3rd HERA-LHC Workshop

DESY, 12-16 March 2007

Heavy Quark Working Group Summary Talk

M. Cacciari, A. Dainese, A. Geiser, H. Spiesberbger

Activity

6 theoretical talks + 11 experimental + joint session with PDF WG

G. Ferrera
S. Klein
G. Kramer
A. Mitov
V. Saleev
G. Zanderighi

M. Cooper-Sarkar
R. Thorne
W.K. Tung

break-down: 5 HERA + 6 LHC

A. Cholewa
B. Kahle
K. Lipka
J. Loizides
M. Turcato

R. Guernane (x2)
K. Harrison
M. zur Nedden
C. Rosemann
A. Starodumov

[LHC > HERA: guess we are on the right track]

Will also summarize the joint session, which addressed the issue of heavy quark treatment in modern PDF's fits

Timeline

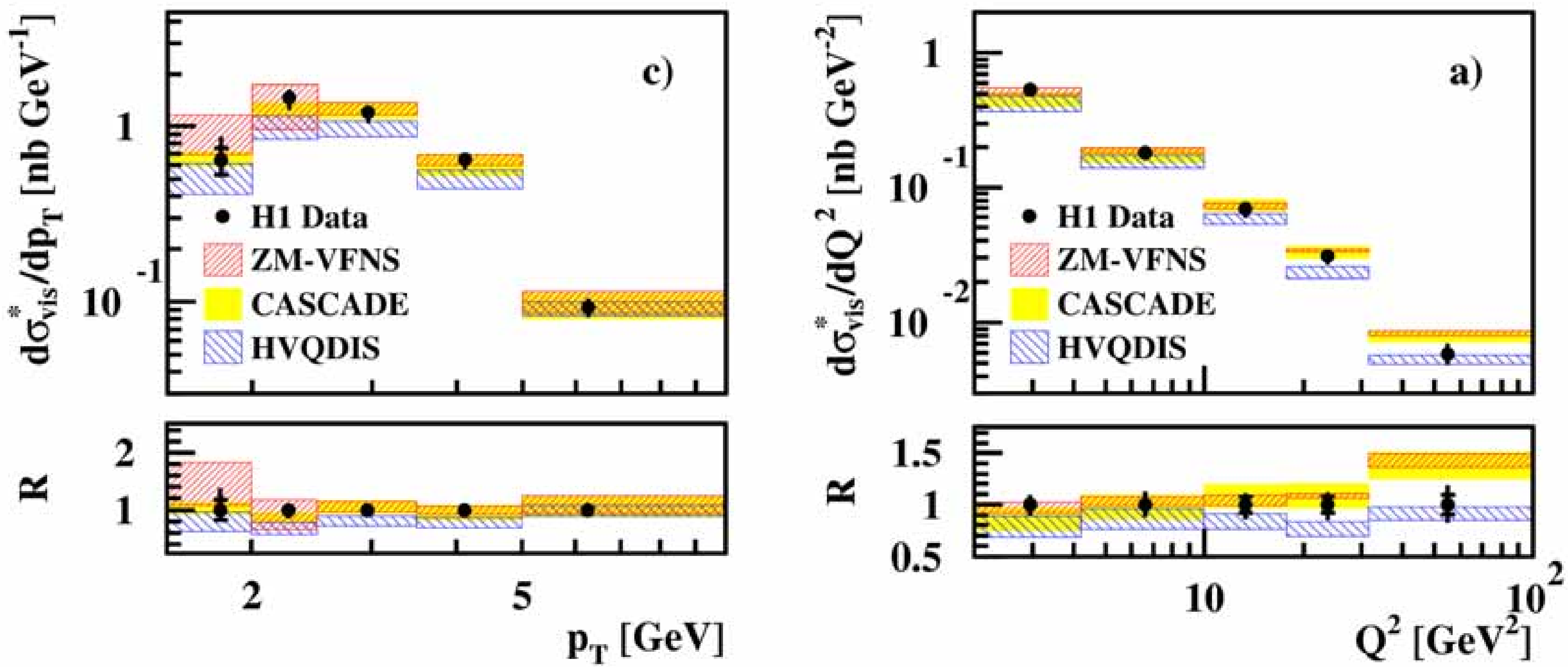
- **HERA**
- LHC
- Theory
- Heavy quarks in PDF's

Disclaimer: some talks will be covered poorly/misinterpreted/neglected altogether, do to lack of comprehension on my part, lack of time for preparation, sheer exhaustion. Apologies in advance to the speakers.
Needless to say, all the slides are available from the agenda

Inclusive D* cross sections - DIS

Turcato

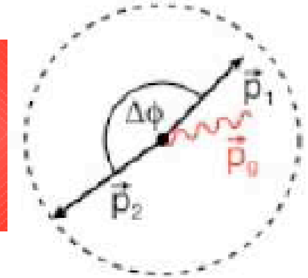
- Inclusive cross section compared with massive and massless calculations: both approaches describe data well.

