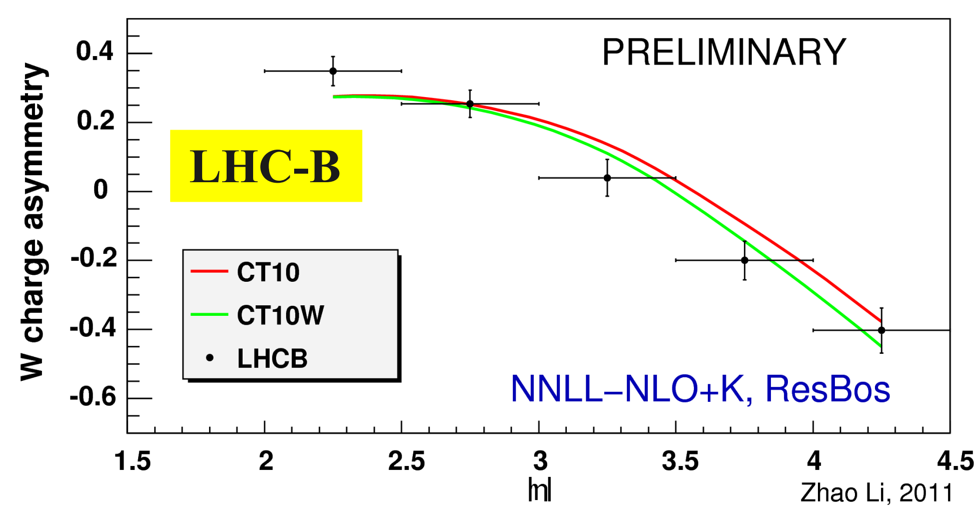
- CMS published results
- Updated ATLAS results (electrons added)

In reasonable agreement with different PDF predictions, but extremely sensitive to shape details

$$A_\mu = \frac{d\sigma(W_{\mu^+}) - d\sigma(W_{\mu^-})}{d\sigma(W_{\mu^+}) + d\sigma(W_{\mu^-})}$$



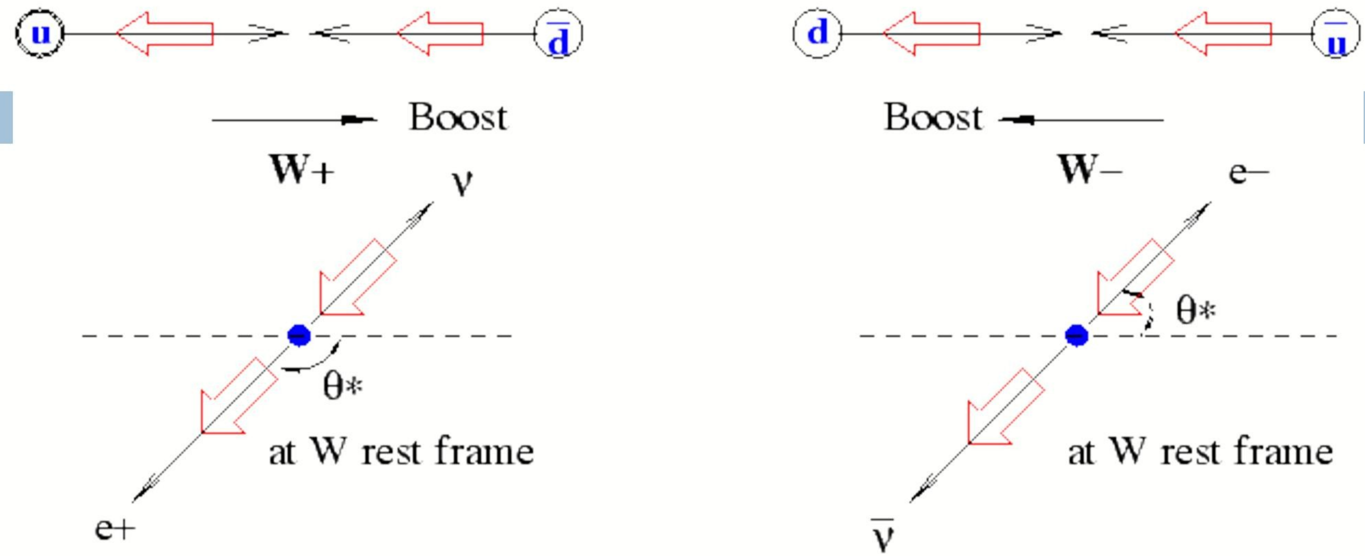




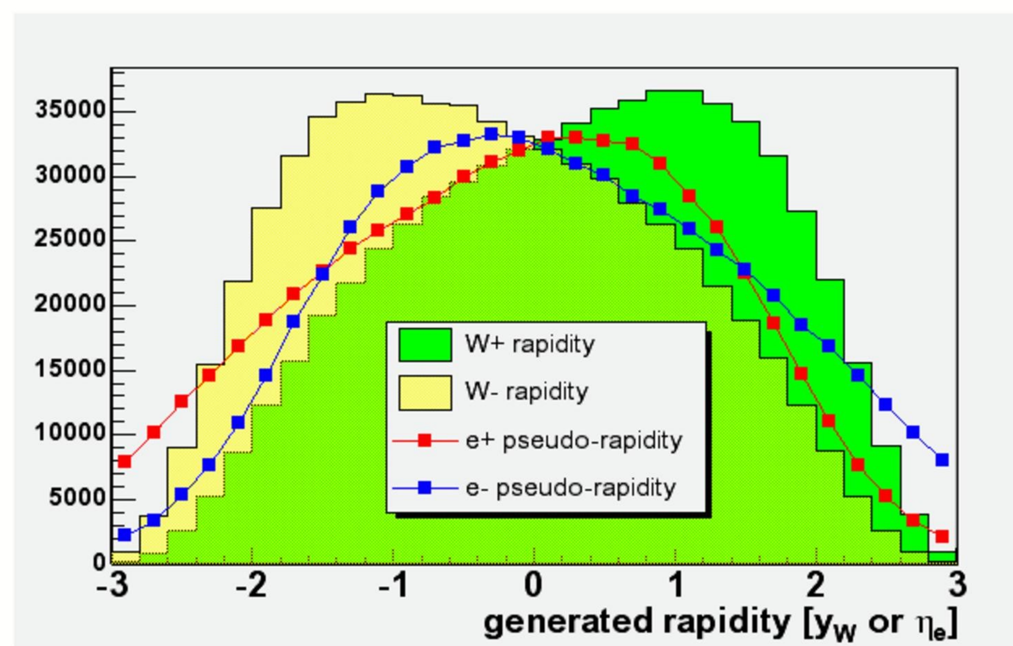
W
Asymmetry
@ Tevatron

$$A_\ell = \frac{d\sigma(W^+ \to \ell^+) - d\sigma(W^- \to \ell^-)}{d\sigma(W^+ \to \ell^+) + d\sigma(W^- \to \ell^-)}$$

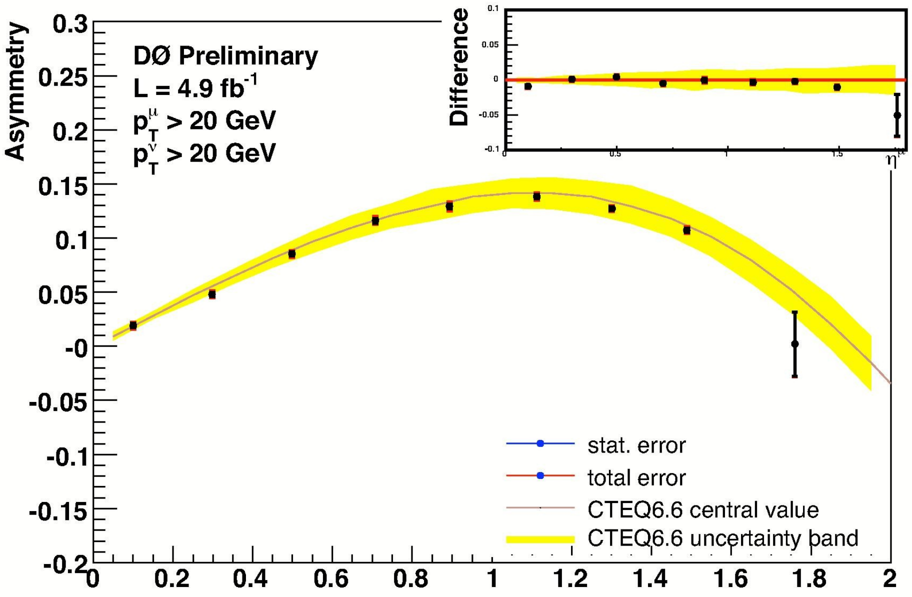
W asymmetry in p-pbar collisions

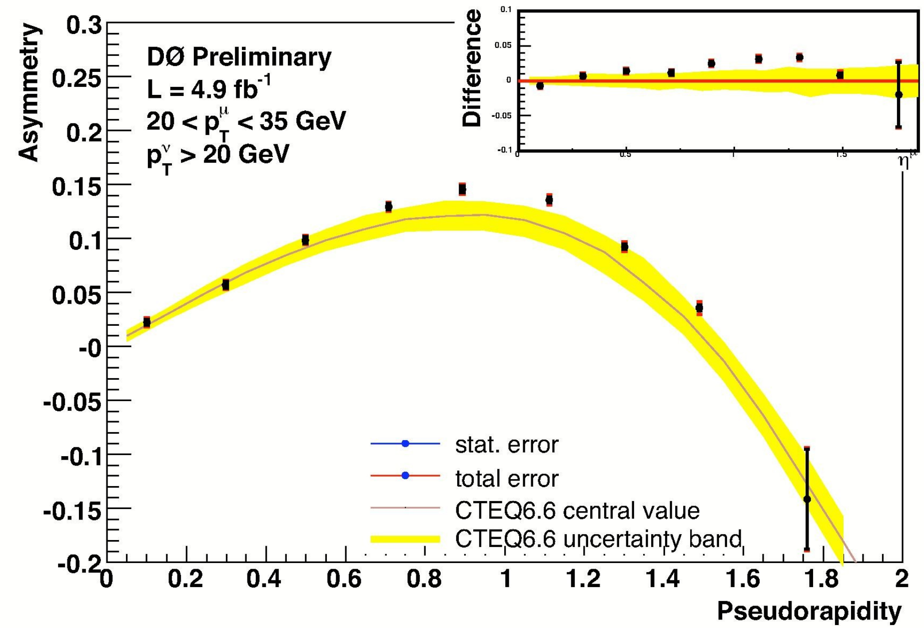


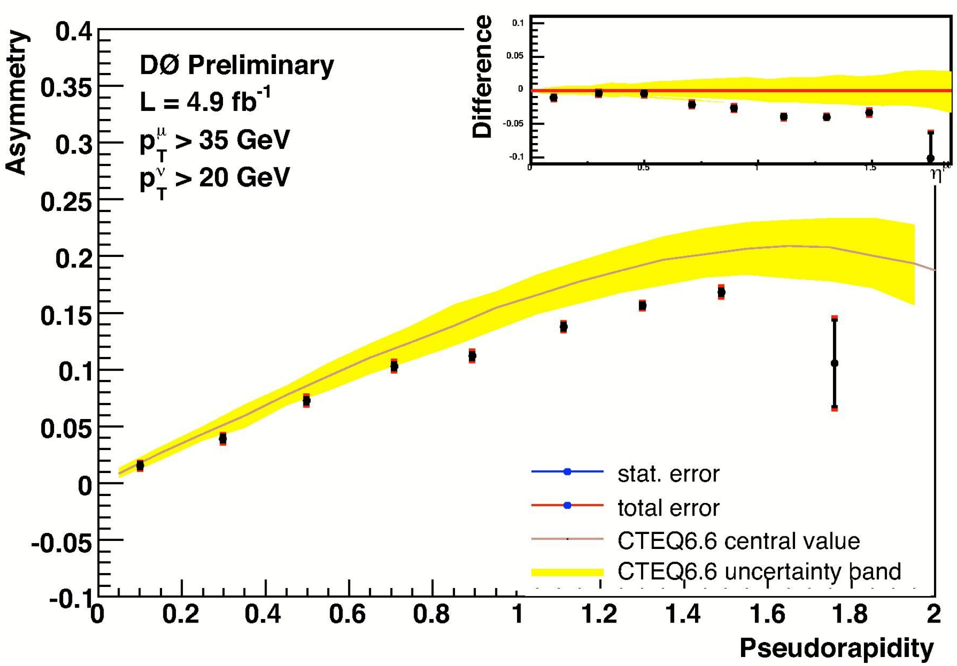
- If u quarks carry more momentum than d quarks, the W^+ will head in the proton direction preferentially.
- Unfortunately, the V-A interaction means that the charged lepton from W decay heads backwards in the W frame



Results compared to RESBOS+CTEQ6.6M







3 muon PT bins, PT(ν) > 20 GeV

Upper Left – PT(μ) > 20 GeV

Upper Right 20 GeV < PT(μ) < 35 GeV

Lower Left PT(μ) > 35 GeV

The puzzle of the CDF/D0 W lepton asymmetry

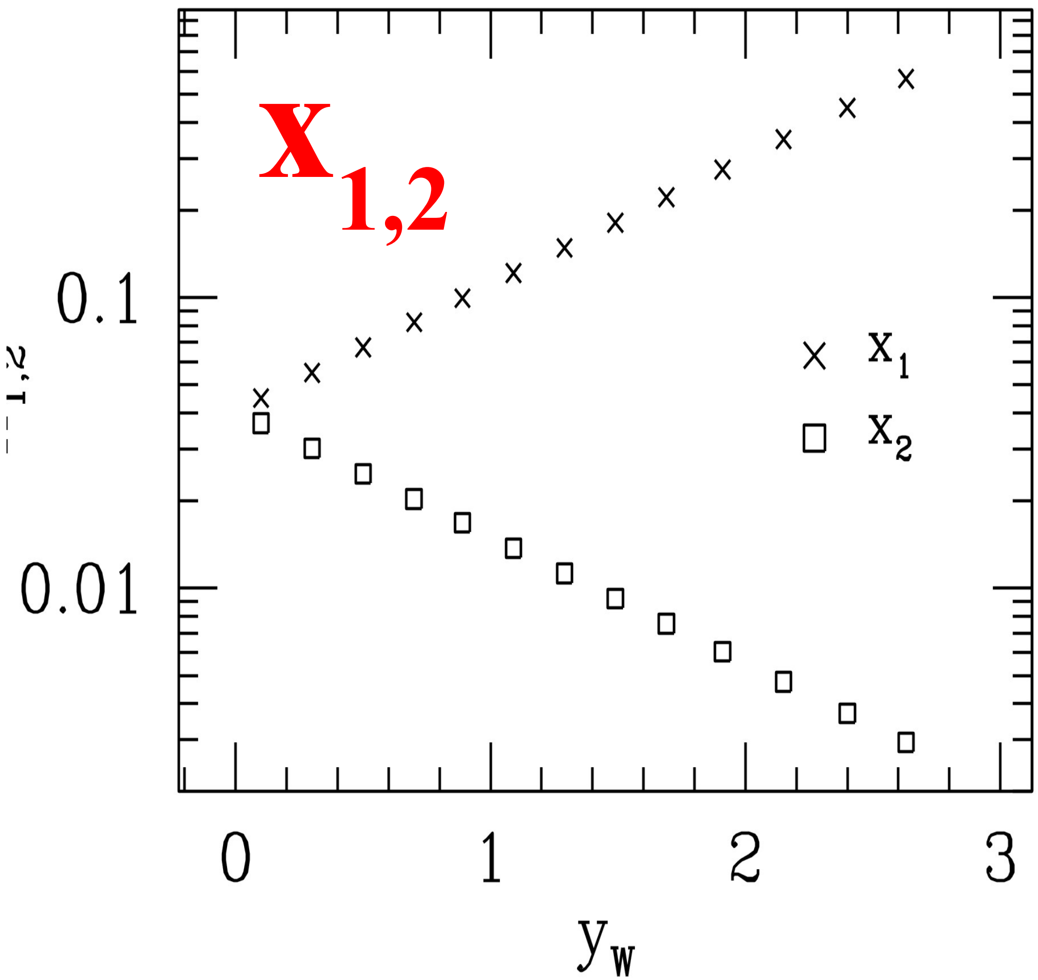
- CT10W set reasonably agrees with 3 $p_{T\ell}$ bins of $A_e(y_e)$ and one bin of $A_\mu(y_\mu)$ from D0 Run-2 (2008).
- NNPDF 2.0 *(arXiv:1012.0836)* agrees with $A_\mu(y_\mu)$, disagrees with two p_{Te} bins of $A_e(y_e)$.
- CT10, many other PDFs fail.

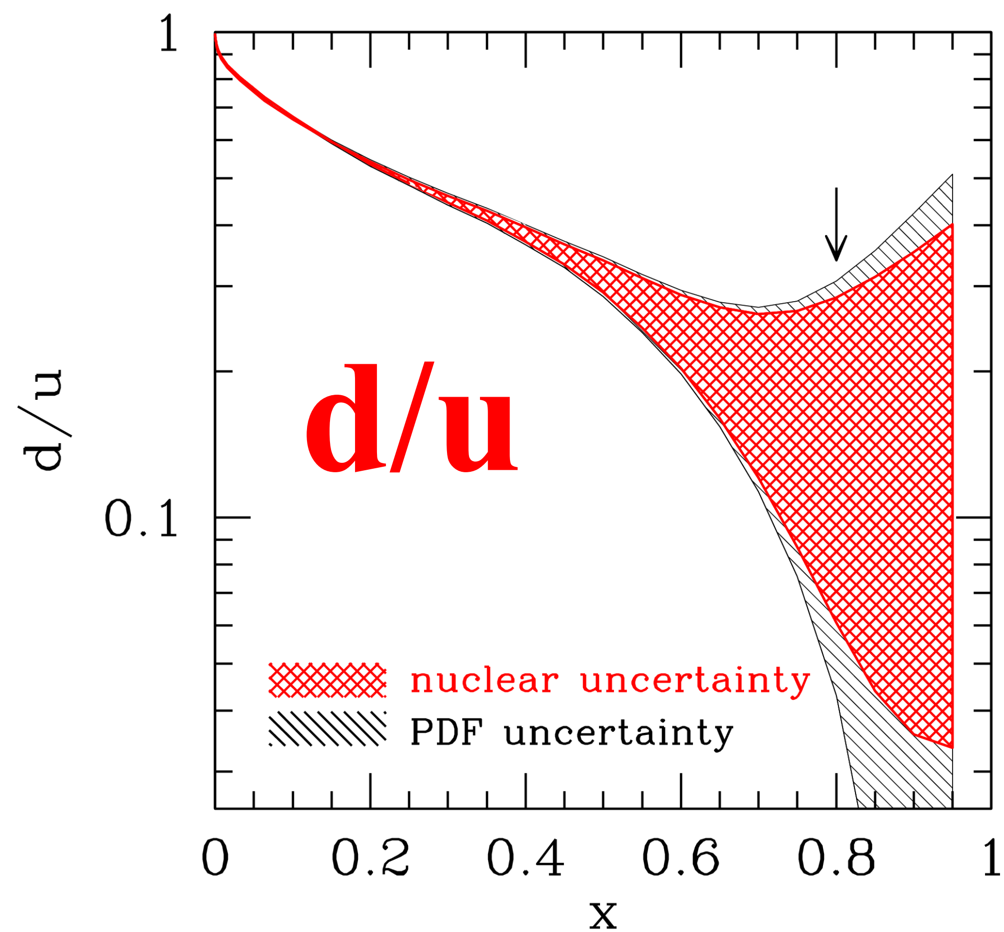
Agreement of PQCD with D0 $A_e(y_e)$	χ^2/npt	Source or comments
CTEQ6.6, NLO	191/36=5.5	*Our study;*
CT10W, NLO	**78/36=2.2** **With $A_\mu(y_\mu)$: 88/47=1.9**	*Resbos, NNLL-NLO*
ABKM'09, NNLO	540/24=22.5	*Catani, Ferrera, Grazzini,*
MSTW'08, NNLO	205/24=8.6	*JHEP 05, 006 (2010)*
JR09VF, NNLO	113/24=4.7	