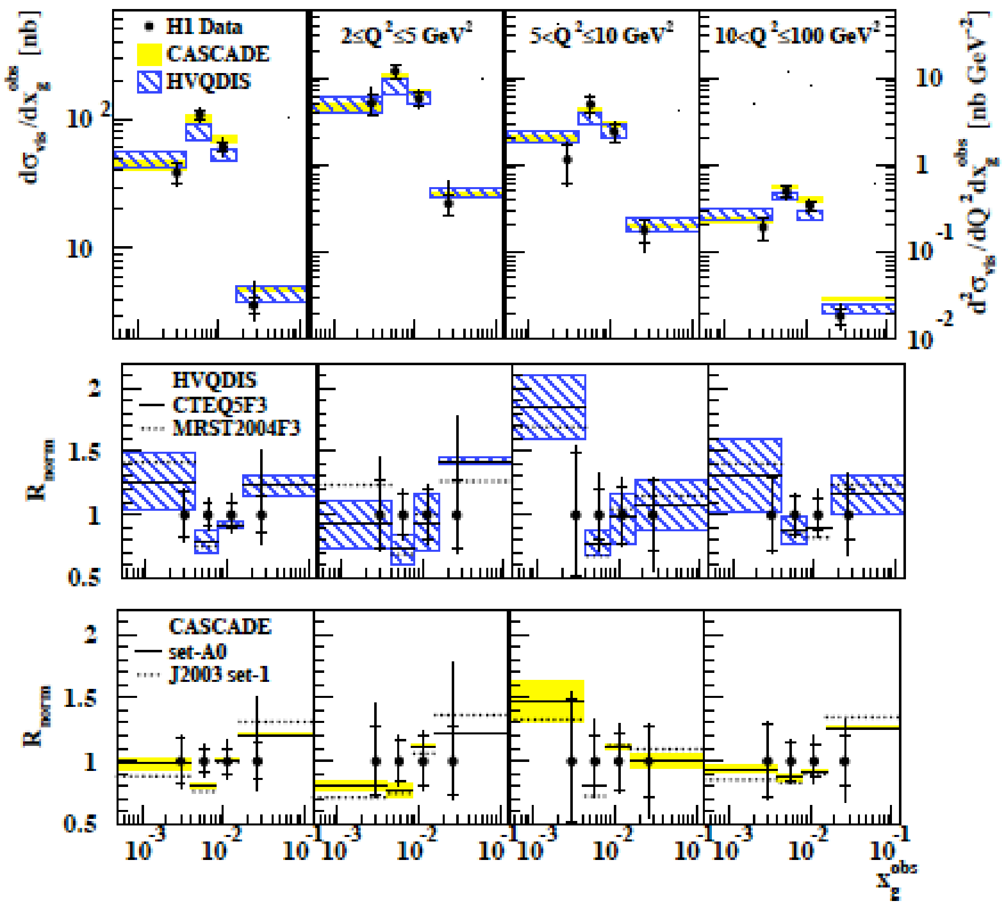


- CTEQ5F used as proton PDF.

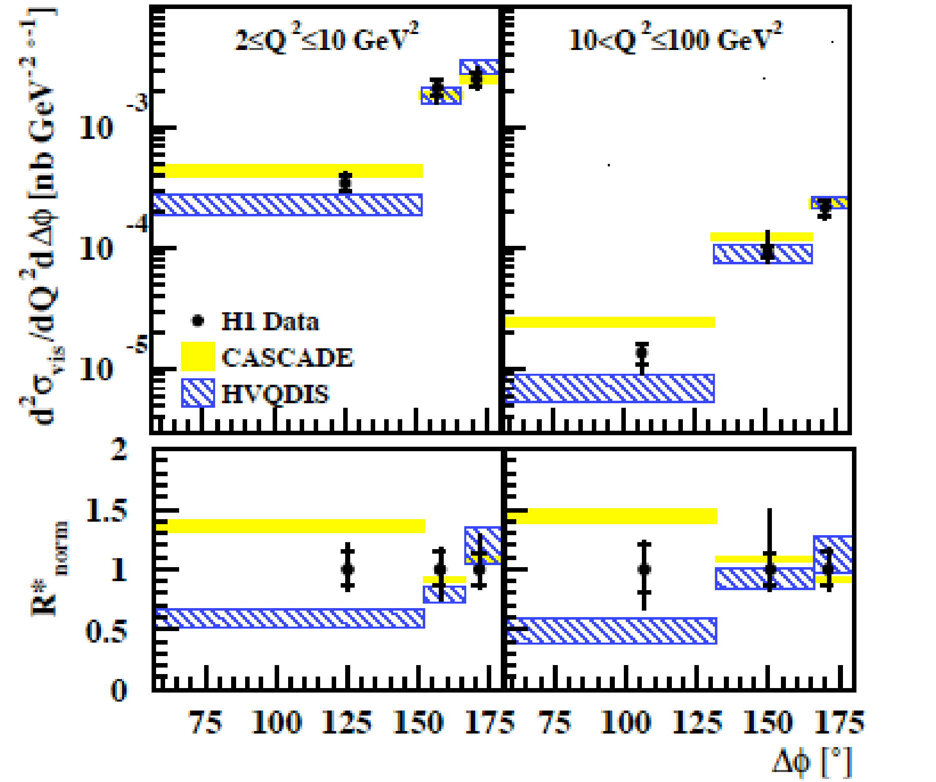
Turcato

D* with dijets – DIS (cont'd)





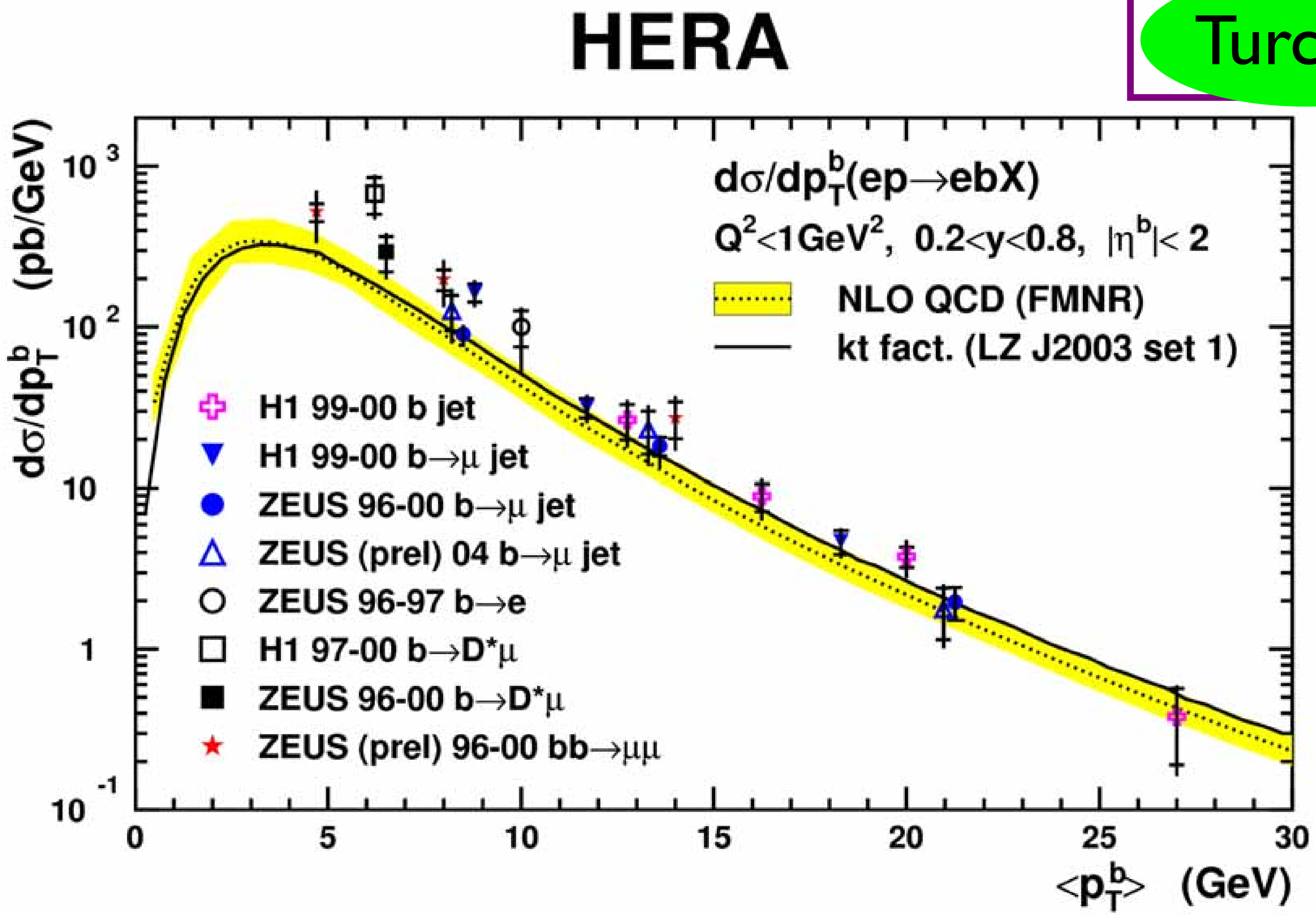
x_g well described by NLO: the gluon distributions from inclusive data are suitable also for charm.



CASCADE: unintegrated gluon density may be too broad, so the non-back-to-back region (high-k_t) is overestimated. The angular correlation between jet and D* is not described. Situation is not changed by using another available gluon density in CASCADE.

Beauty in photoproduction: summary

Turcato



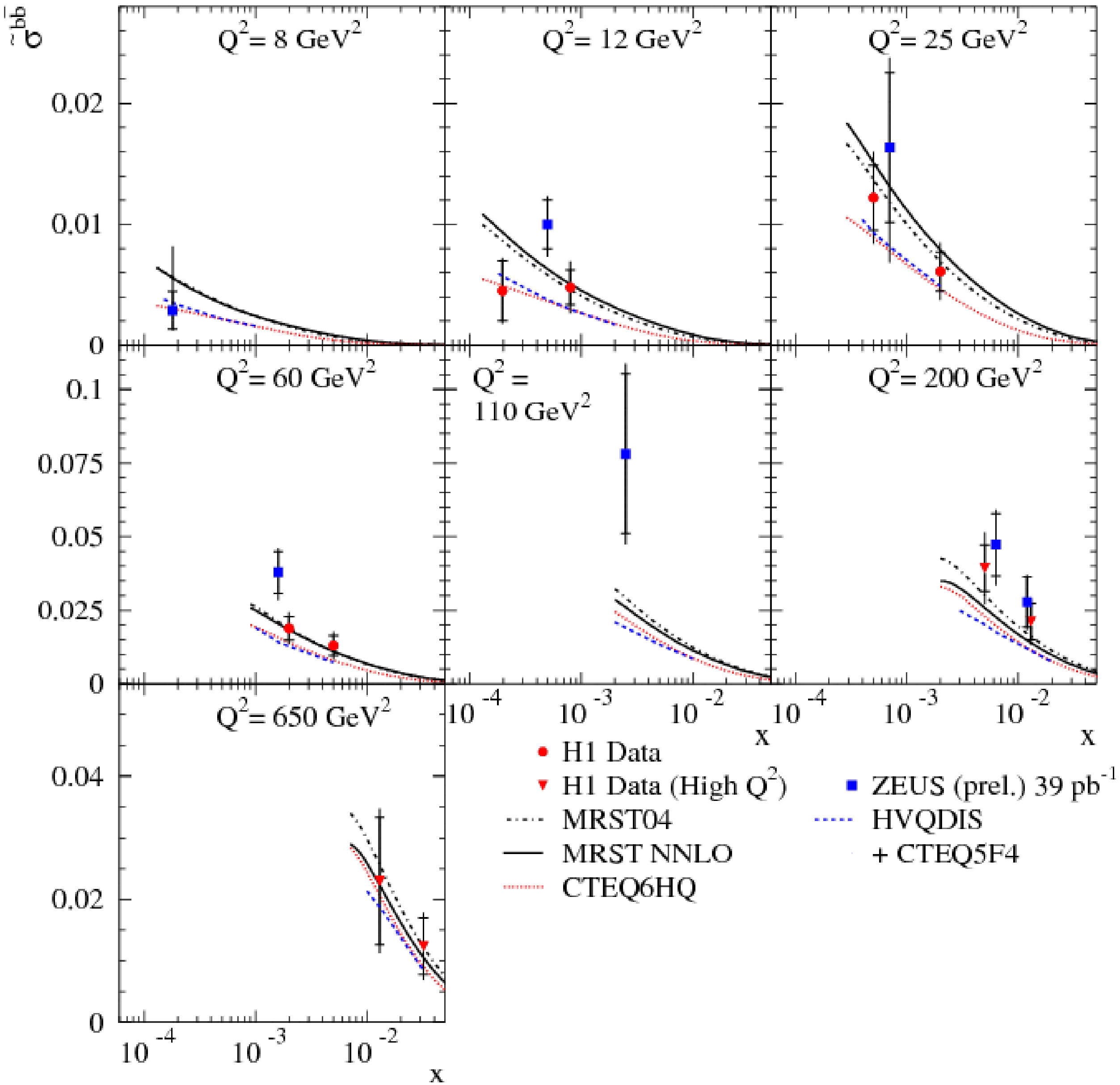
Conclusions for HERA/LHC

- HERA: Charm and beauty cross sections reasonably described by NLO QCD predictions, except in special regions of phase space

- LHC: Enhances confidence in charm, beauty and top cross section predictions
  (SM QCD and background for new physics)

F_2^{bb} at ZEUS and H1

Kahle



ZEUS data lie above H1 data but compatible within errors.