What is happening with d/u

This combination rather unique

$$A_\ell = \frac{d\sigma(W^+ \to \ell^+) - d\sigma(W^- \to \ell^-)}{d\sigma(W^+ \to \ell^+) + d\sigma(W^- \to \ell^-)}$$





Determined from DIS and DY on p and d

$$x_{1,2} \sim \frac{M}{\sqrt{s}} e^{\pm y}$$

LHC values scaled appropriately

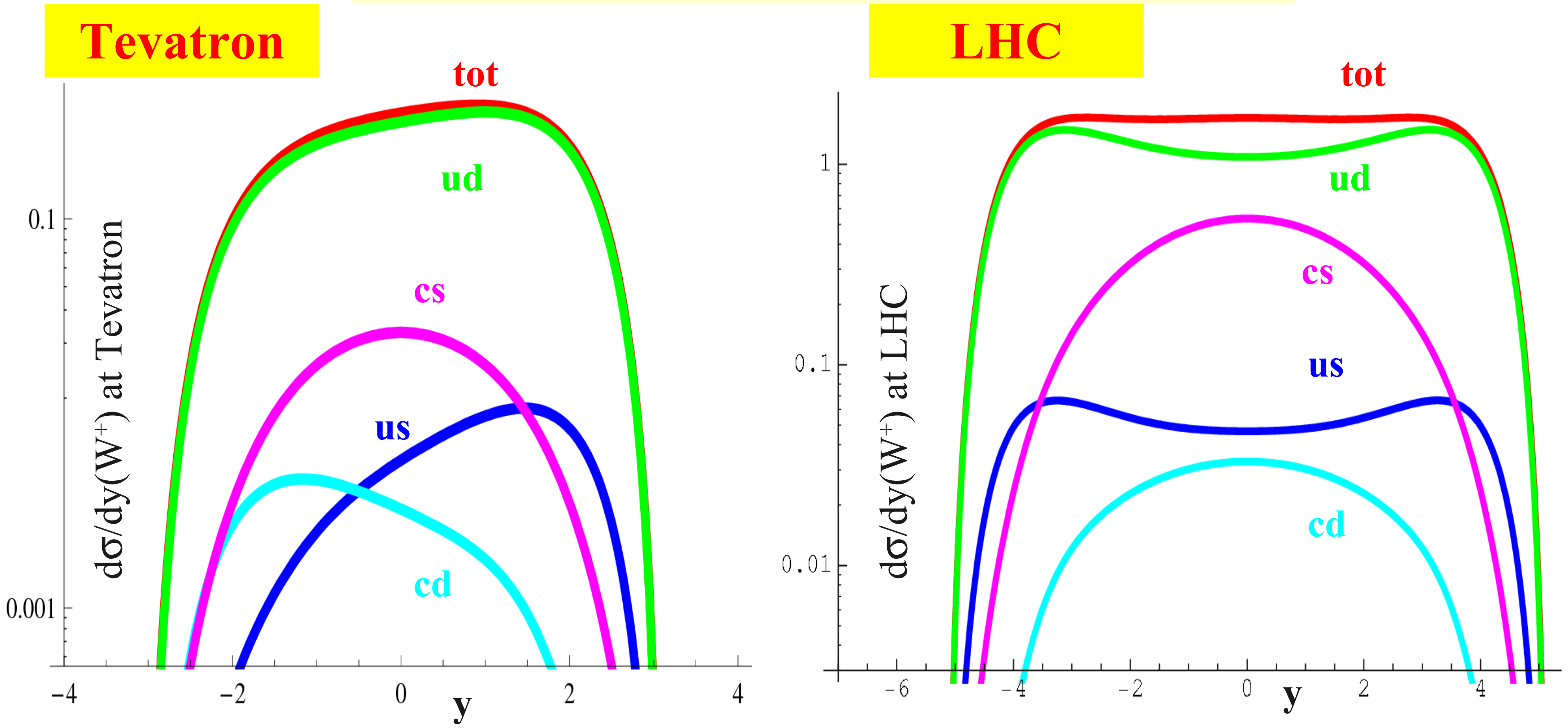
Uncertainties in determining parton distributions at large x.
A.Accardi, W.Melnitchouk, J.F.Owens, M.E.Christy, C.E.Keppel, L.Zhu, J.G.Morfin
arXiv:1102.3686 [hep-ph]

W/Z Production

On the theoretical side …

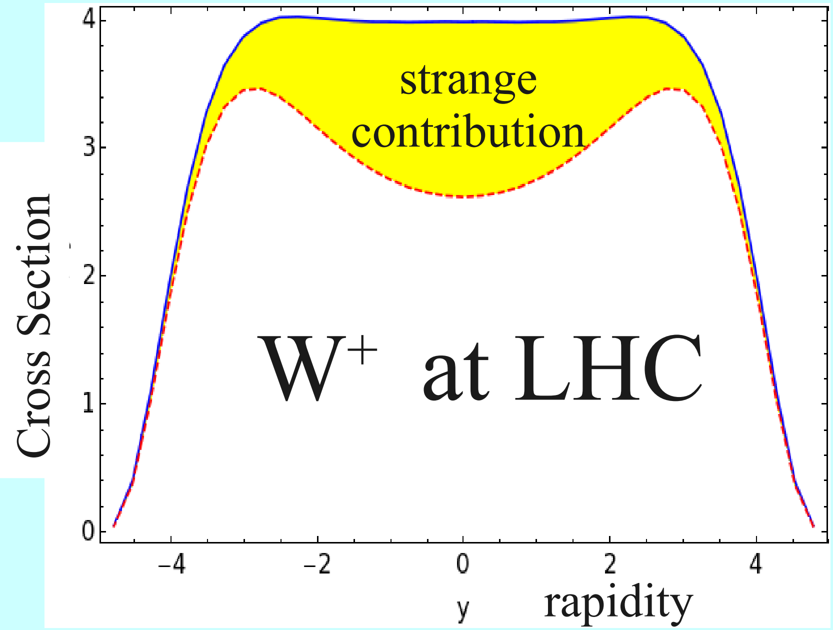
W Production at LHC: A Benchmark Cross Section

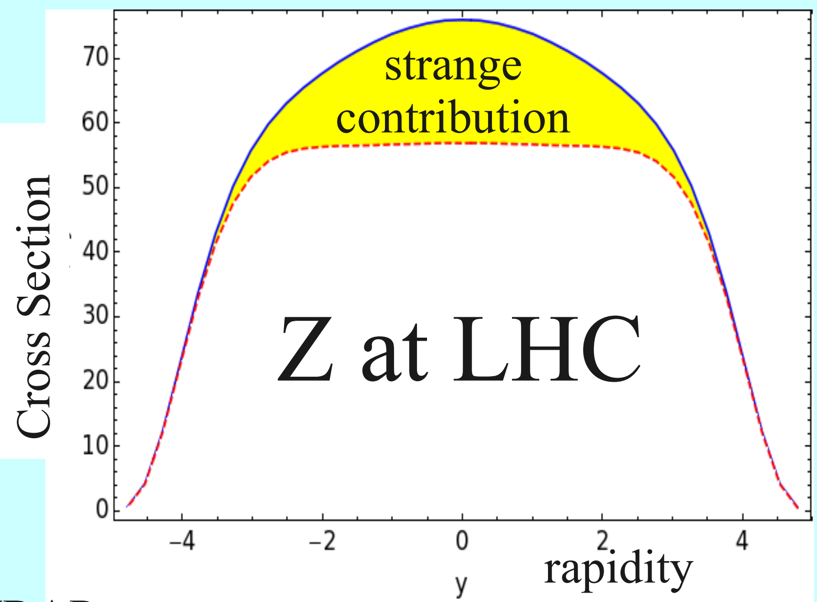
Heavy quark PDFs are essential ingredient



Heavy Quark components play an increasingly important role at the LHC

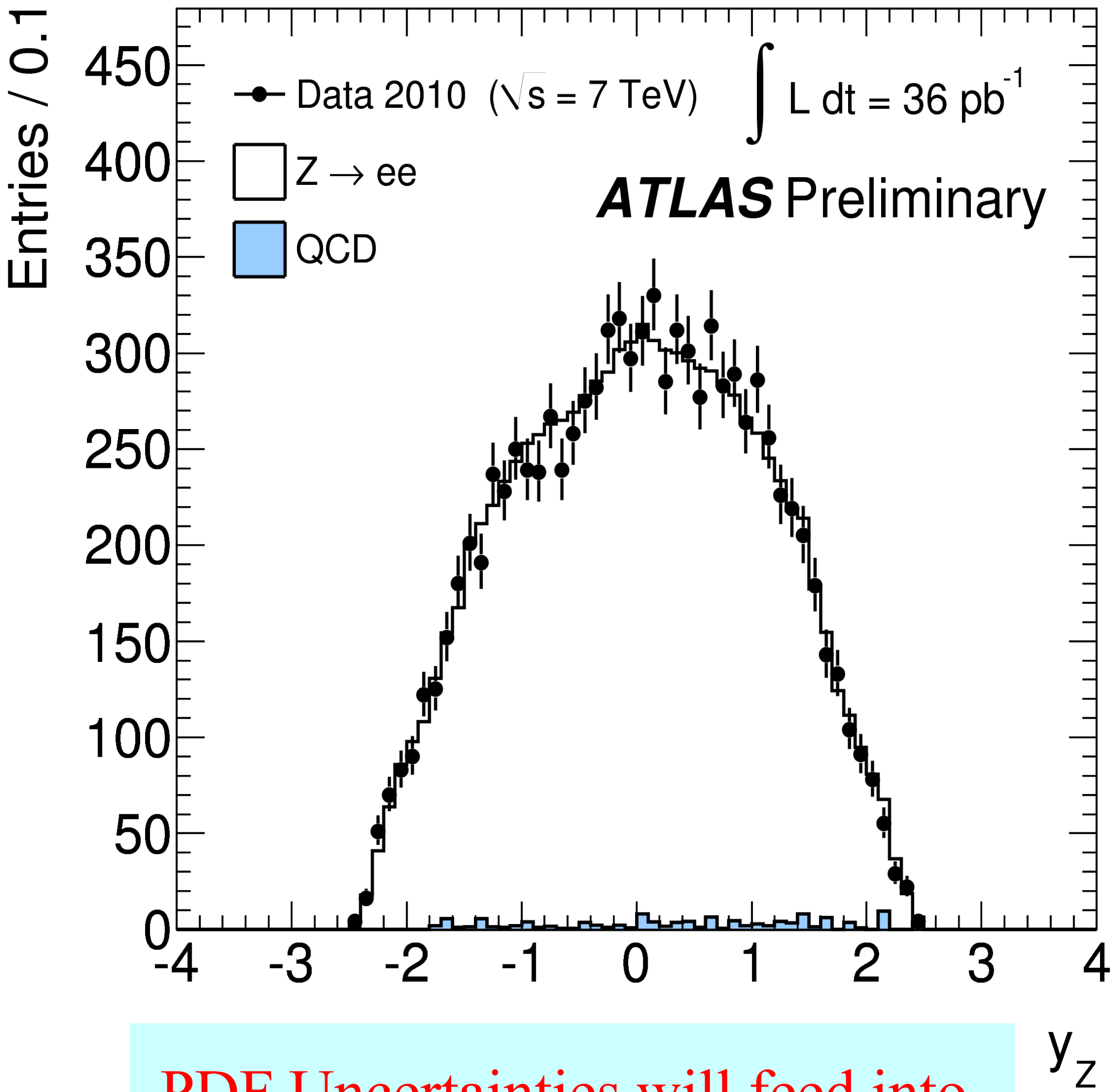
PDF Uncertainties ⇒ S(x) PDF ⇒ W/Z at LHC





VRAP Code

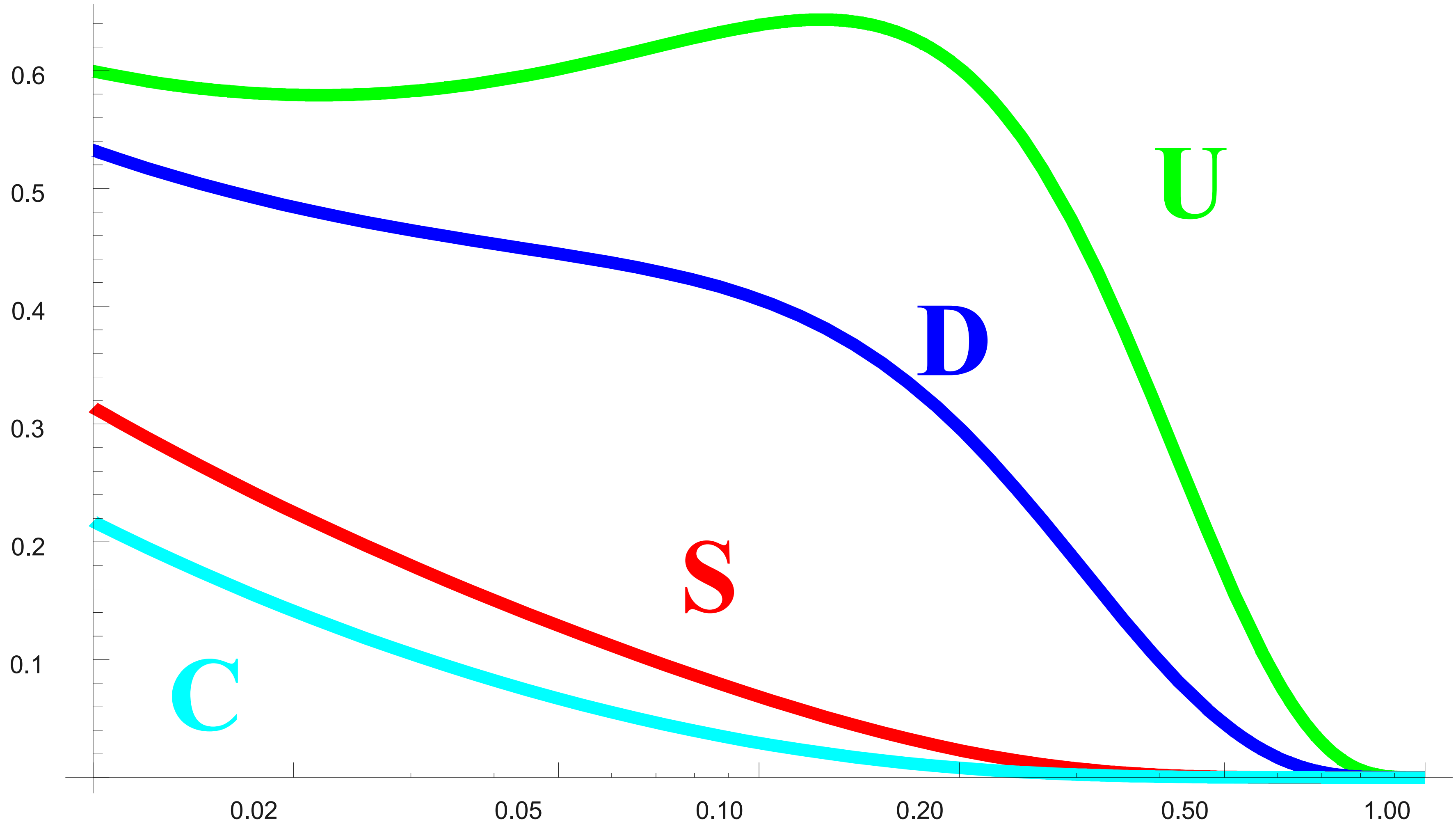
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.



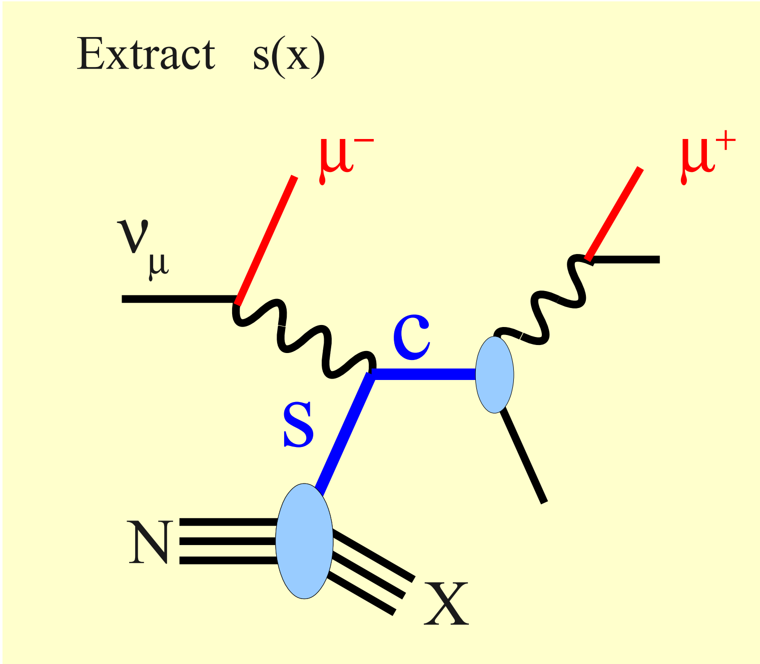
PDF Uncertainties will feed into LHC "Benchmark" processes

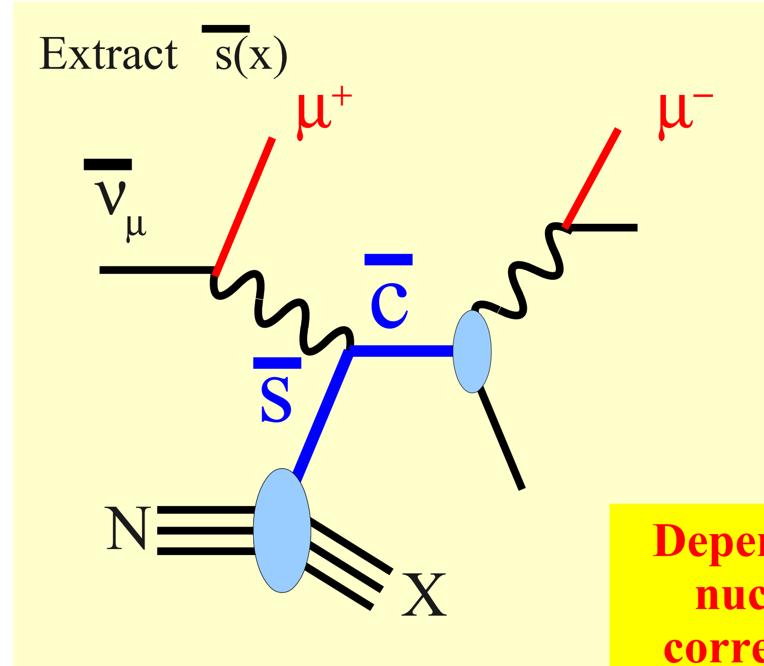
Comparison with new NNPDF sets: Les Houches 2009

What constrains the Strange???



Di-muon production ⇒ Extract s(x) Parton Distribution



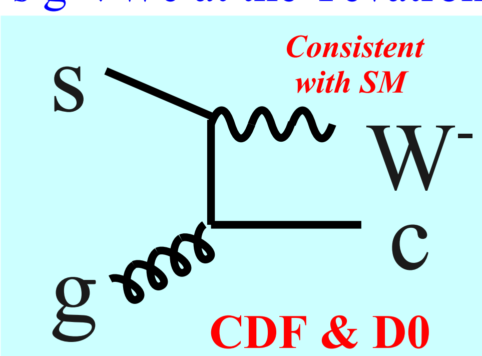


Depends on nuclear corrections

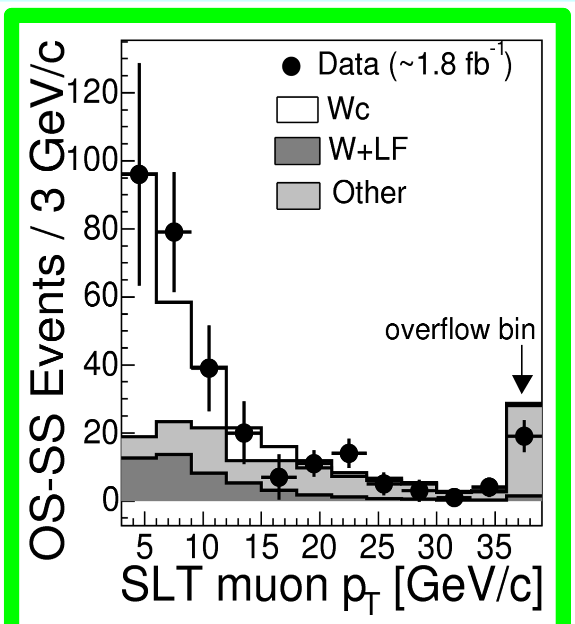
s(x) and $\bar{s}$(x) are essential in extraction of Sinθ_W

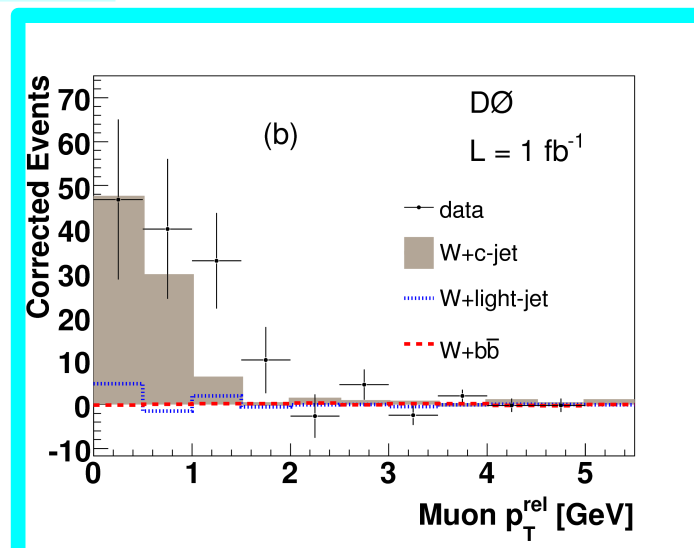
Used in CTEQ6 Fits

s g→Wc at the Tevatron



CDF: PRL 100:091803,2008.
D0: PLB666:23,2008.





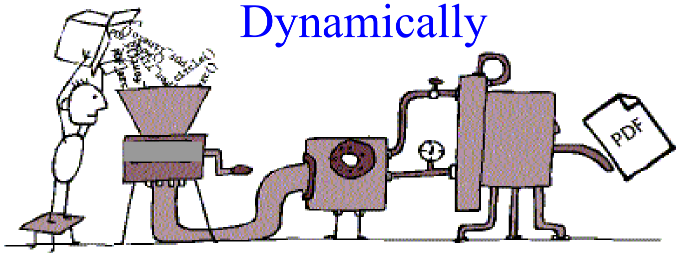
Also a challenge at LHC

Nuclear Corrections

???

Traditional Input to Global PDF Fit

Include Nuclear Dimension Dynamically



Start with Neutrino data on heavy targets (Fe, Pb, ...)

Nuclear Correction

"Corrected" data for isoscalar

Isospin Symmetry

"Corrected" data for proton

Nuclear Correction "Frozen"

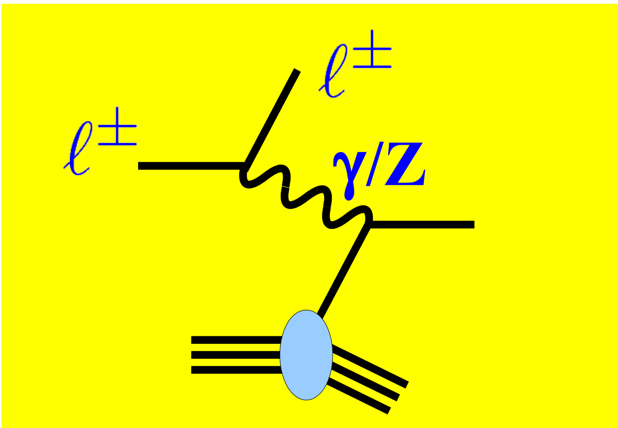
Global PDF Fit

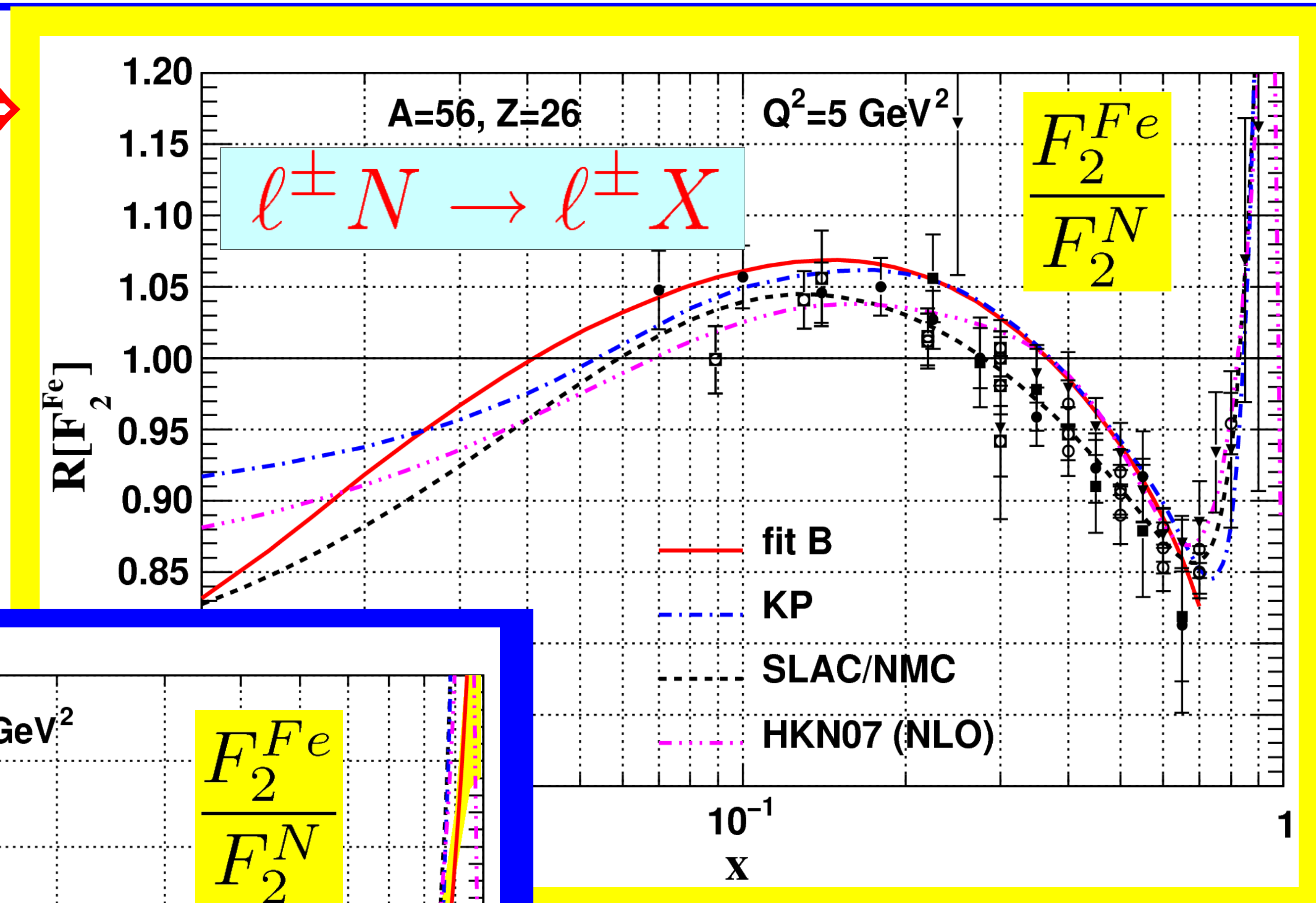
No Feedback!!!

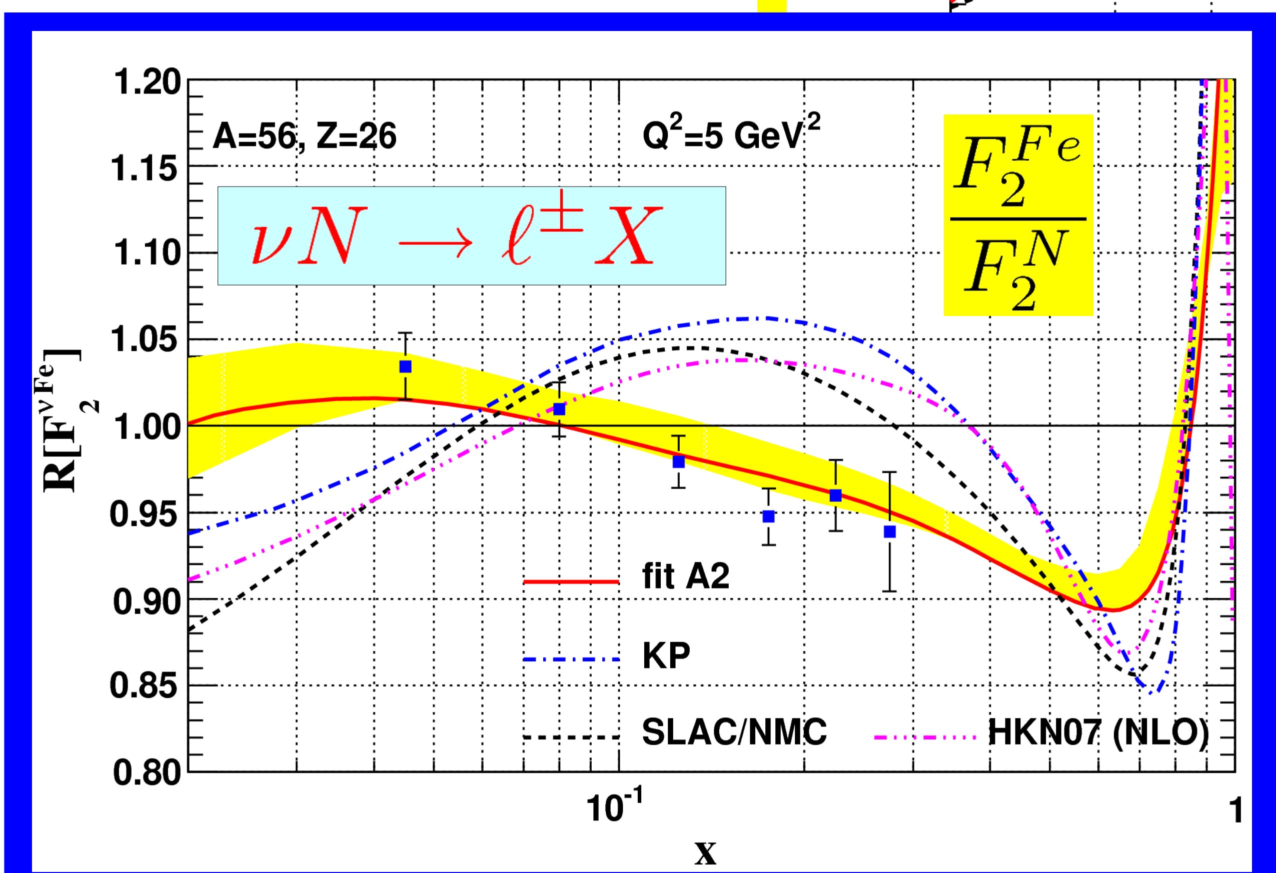
Oooooops!

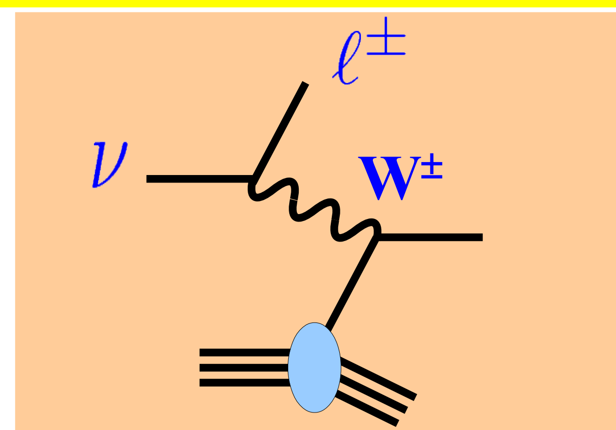
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

Charged Lepton DIS ⇒





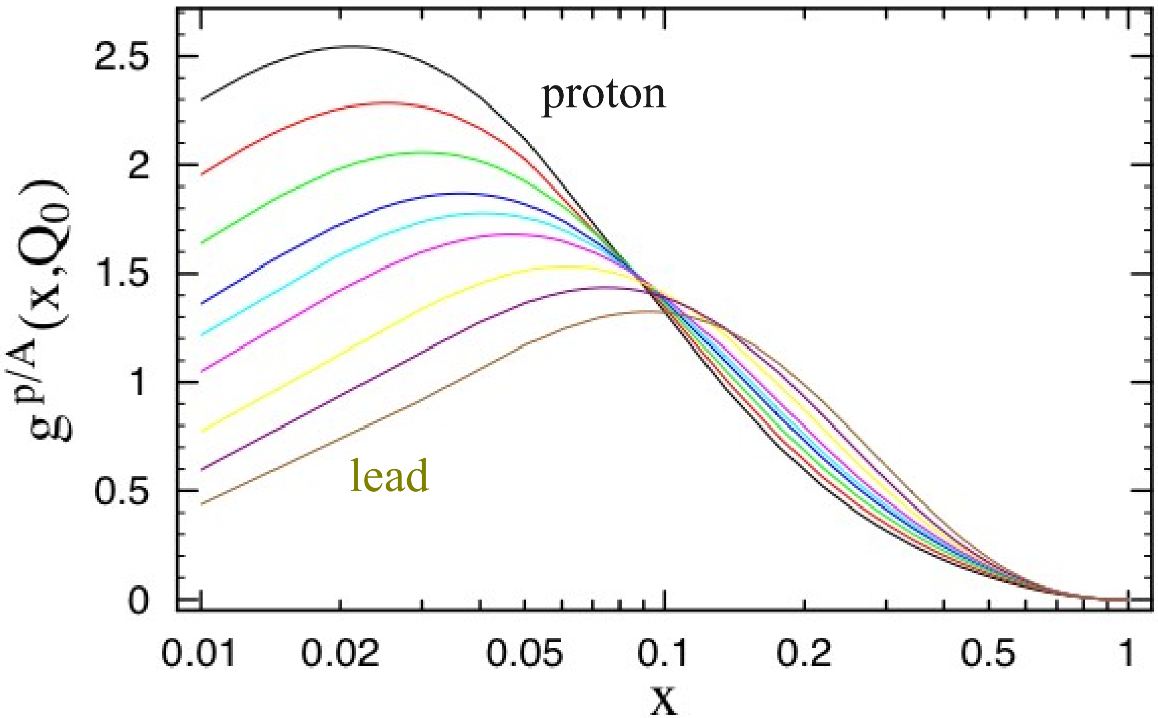




⇐ Neutrino DIS

nCTEQ Nuclear PDF's

- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

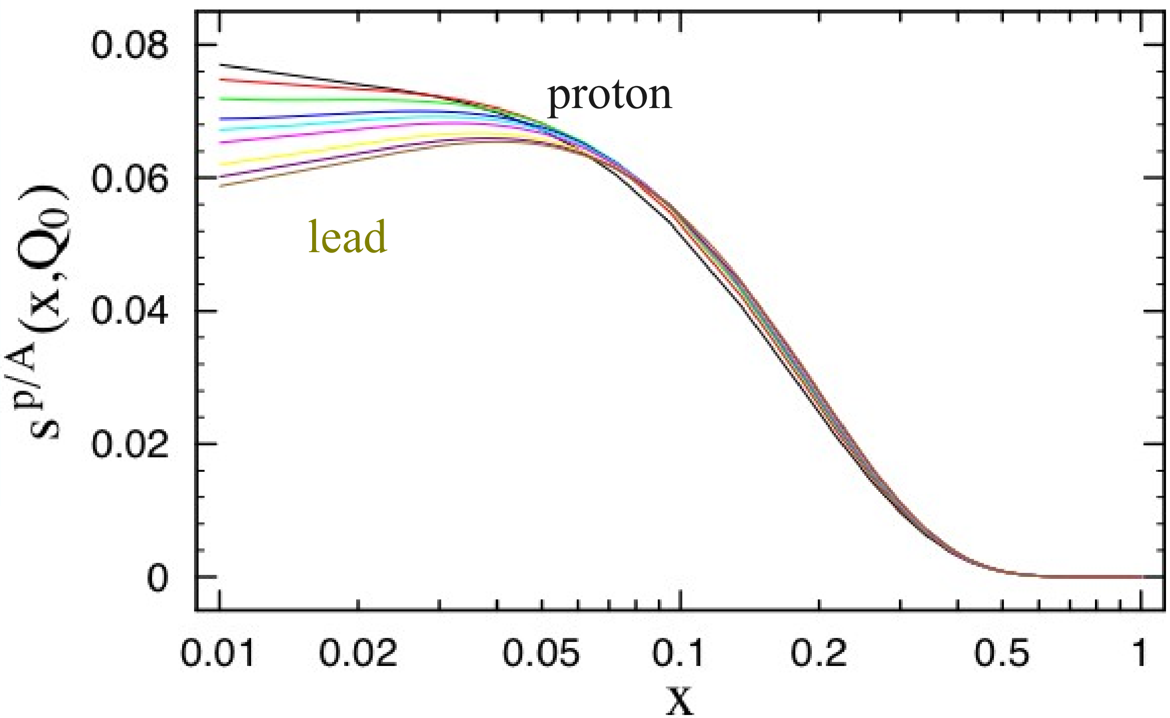


A-Dependent PDFs

$$xf(x) = x^{a_1}(1-x)^{a_2}e^{a_3 x}(1+e^{a_4}x)^{a_5}$$

$$a_i \rightarrow a_i(A)$$

$$a_k = a_{k,0} + a_{k,1}(1 - A^{-a_{k,2}})$$



Nuclear PDFs from neutrino deep inelastic scattering.
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin,
F. Olness, J.F. Owens. Phys.Rev.D77:054013,2008.

Nuclear CTEQ parton distribution functions - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://projects.hepforge.org/ncteq/

The CTEQ Meta-Page | Nuclear CTEQ parton distri...

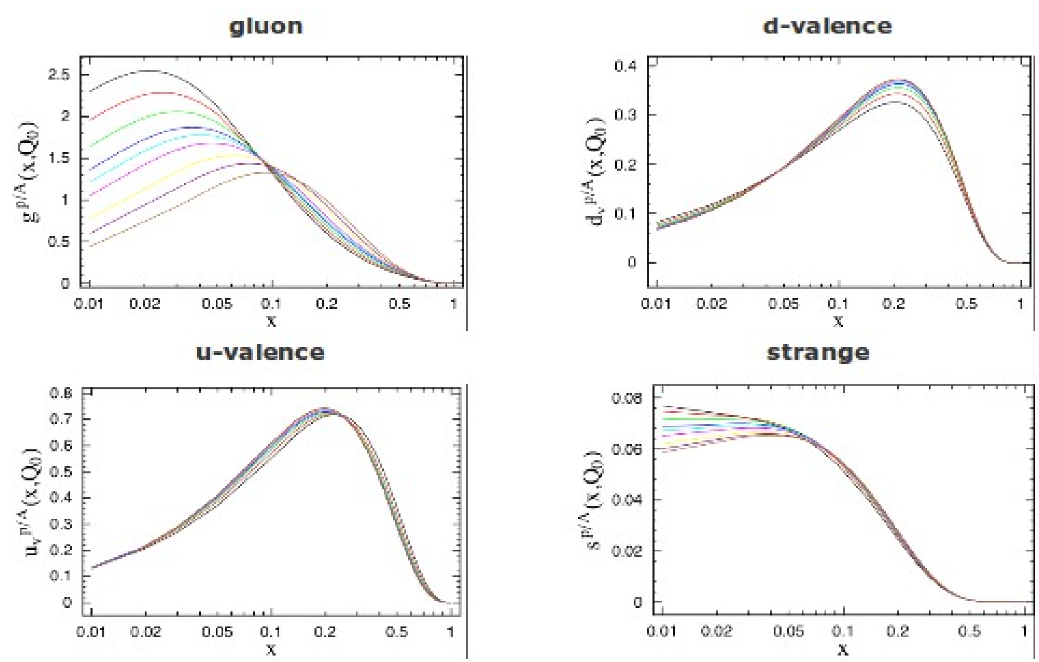
nCTEQ Go! hosted by **CEDAR HepForge**

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework and the first results can be found in arXiv:09072357 [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities



where all black curves stand for free proton PDF and red, green, blue, cyan, pink, yellow, magenta and brown curves show PDF in protons bound in nuclei - from deuterium (red) to lead (brown).