HVQDIS+CTEQ5F4 agrees with similar predictions by H1

ZEUS: 39 pb^{-1}

H1: 57.4 pb^{-1}

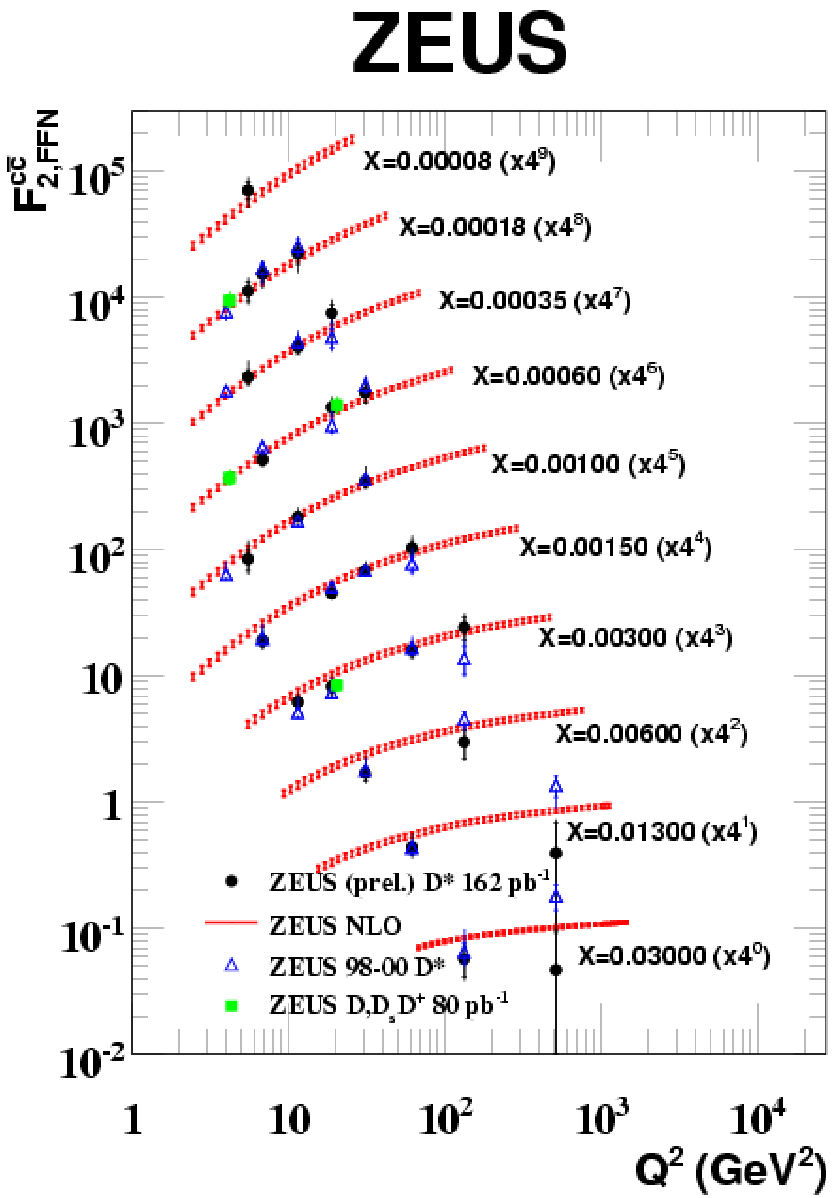
Theory predictions except HVQDIS+CTEQ5F4 provided by P.D.Thompson, hep-ph/0703103

ZEUS data point at Q^2=200GeV^2; x=0.13 is shifted to lower x value to be separated from the H1 point

Only about 10% of available data analysed.

Extraction of F_2^{cc} - HERA II

Loizides



HERA II(162 pb^{-1}) data analysed

Similar errors to the HERA I analysis. ⇒ Total HERA II set will be ~ 450 pb^{-1}.

→Good agreement with NLO QCD.

Combine results from HERA I and HERA II in the near future.

⇒ Impact of charm data on PDF fits. ?

[More about this later on]

Cholewa

Results - different quarks

χ^2 minimisation with F_2 data

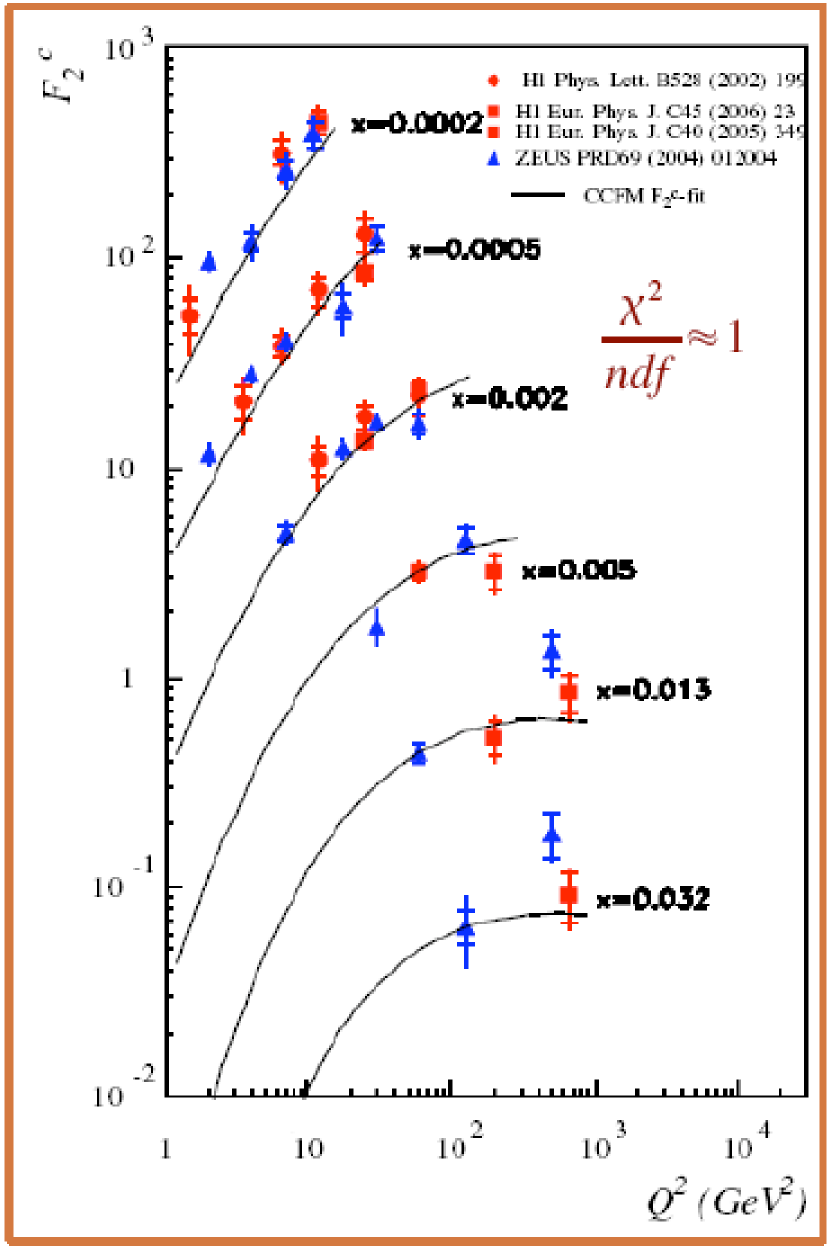
- Fitting data above starting scale $Q_0^2 = 5\,GeV^2$ and below $x_{cut} = 0.005$
- Fit yields good description of F_2 resulting in

$$\frac{\chi^2}{ndf} \approx 2$$

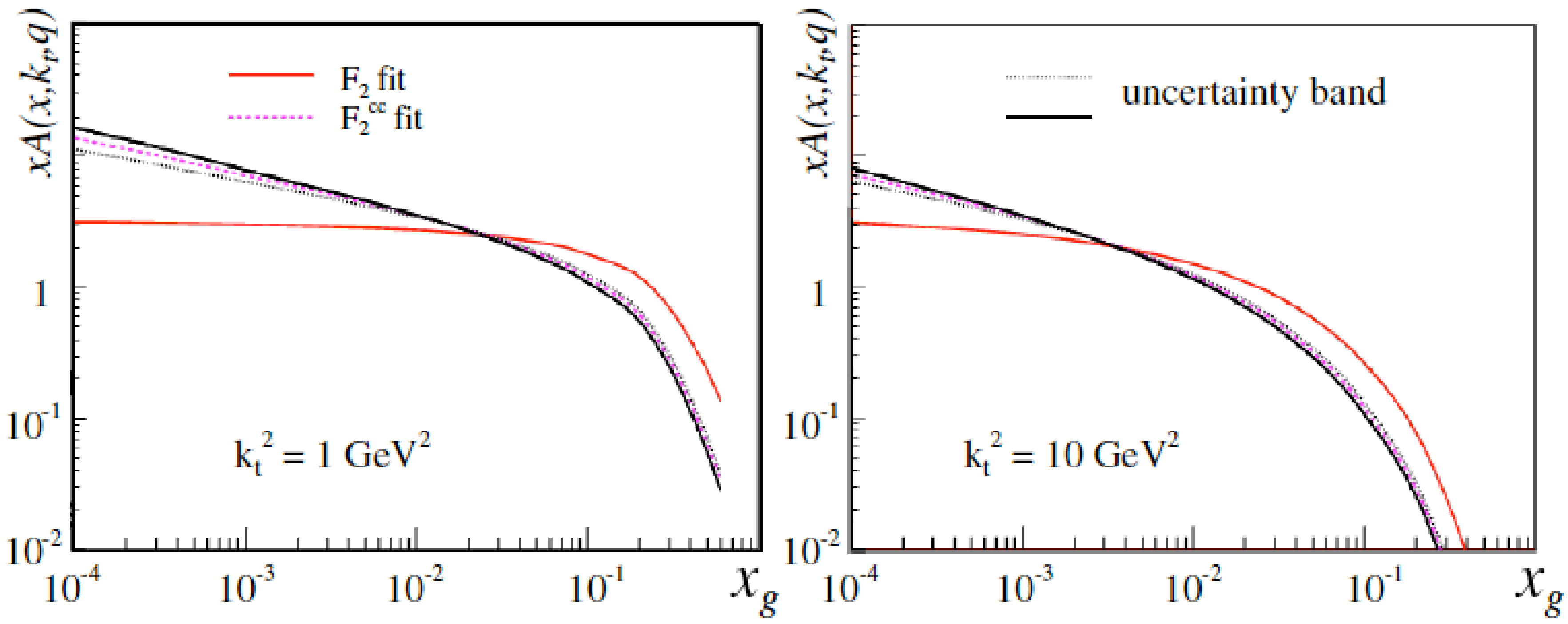
χ^2 minimisation with F_2^{cc} data

- Fitting data above starting scale $Q_0^2 = 1\,GeV^2$ without x_{cut}
- Description of F_2^{cc} very good, giving