K Kovarik,
I. Schienbein,
J.Y. Yu,
T. Stavreva,
T Jezo,
C. Keppel,
J.G. Morfin,
F. Olness,
J.F. Owens.

Done

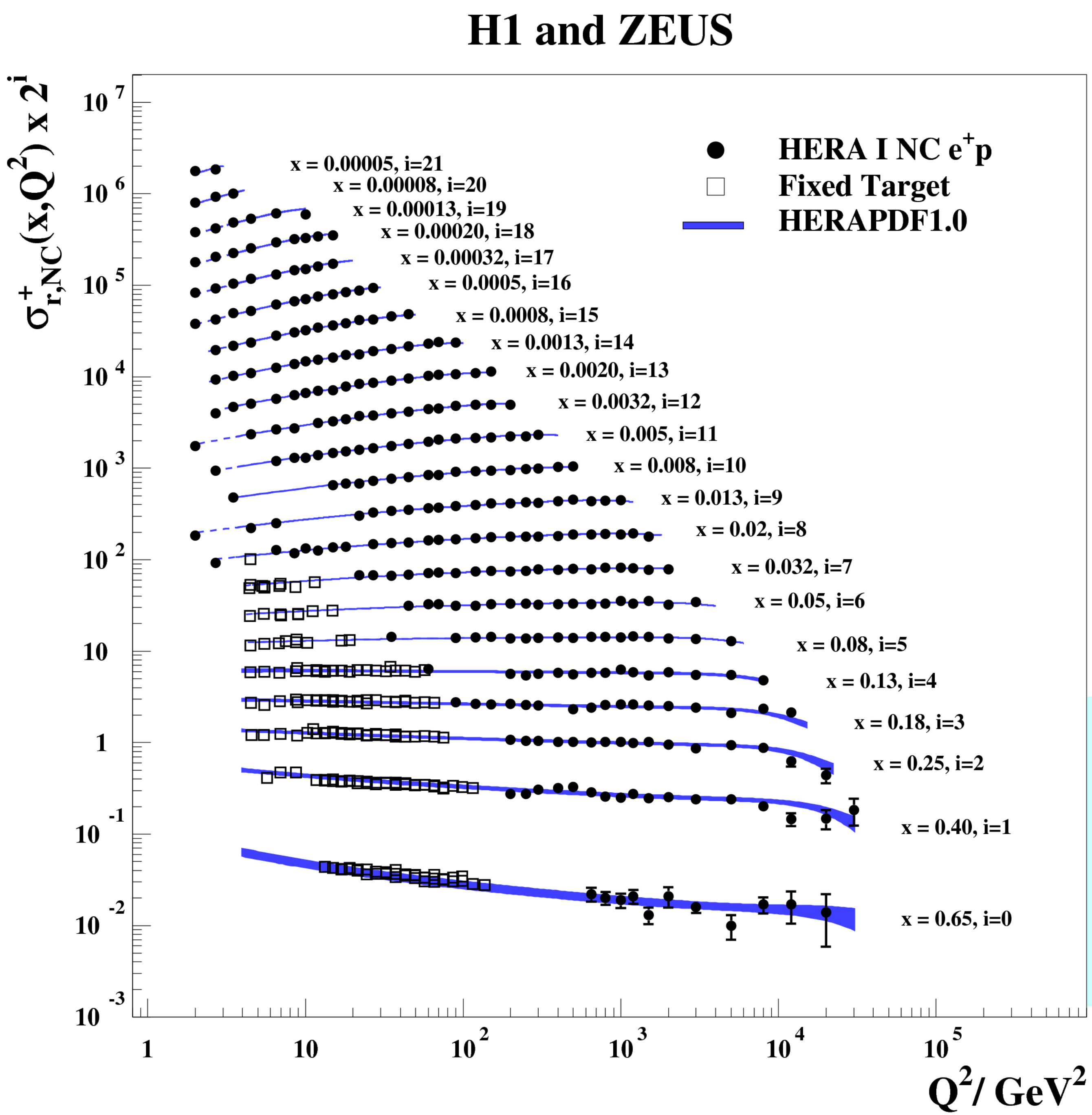
... what about the

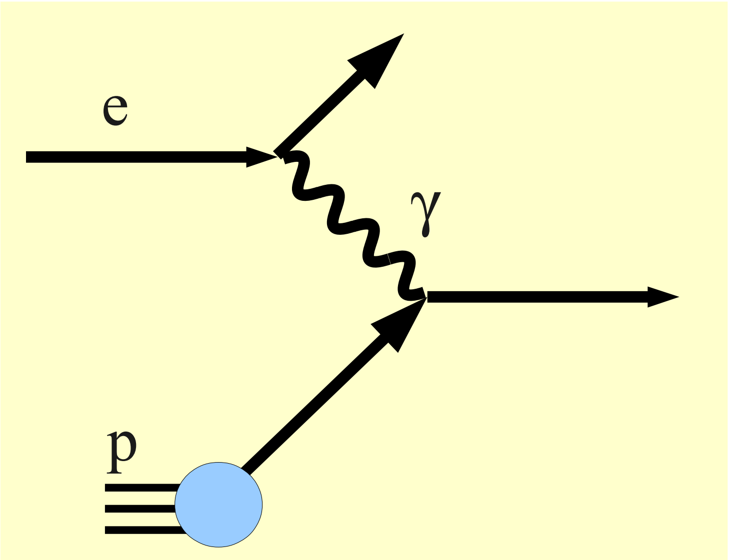
Heavy Quarks

c & *b*

Extrinsic & Intrinsic

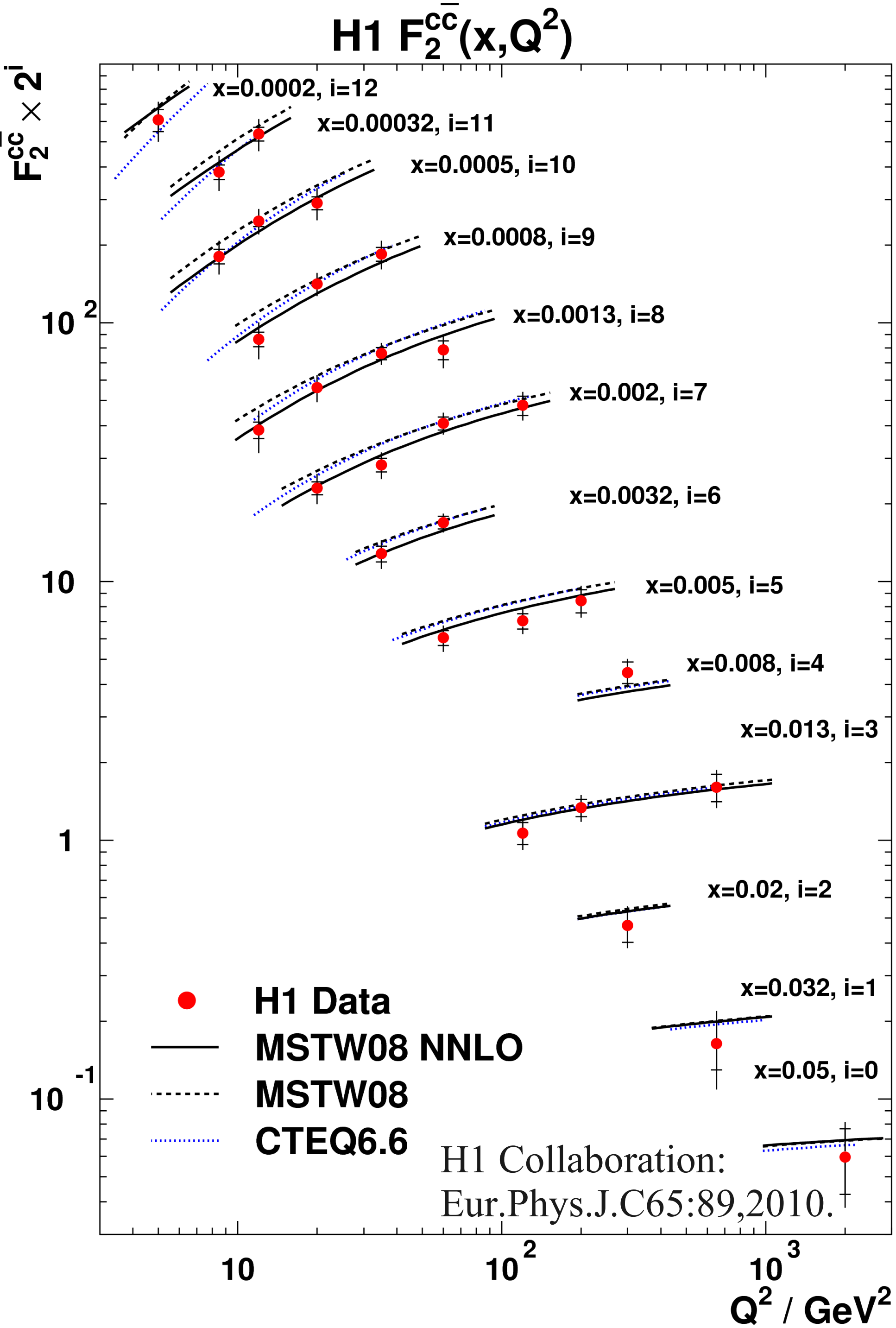
F2 from HERA: Essential ingredient for PDF analysis





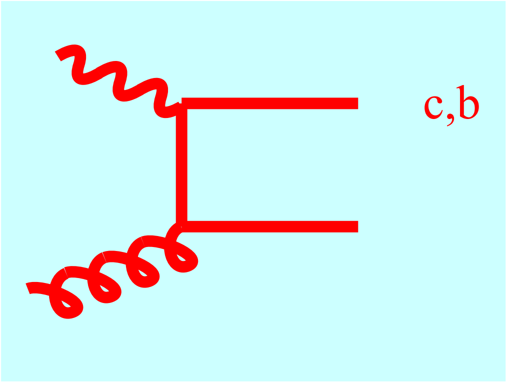
$$F_2^{ep} \sim \frac{4}{9}(u + \bar{u} + c + \bar{c})$$
$$+ \frac{1}{9}(d + \bar{d} + s + \bar{s})$$

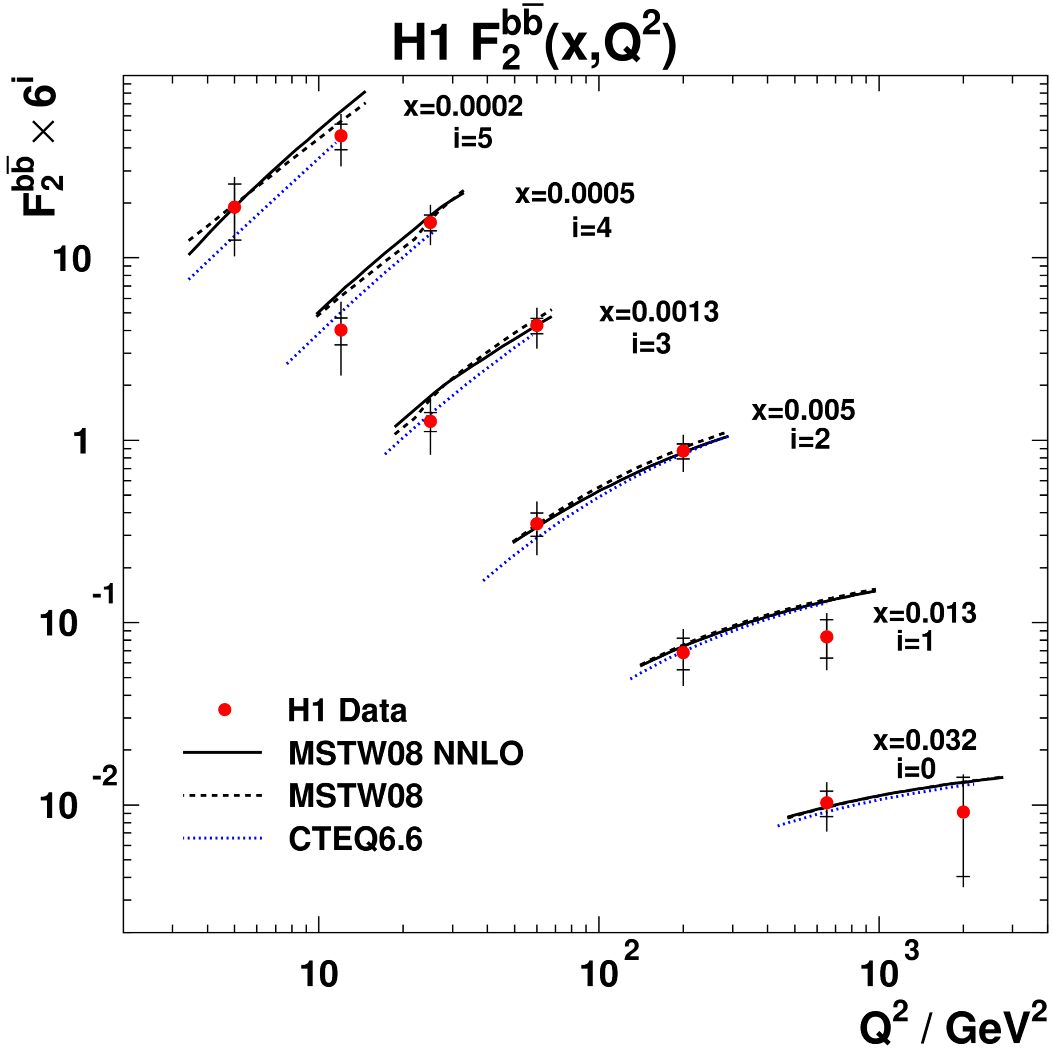
Heavy Flavor Components will play prominent role at LHC



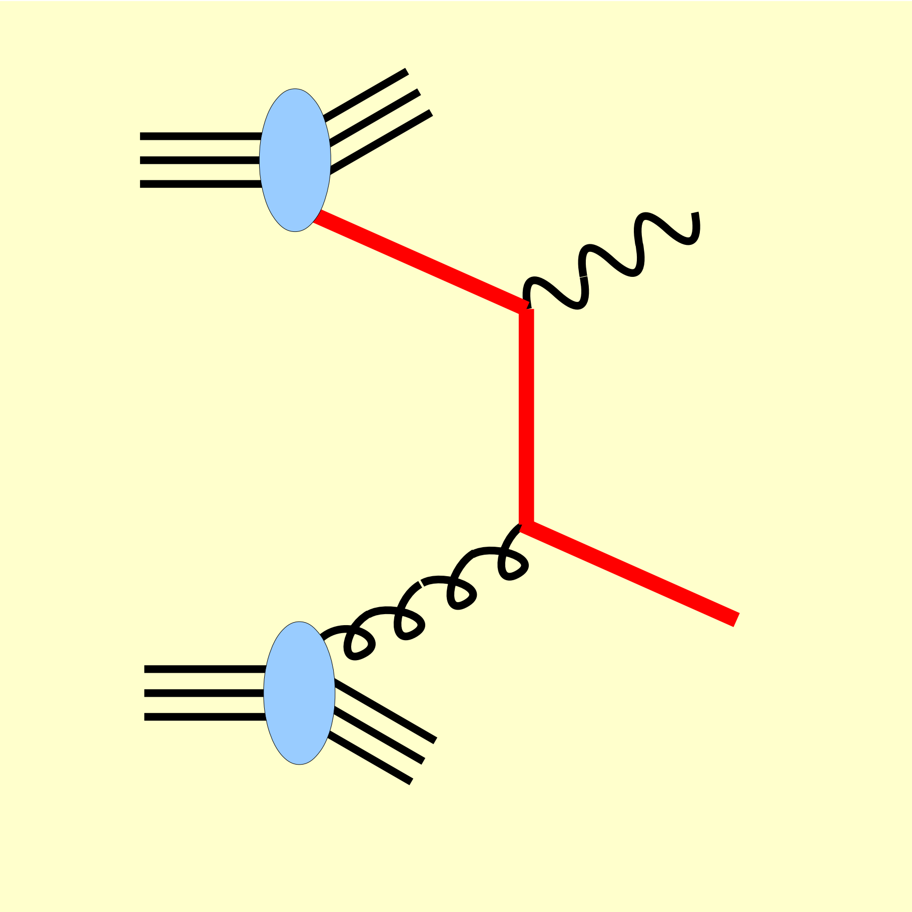
H1 Collaboration:
Eur.Phys.J.C65:89,2010.

c & b tied to gluon PDFs





How to Access Heavy Flavor Components Directly???