$$\frac{\chi^2}{ndf} \approx 1$$



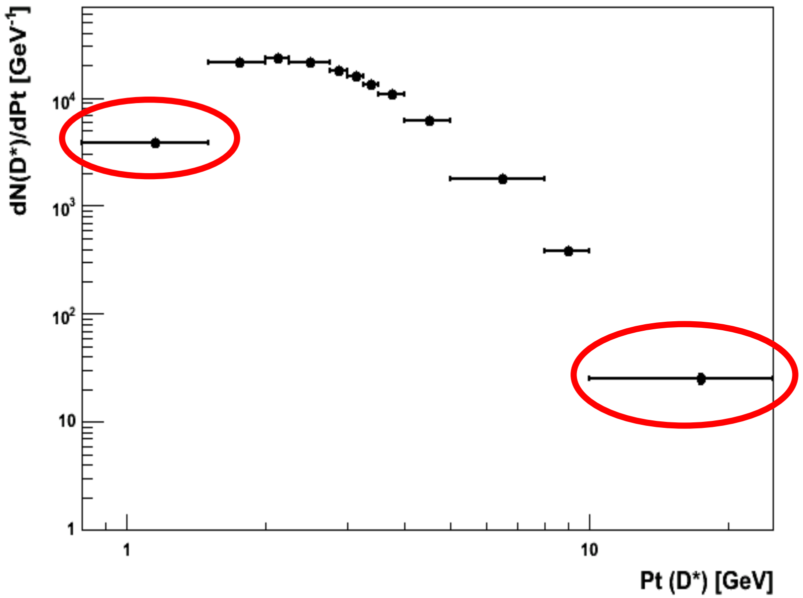
Results - different quarks, different gluons?

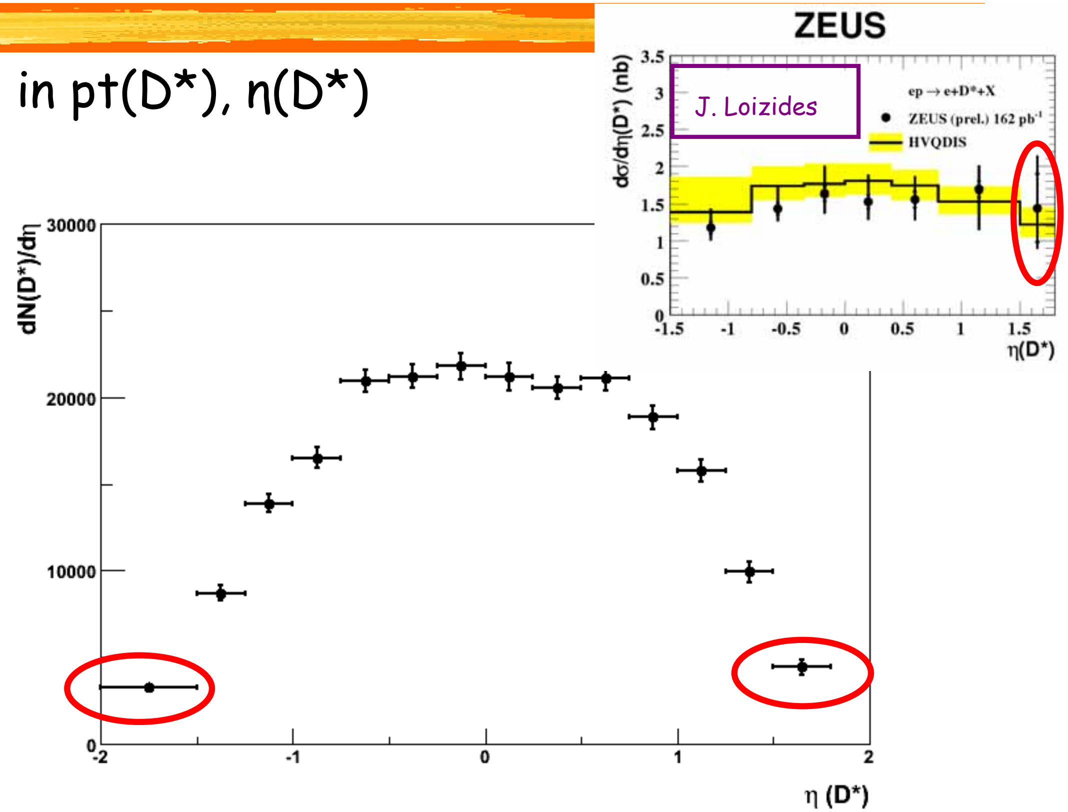


H1 F^c_2 prospects for HERA II

Lipka

New phase space regions in pt(D*), η(D*)





HERA I |η|< 1.5 , p_T (D*) > 1.5 GeV, average extrapolation factor 3.4

HERA II p_T(D*) > 0.8 GeV, |η|< 1.9 (central detector) average extrapolation 1.9

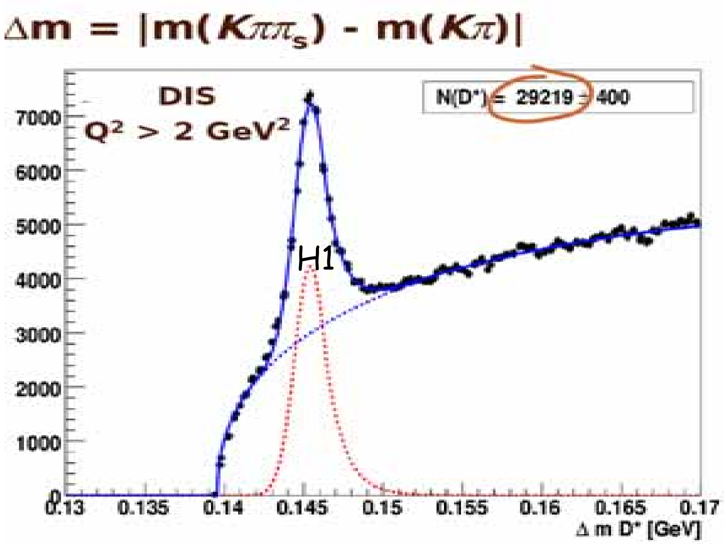
+ Backward Silicon Tracker -2.75 < η < 1.9 average extrapolation 1.6