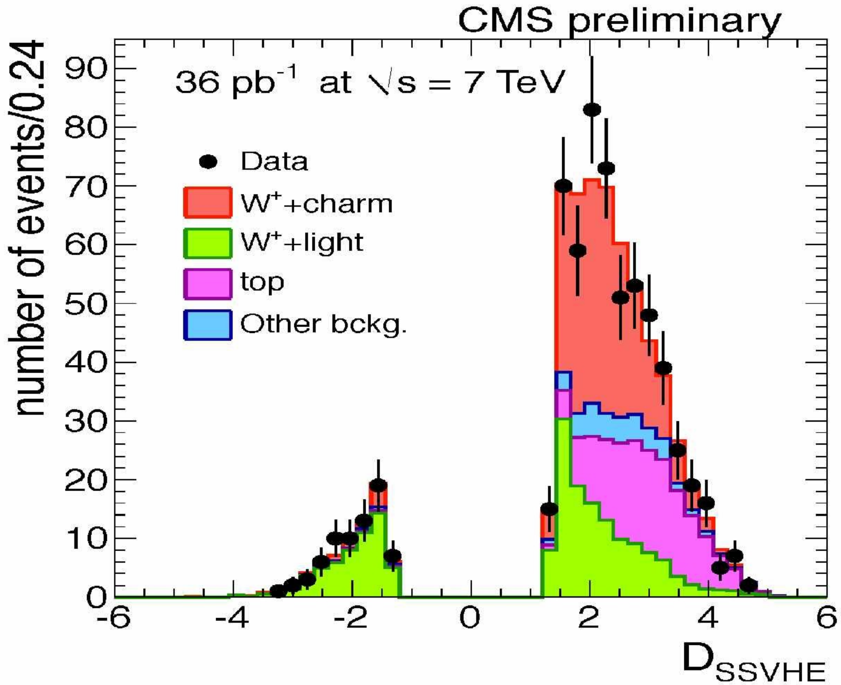
$c\ g \rightarrow c\ \gamma$

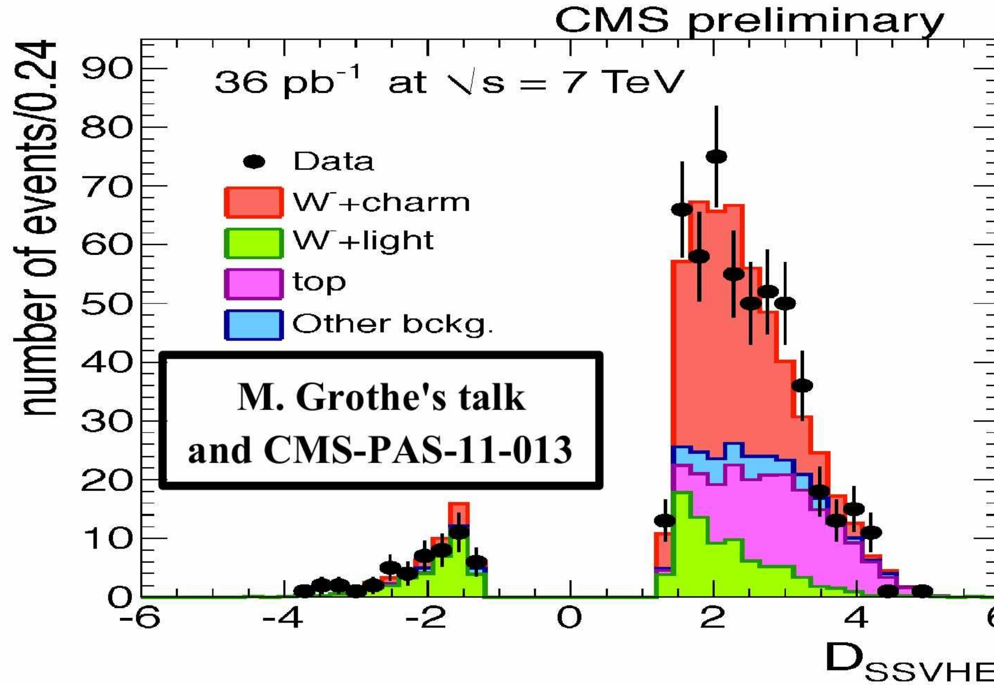
$b\ g \rightarrow b\ \gamma$

$s\ g \rightarrow c\ W$

$c\ g \rightarrow b\ W$

First LHC results on W+charm (CMS)





- Sensitive to strange quark PDFs (process dominated by s+g → W + charm):
  - PDF uncertainties from the second quark generation are a potential source of uncertainty for the W mass measurement at the LHC
  - Data-driven control of light-quark and top backgrounds
  - Enormous margin for improvement (only 2010 statistics used), new method (secondary vertex tagging), complementary to the one employed until now at Tevatron (semileptonic charm decay tagging):

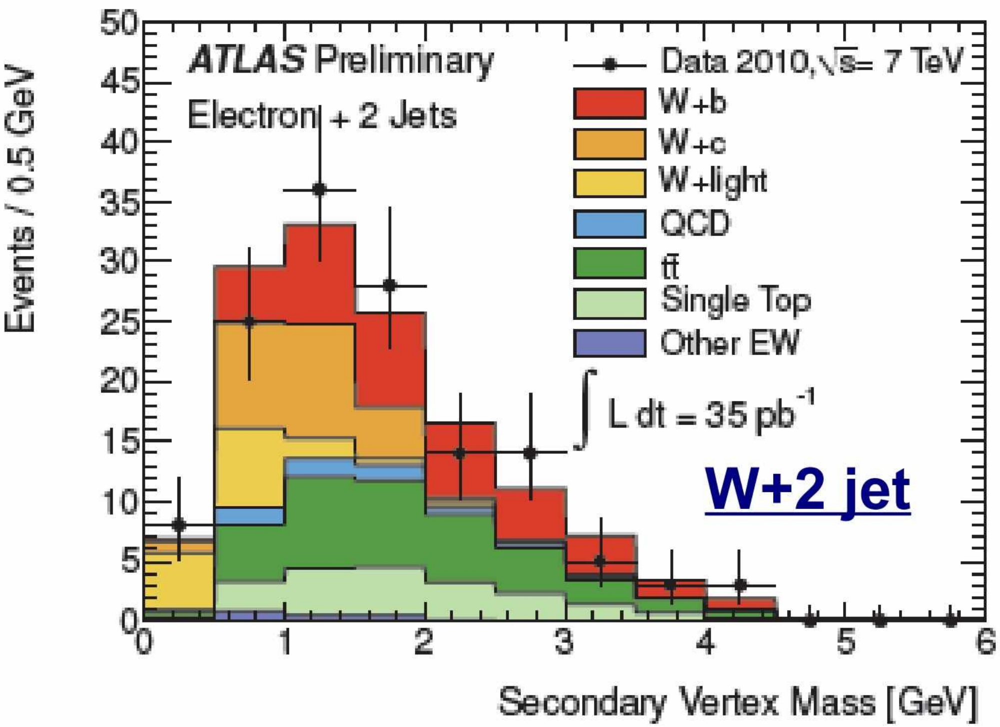
$$\underline{For \quad p_T^{jet} > 20 \quad GeV, |\eta^{jet}| < 2.1}:$$

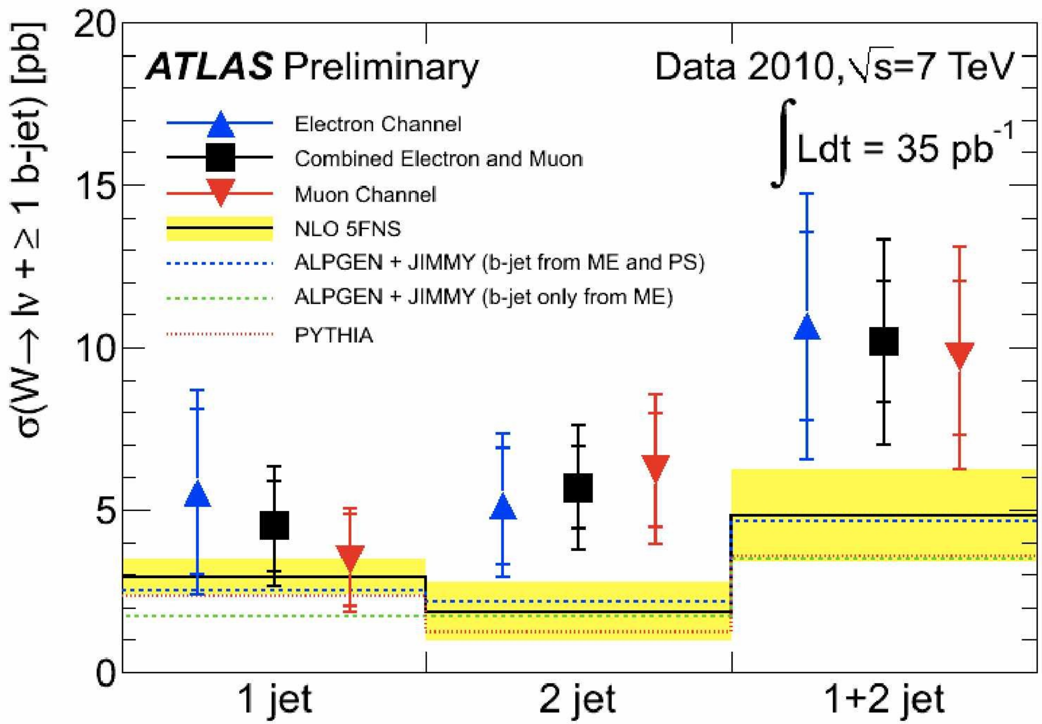
$$\frac{\sigma(W^{+} + charm)}{\sigma(W^{-} + charm)} = 0.92 \pm 0.19(stat.) \pm 0.04(syst.); \quad \frac{\sigma(W + charm)}{\sigma(W + jets)} = 0.142 \pm 0.015(stat.) \pm 0.024(syst.)$$

First LHC W+b results (ATLAS)

- **Important background for Higgs searches: W+H (H → $b\bar{b}$) at low Higgs masses. Also a background for $t\bar{t}$ and single-top measurements**
- **W+b excess over expectations published by CDF**

A. Messina's talk

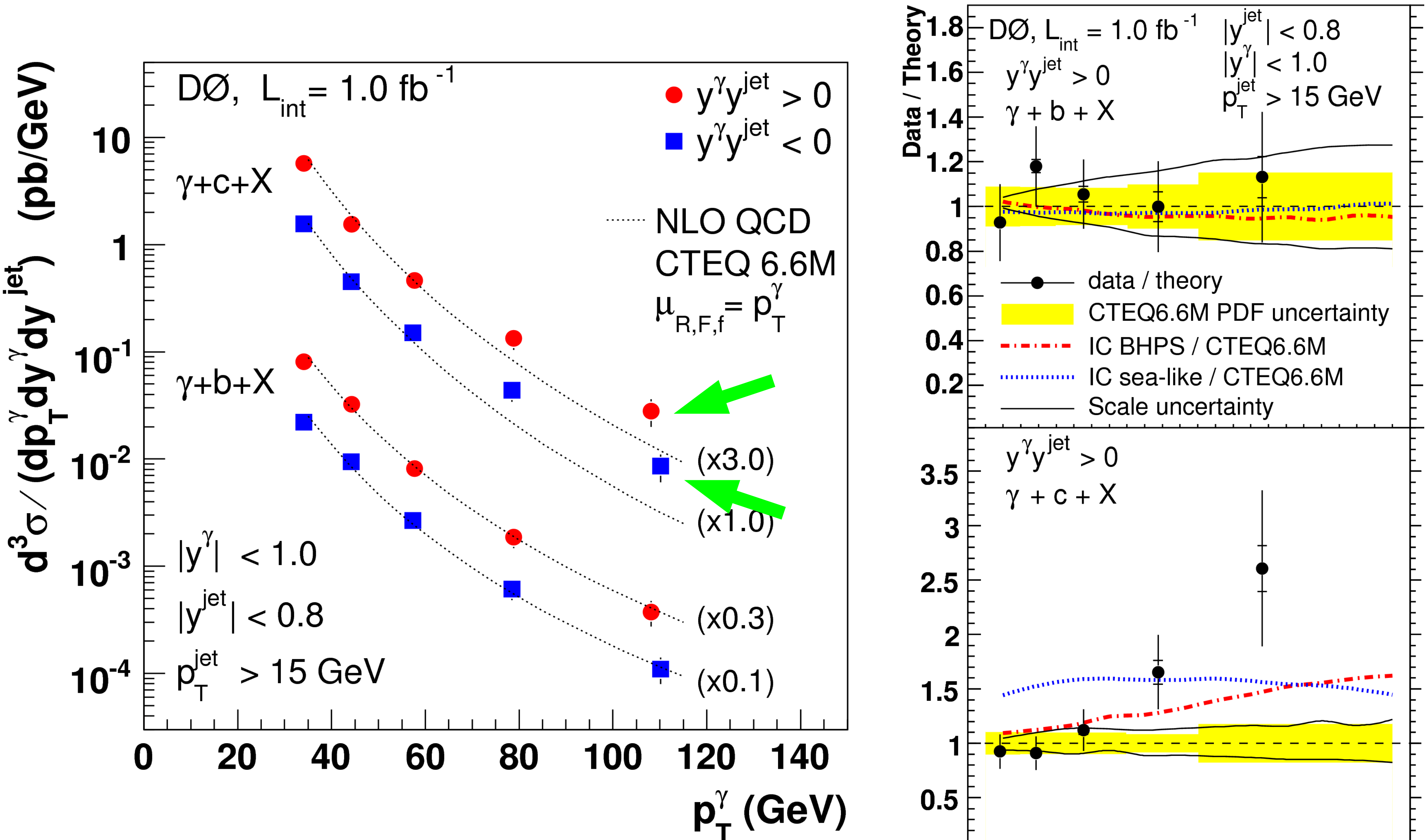




- **Significant decay length (>5.85 σ), fit to the reconstructed mass at secondary vertex**
- **Challenging analysis: it requires significant reduction and control of top backgrounds and W+charm. Analysis performed independently for 1 and 2 b-tags in the event**

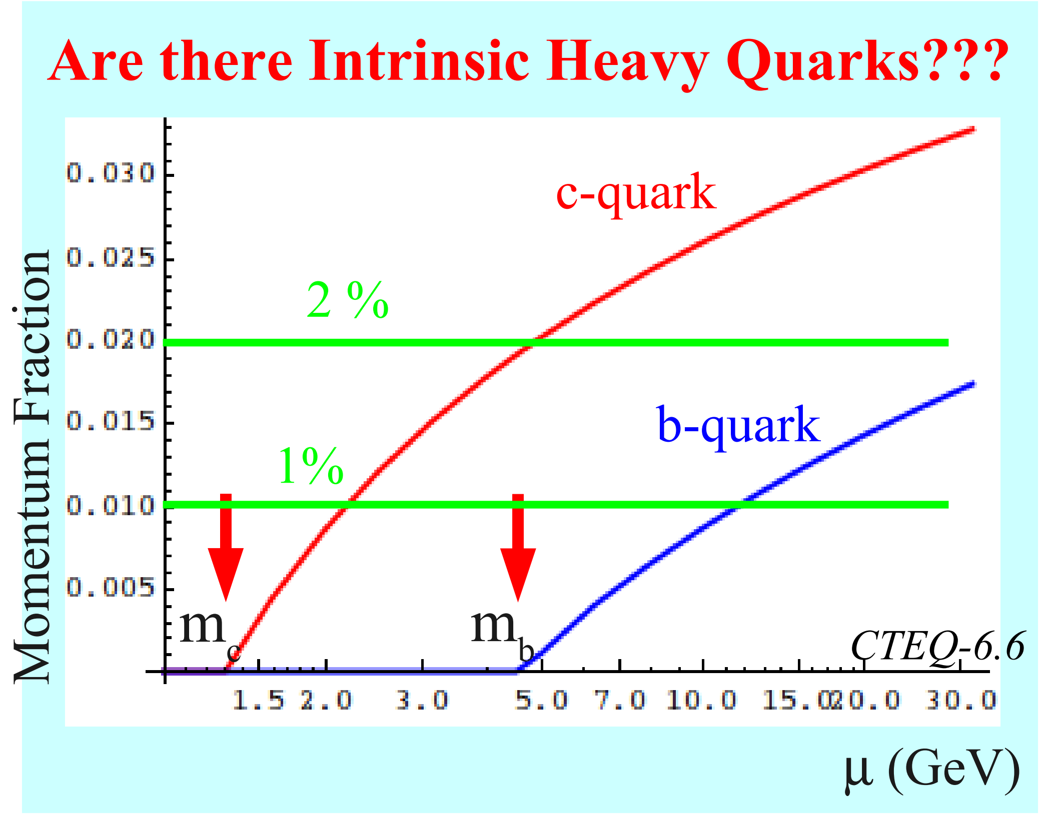
Agreement with theoretical predictions at the 1.5 σ level

Heavy Quarks at the Tevatron



D. Duggan (D0) arXiv:0906.0136

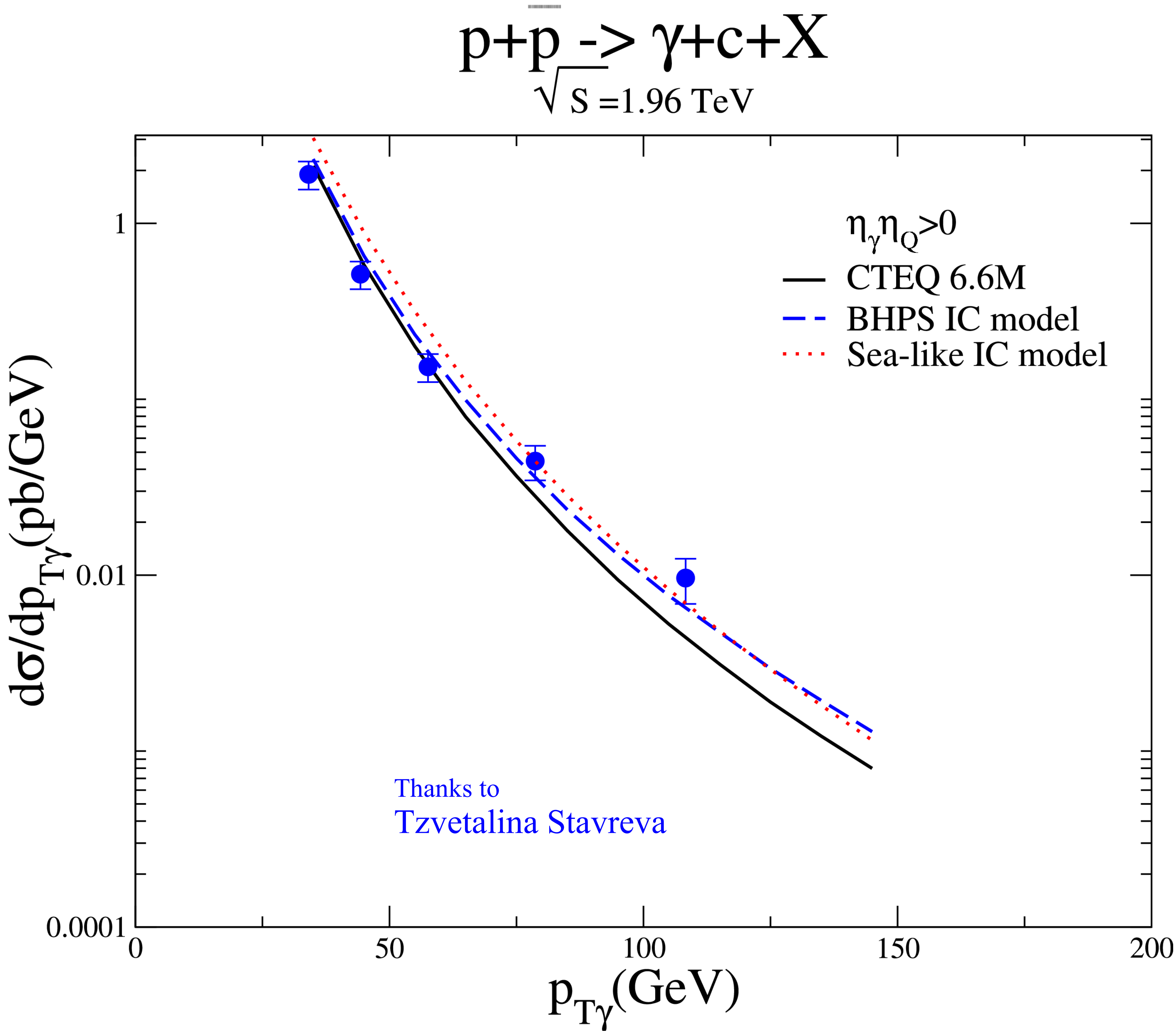
Are there Intrinsic Heavy Quarks??? Do they matter???



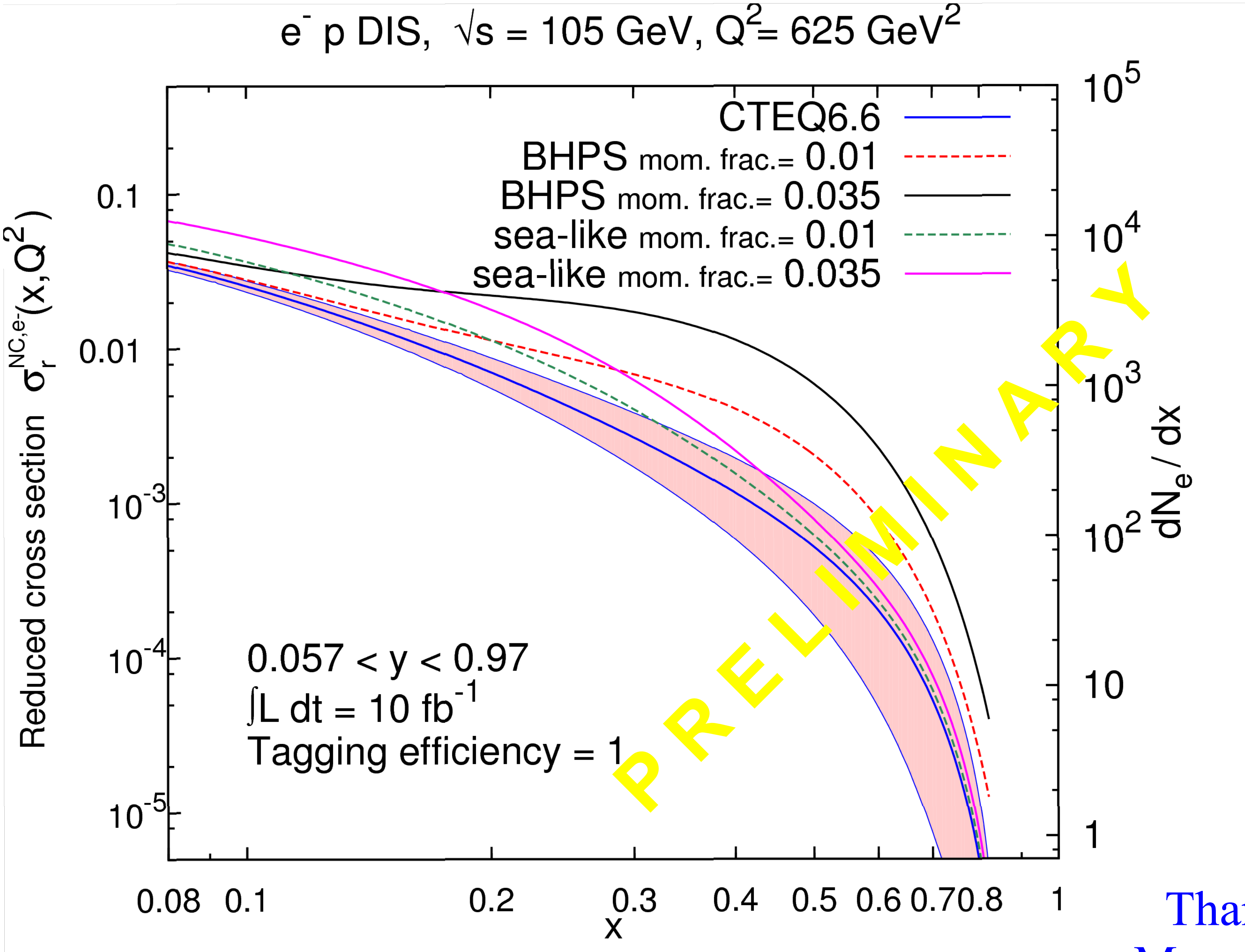
* Most sensitive near threshold
* What happens if we allow the evolution to determine charm?

Zero:	No intrinsic charm
Positive:	Intrinsic charm
Negative:	Inconsistent

Sample Cross Section for an Electron Ion Collider



Sample Cross Section for an Electron Ion Collider



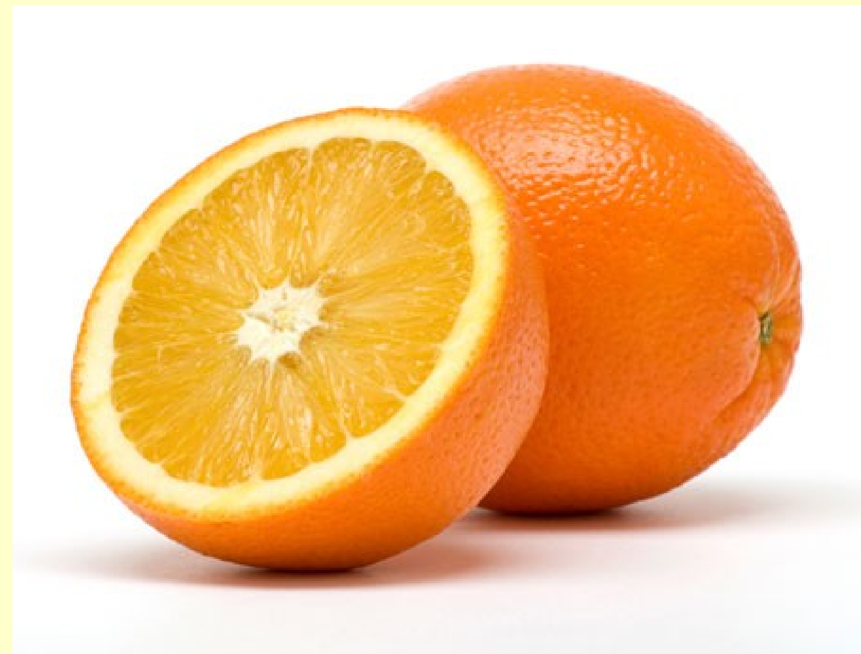
Thanks to Marco Guzzi for this calculation

What is the proper treatment of masses???

2009 Les Houches Comparative Studies

The SM and NLO Multileg Working Group: Summary report.

e-Print: arXiv:1003.1241 [hep-ph]

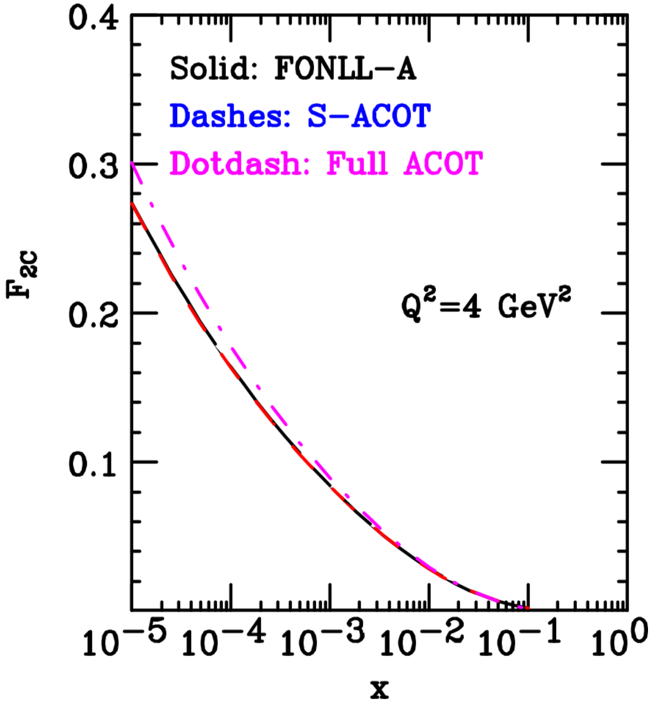


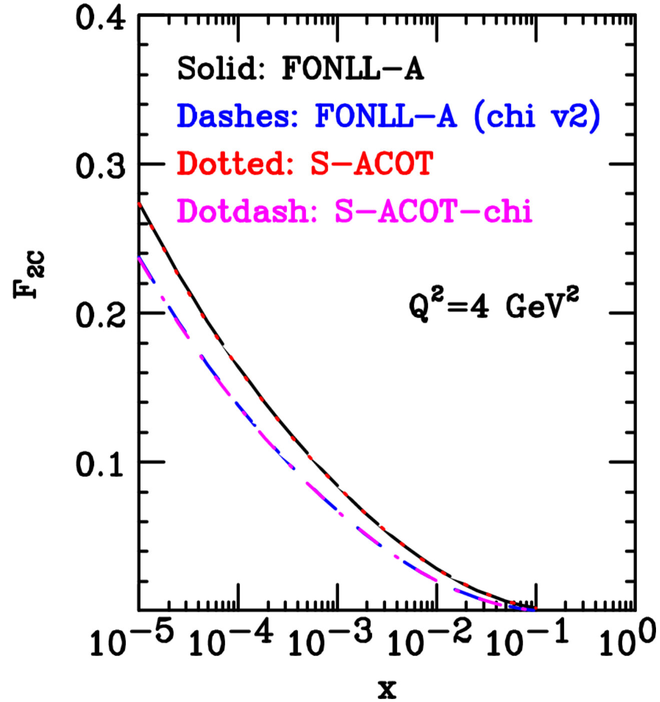
Physics at TeV Colliders

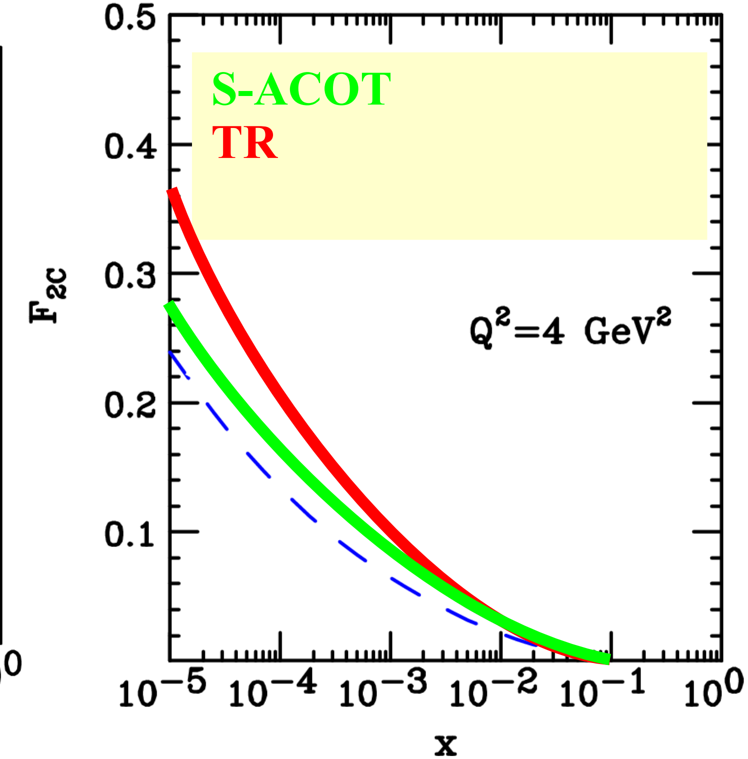
Les Houches 8-26 June 2009

LES HOUCHES centre de physique

2009 Les Houches Comparative Study







ACOT & S-ACOT essentially identical

... scheme differences are higher order

FONNL & S-ACOT

Numerically similar

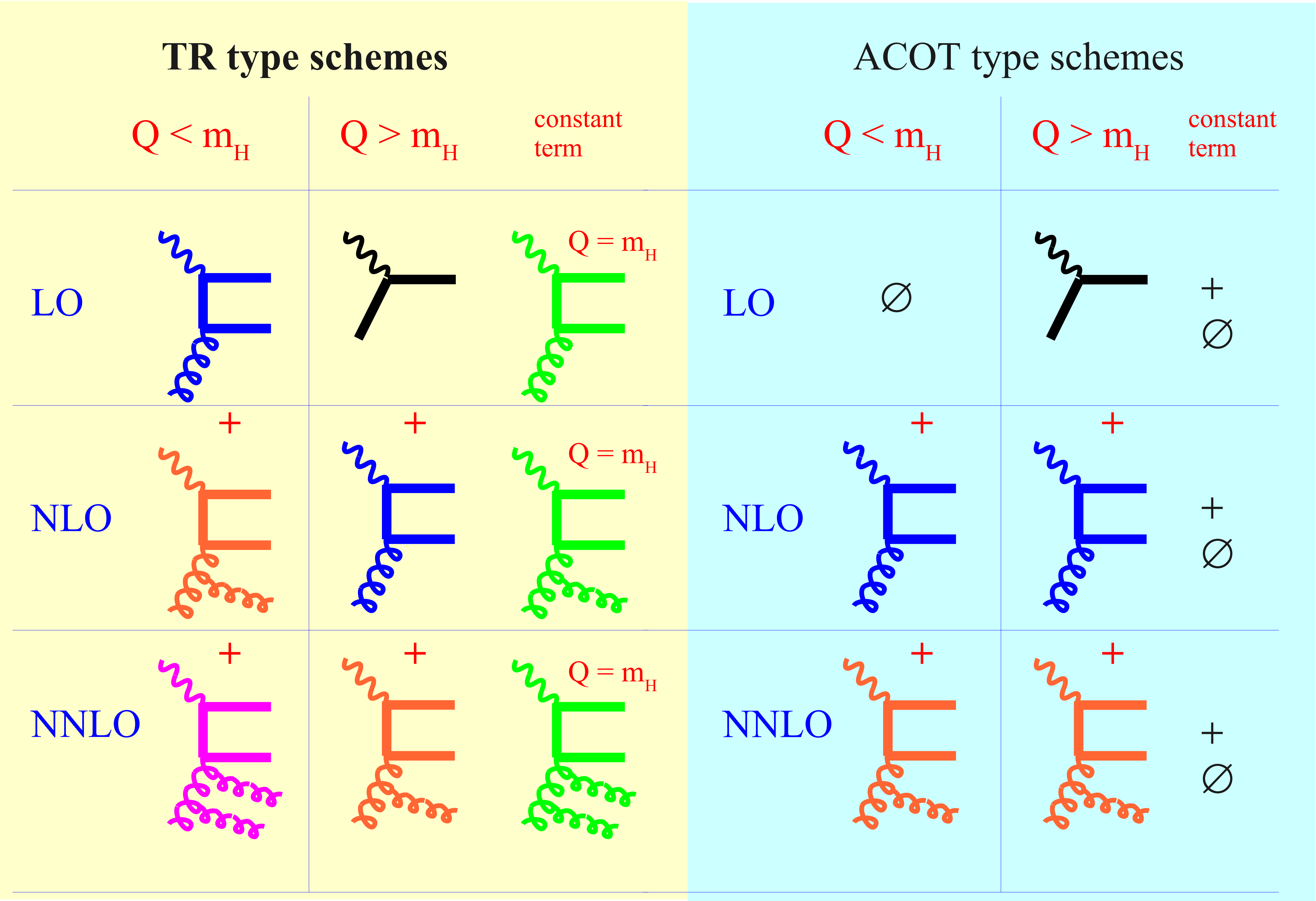
MSTW09

We can quantify <u>theoretical</u> scheme diffferences

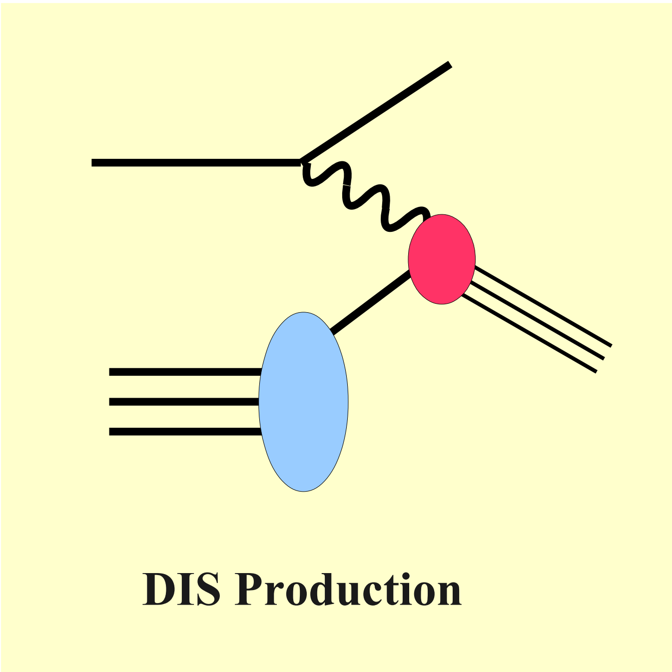
The SM and NLO Multileg Working Group: Summary report.

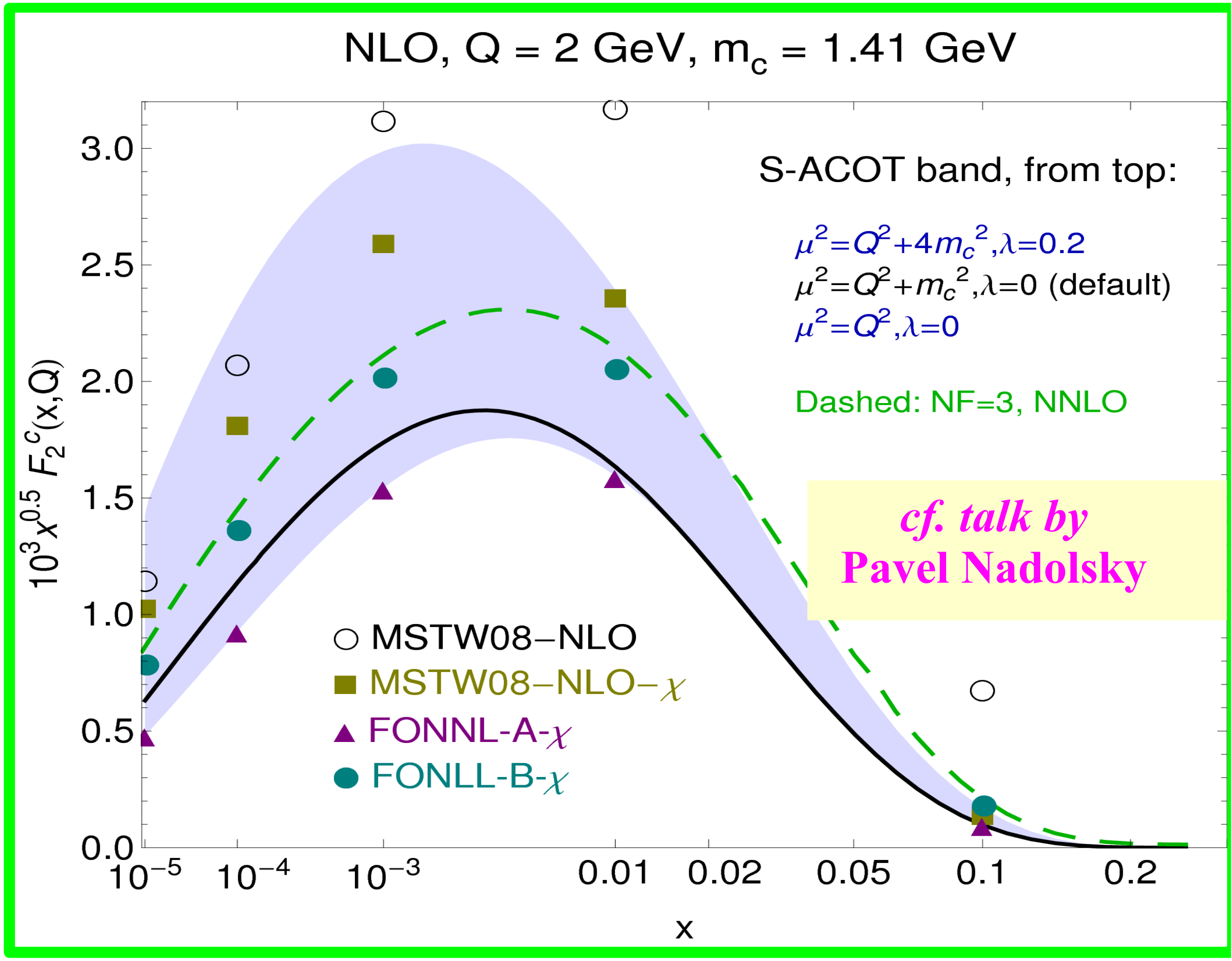
J. Rojo, et al., e-Print: arXiv:1003.1241 [hep-ph]