Increase of visible range used in analysis from 30% to 60%

Extremely helpful to avoid theoretical bias in extrapolations

Conclusions for HERA/LHC

- HERA: converge towards quantitative direct measurement of gluon distribution from charm production
  - HERA I data not yet precise enough to reduce error on gluon, but valuable cross check (M. Cooper-Sarkar)
  - HERA II results are starting to emerge
    -> expect significant improvements
    (J. Loizides, K. Lipka, A. Cholewa)

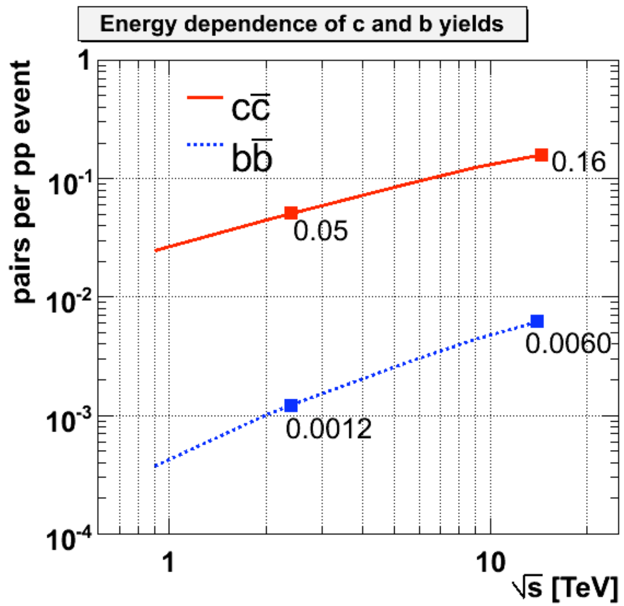


- LHC: gluon distribution determined by HERA is basis for many cross section predictions

Timeline

- [x] HERA
- [ ] **LHC**
- [ ] Theory
- [ ] Heavy quarks in PDF's

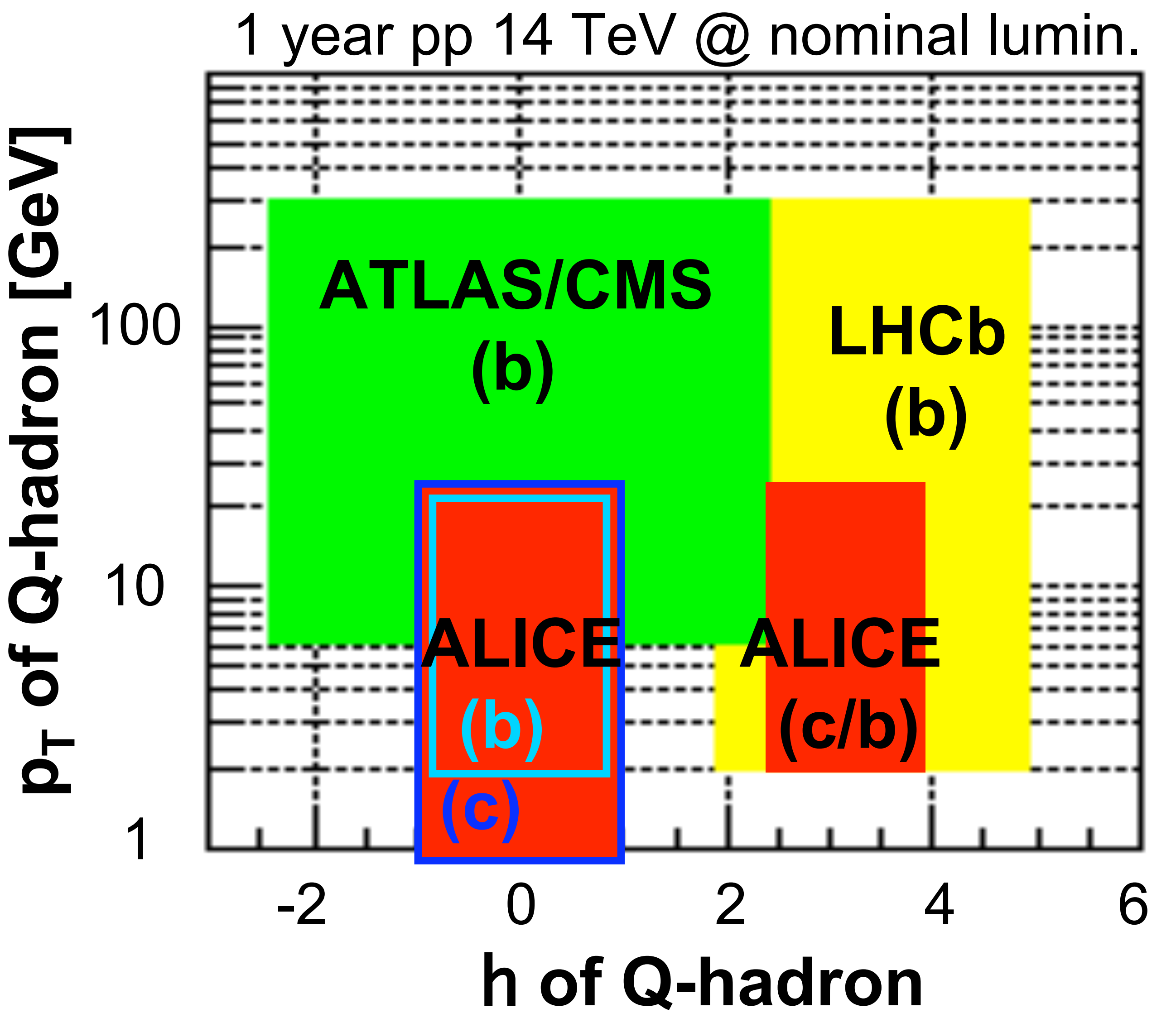
The (Near) Future
LHC: heavy quarks factory