Schematic Summary of ACOT & TR Schemes

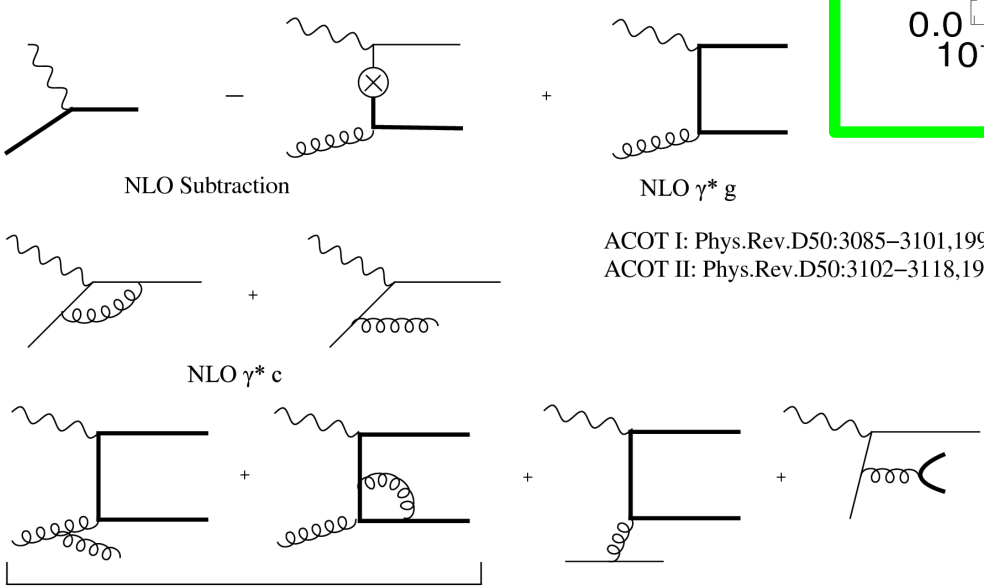


Step toward NNLO CTEQ





cf. talk by
Pavel Nadolsky



NLO Subtraction

NLO γ^* g

ACOT I: Phys.Rev.D50:3085–3101,1994
ACOT II: Phys.Rev.D50:3102–3118,1994

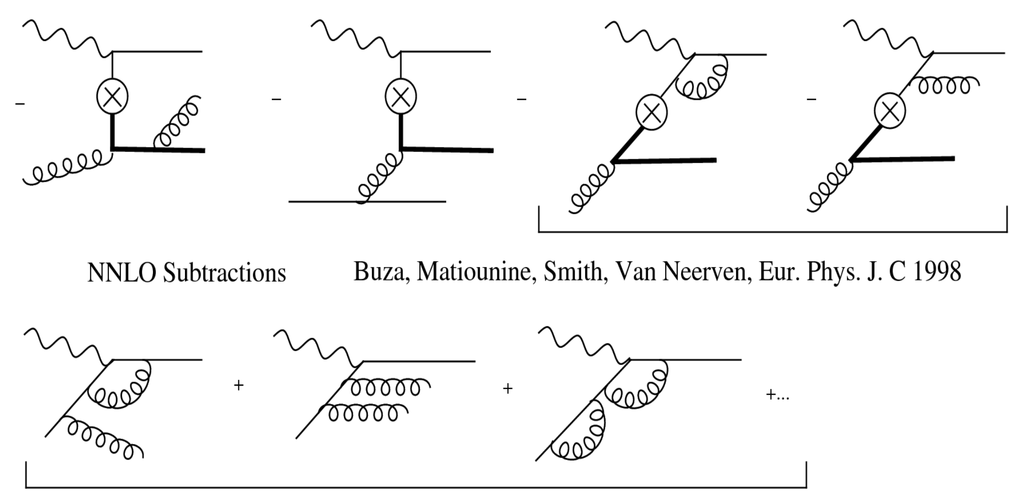
NLO γ^* c

NNLO: γ^* g

NNLO: γ^* Σ

NNLO: γ^* q NS

Riemersma et. al. Phys.Lett. B347 (1995)



NNLO Subtractions

Buza, Matiounine, Smith, Van Neerven, Eur. Phys. J. C 1998

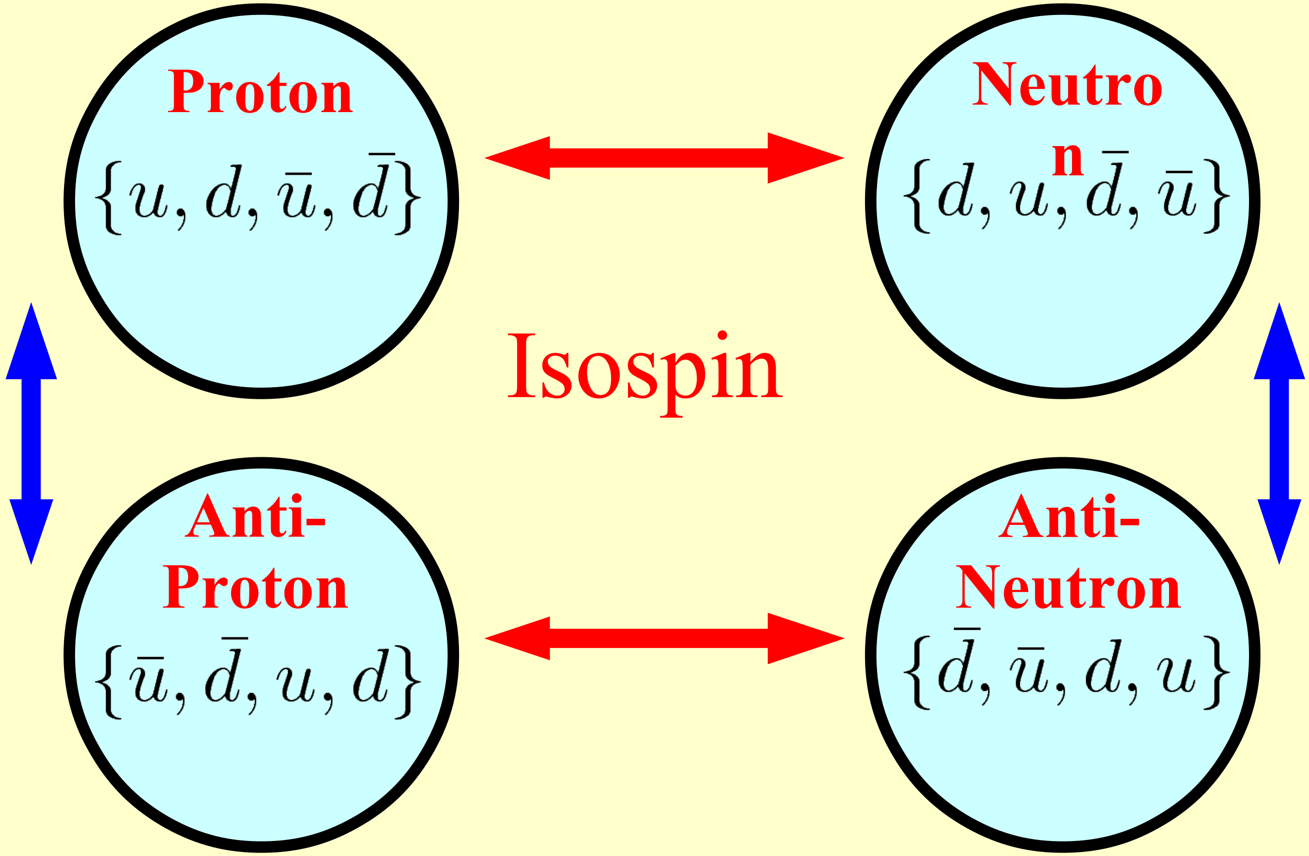
NNLO γ^* c

Moch, Vermaseren and Vogt, Nucl.Phys.B724, 2005

Isospin Symmetry

... taken for granted

Isospin Symmetry used to relate PDFs



$$q \Leftrightarrow \bar{q}$$

A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

$$\Delta x F_3^A = x F_3^{\nu A} - x F_3^{\bar{\nu} A} = +2x s_A^+ - 2x c_A^+ + x \delta I_A$$

$$\Delta F_2^A = \frac{5}{18} F_2^{CC} - F_2^{NC} = +\frac{1}{6} x\, s_A^+(x) - \frac{1}{6} x\, c_A^+(x) + \frac{1}{6} x\, \frac{N}{A}\, \delta I_A$$

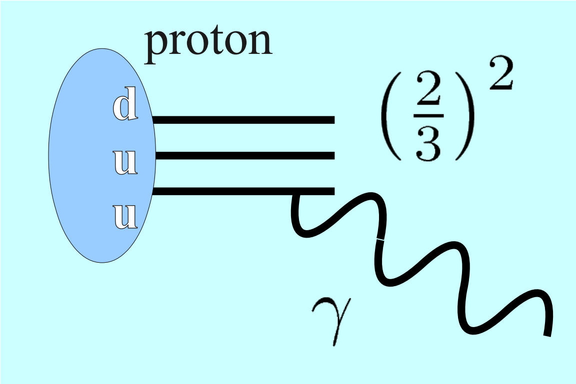
$$\delta I_A = (\delta d + \delta \bar{d}) - (\delta u + \delta \bar{u})$$

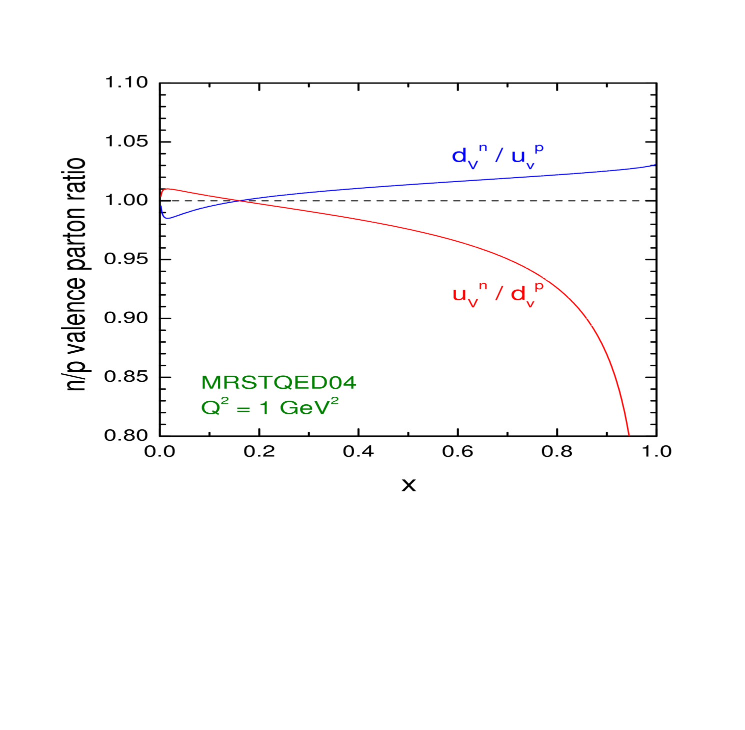
$$\delta u = \delta u_p - \delta d_n$$

Isospin Symmetry is violated by Electroweak DGLAP Evolution

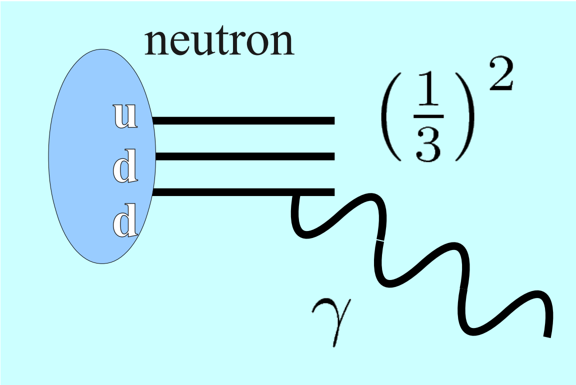
MRST-QED 04

Photon is not flavor blind!!!





MRST, Eur.Phys.J.C39:155-161,2005.

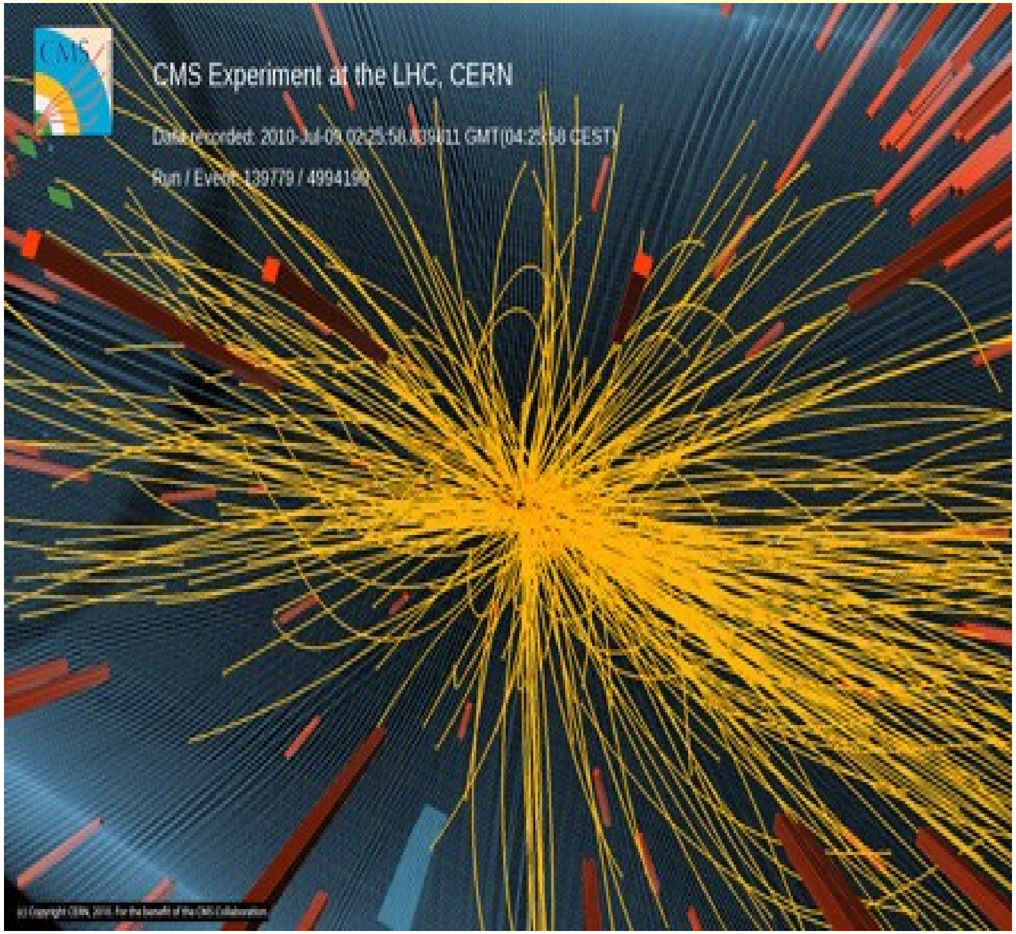


Isospin terms are comparable to NNLO QCD

Could Isospin terms affect Tevatron W-Asymmetry???

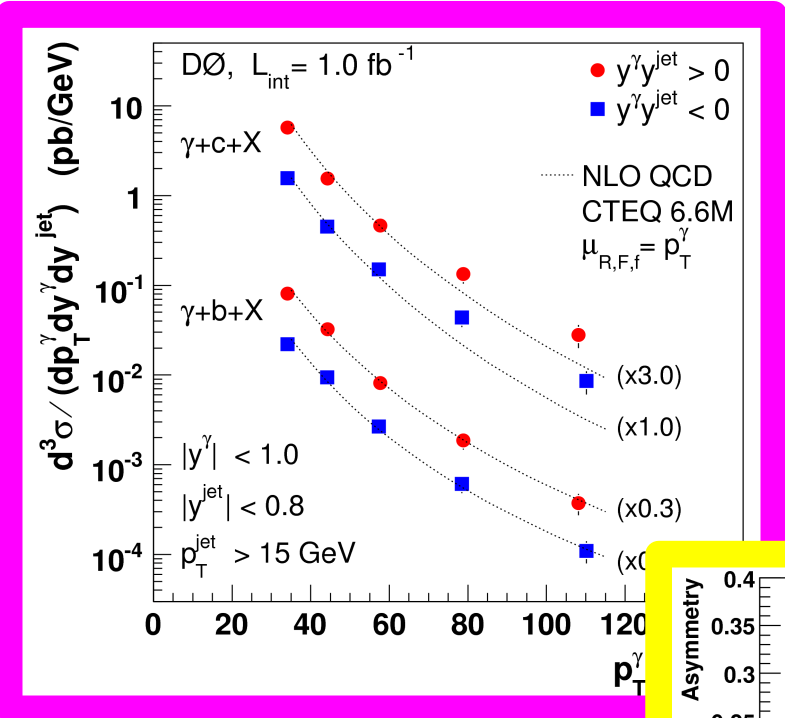
Search for "new physics" requires dependable foundation

Ability to discover
"New Physics"
is dependent on distinguishing
"Old Physics"

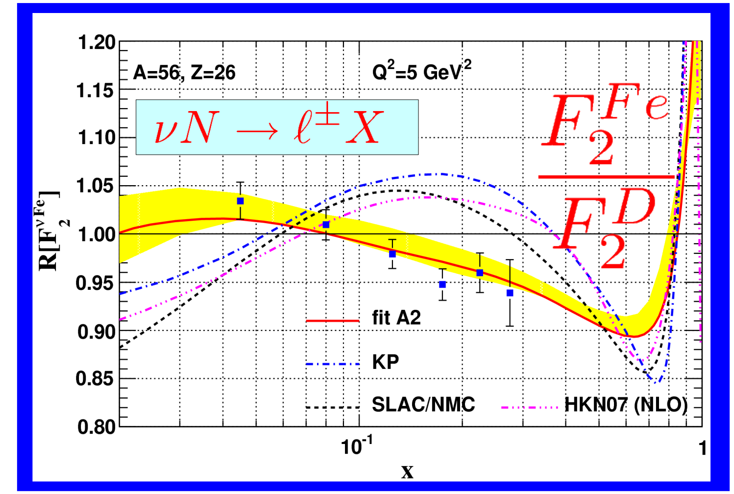


As experimental precision has increased, we need to be concerned about the details

The Puzzles

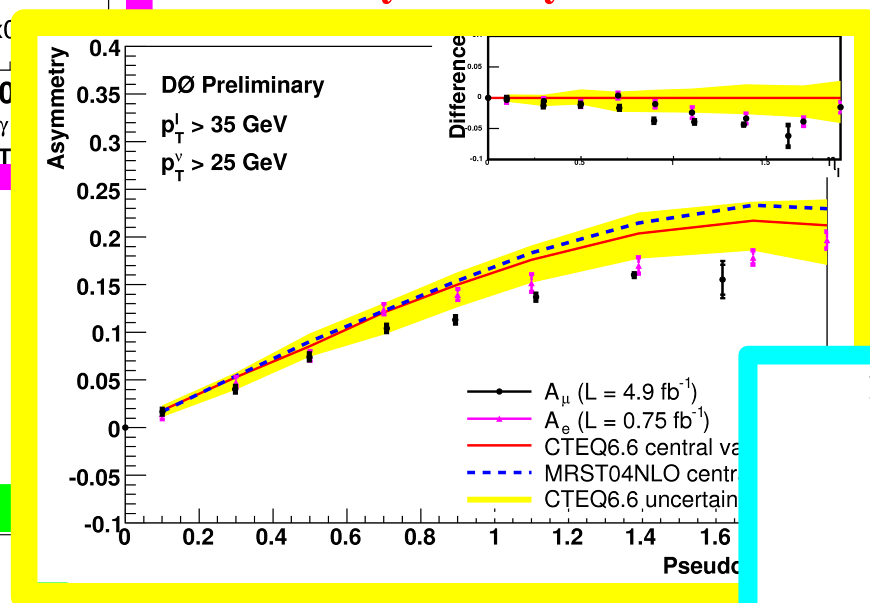


Charm+γ at Tevatron

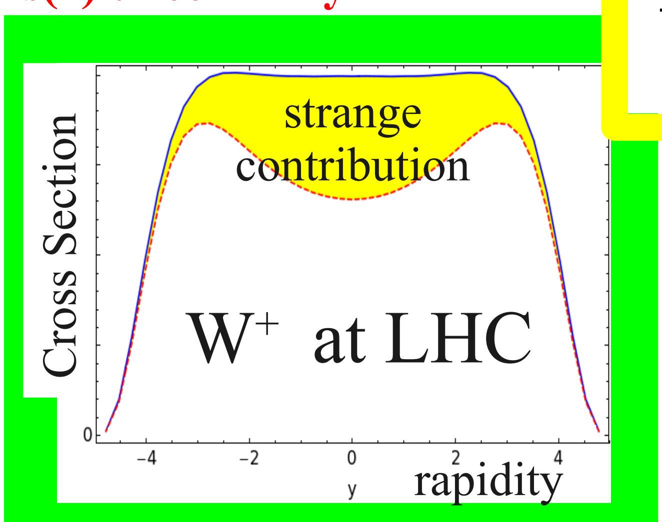


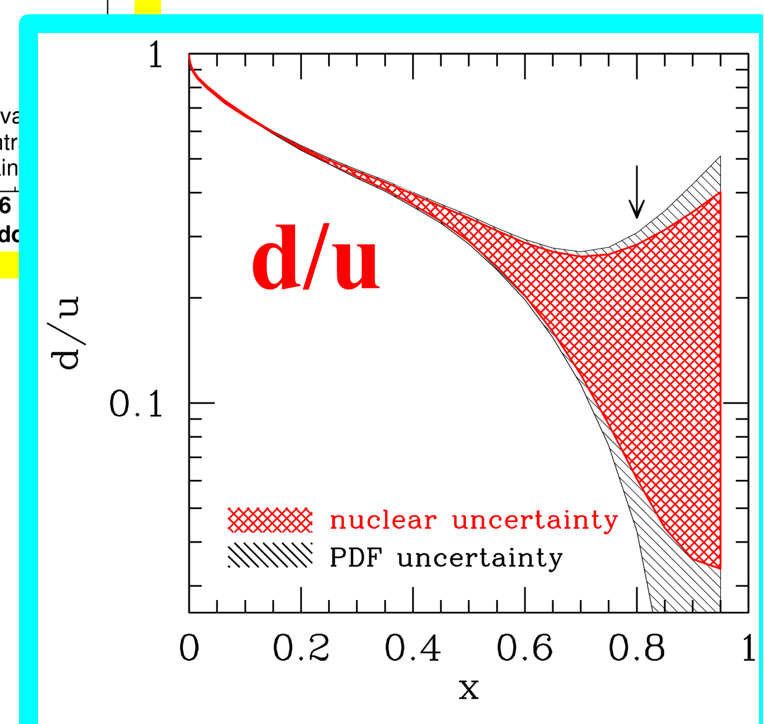
Nuclear Modifications limit PDFs

W Asymmetry



s(x) uncertainty





Backup

F L

Why is F_L so special ???

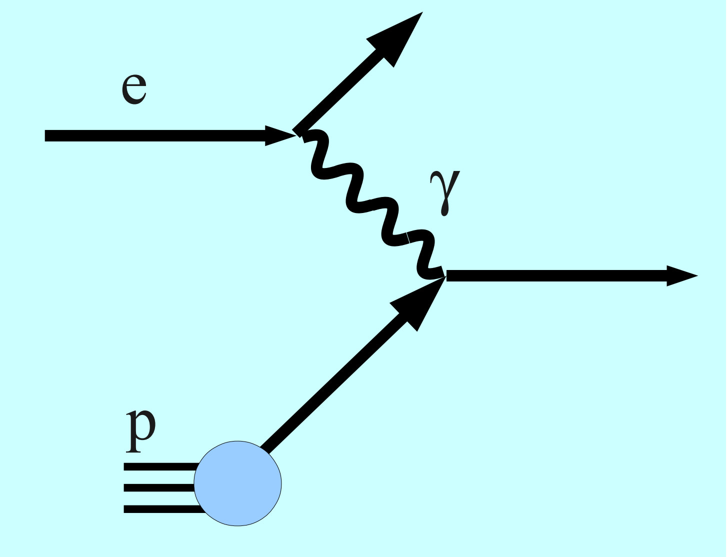
$$\frac{d\sigma^{\nu\, DIS}}{dx\, dy} = (1-y)^2\, \bar{q}(x) + (1-y)\, \phi(x) + q(x)$$

$$\frac{d\sigma^{\nu\, DIS}}{dx\, dy} = (1-y)^2\, F_+(x) + (1-y)\, F_0(x) + F_-(x)$$

$$F_0 = \frac{F_2}{2x} - F_1$$

$$F_0 = 0 \quad \Longrightarrow \quad F_2 = 2xF_1$$

Callan-Gross



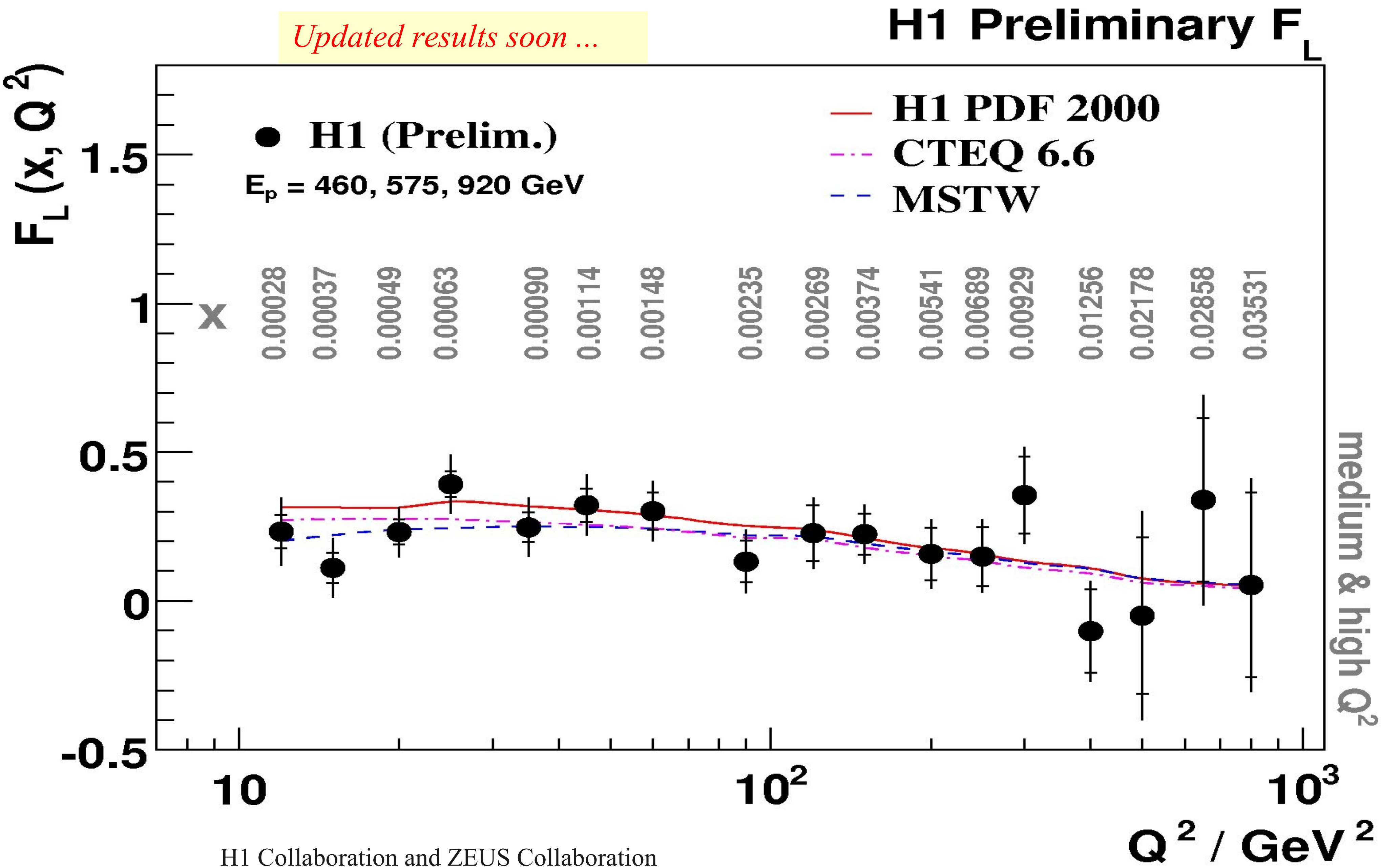
$$F_L \sim \frac{m^2}{Q^2}\, q(x) + \alpha_S \left\{ c_g \otimes g(x) + c_q \otimes q(x) \right\}$$

Masses are importan

Higher Orders are important

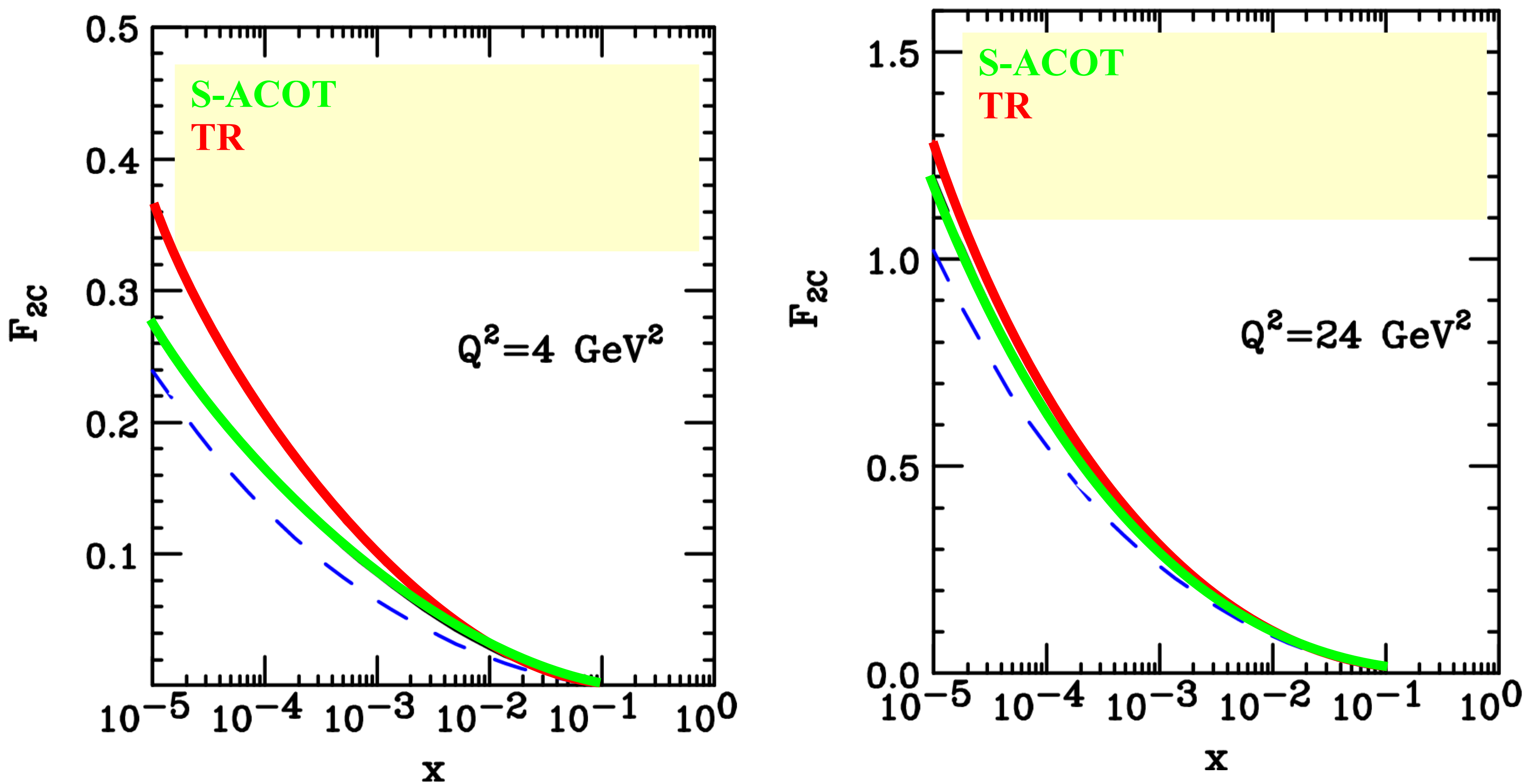
New F_L Measurements: New Perspective

Updated results soon ...



H1 Collaboration and ZEUS Collaboration
(S. Glazov for the collaboration).
Nucl.Phys.Proc.Suppl.191:16-24, 2009.

Comparison of ACOT & TR Schemes



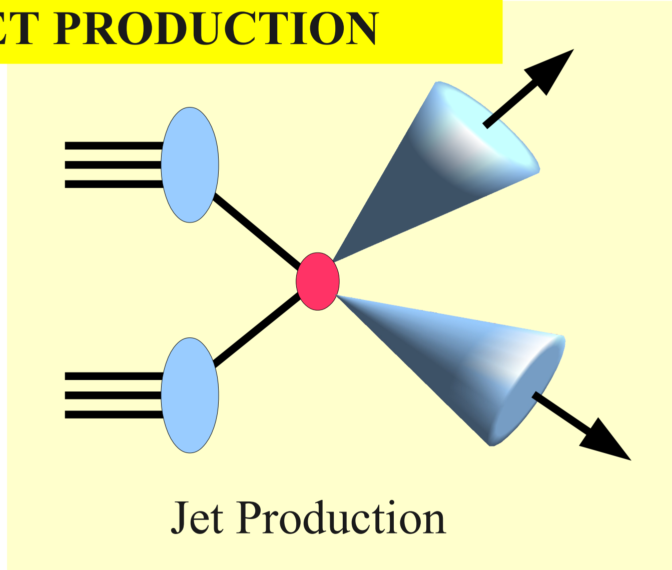
Different schemes ⇒ Different PDFs ⇒ yet consistent σ

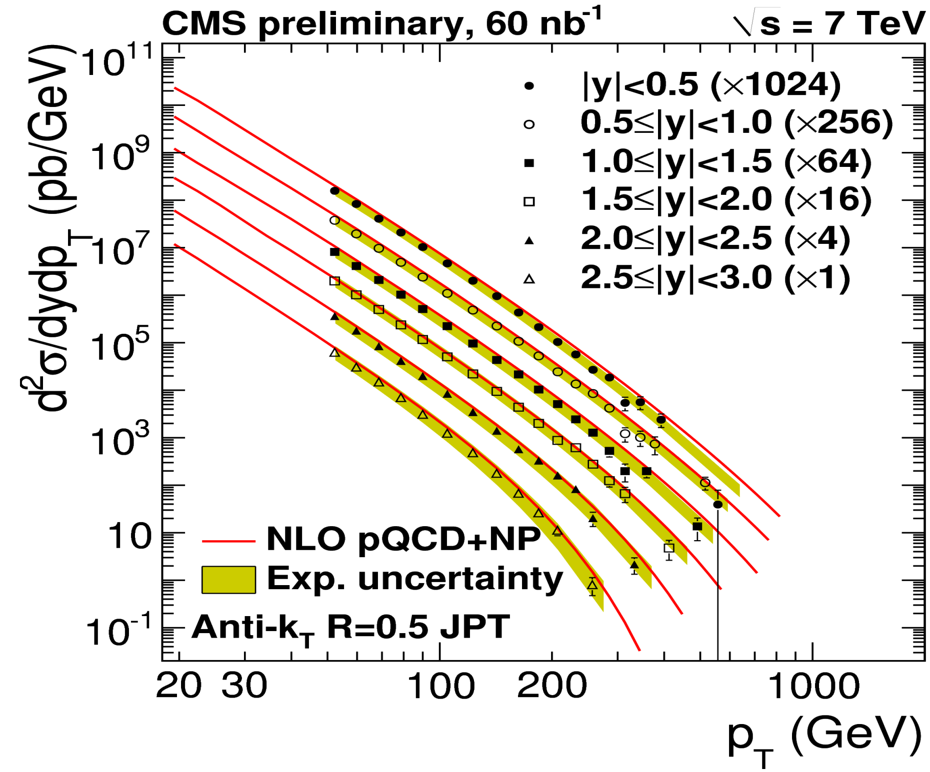
Differences reduce at:

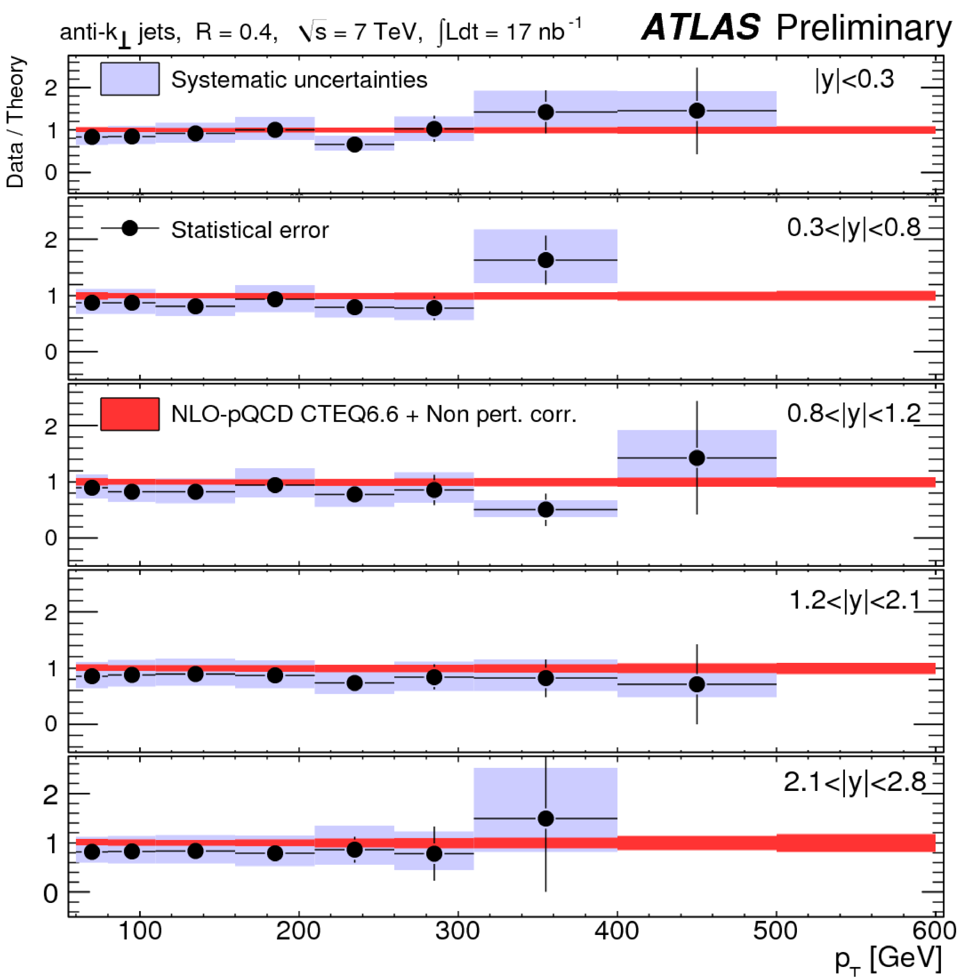
1) higher Q,
2) higher order

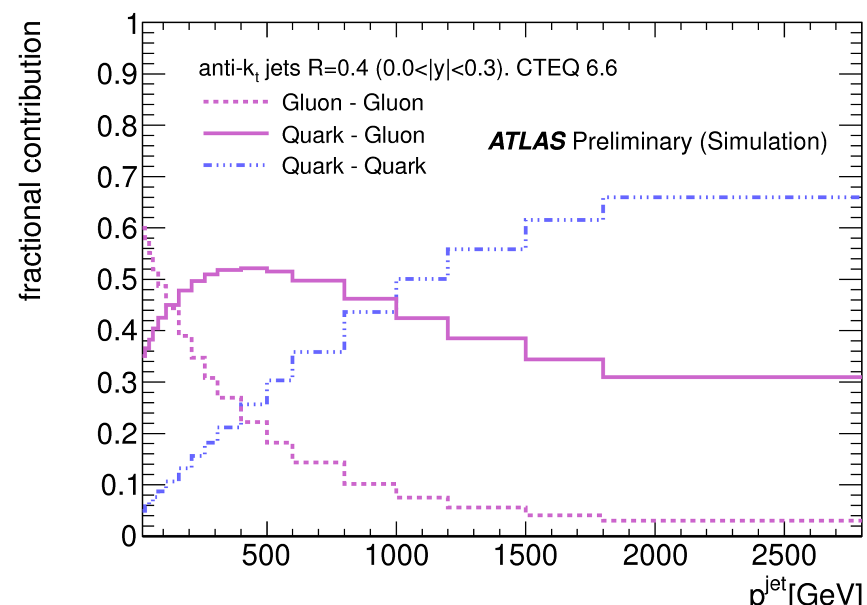
If experiments are sensitive, time to compute to higher order

JET PRODUCTION









Parton discrimination