- Cross sections: NLO (MNR)
  - m_c=1.2 GeV, m_F=m_R=2m_c; m_b=4.75 GeV, m_F=m_R=m_b
- Yields: assuming s_{pp}^{inel} = 70 (40) mb at 14 (0.9) TeV

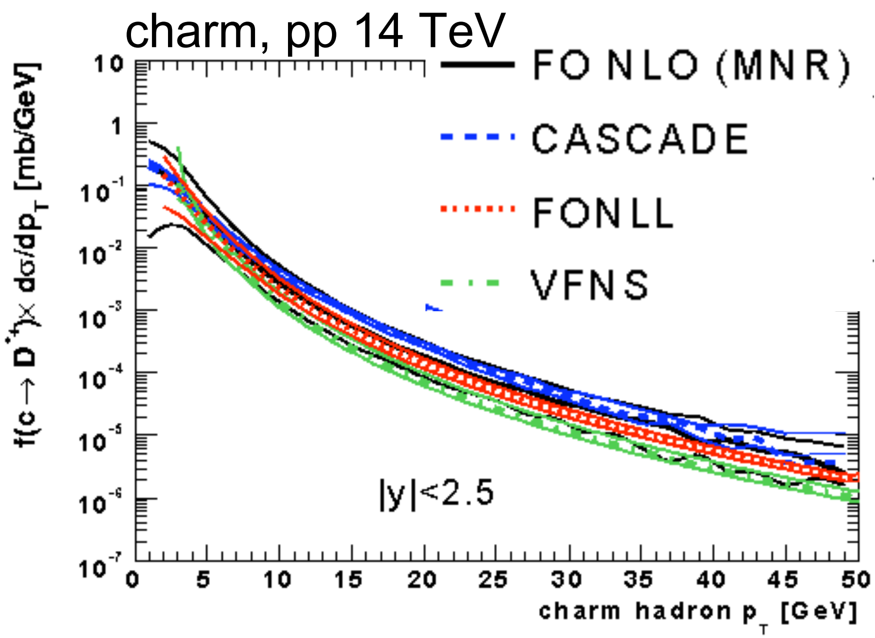
	PbPb 5.5 TeV		pp 14 TeV	
	0-5% centr.			
	$c\bar{c}$	$b\bar{b}$	$c\bar{c}$	$b\bar{b}$
σ(NN) [mb] (*)	6.64	0.21	11.2	0.51
EKS98 shadowing	0.65	0.86		
N per collision	115	4.56	0.16	0.0072

Acceptance for open heavy flavor at LHC



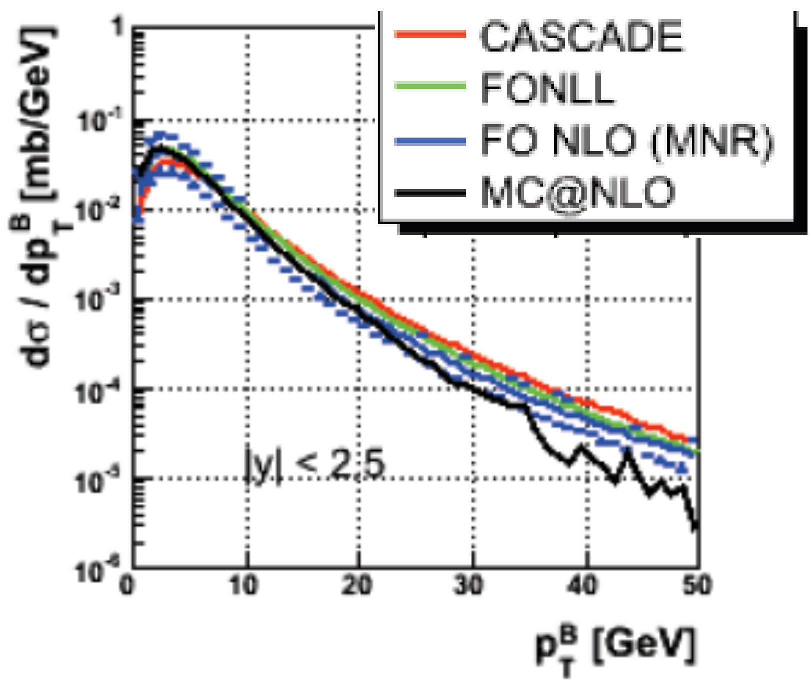
important: complementarity of the 4 experiments

Updated benchmark cross sections



from HERA-LHC 04/05 Proceedings

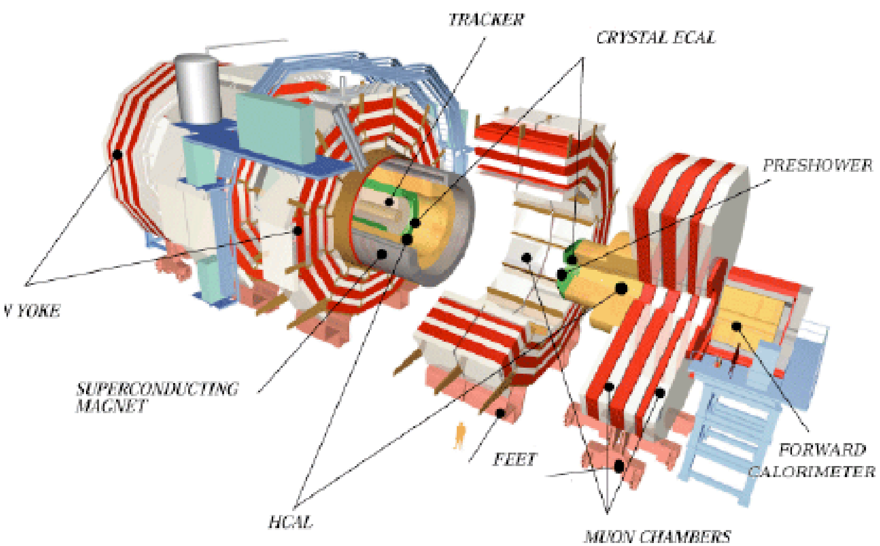
Update for b (R. Guernane):

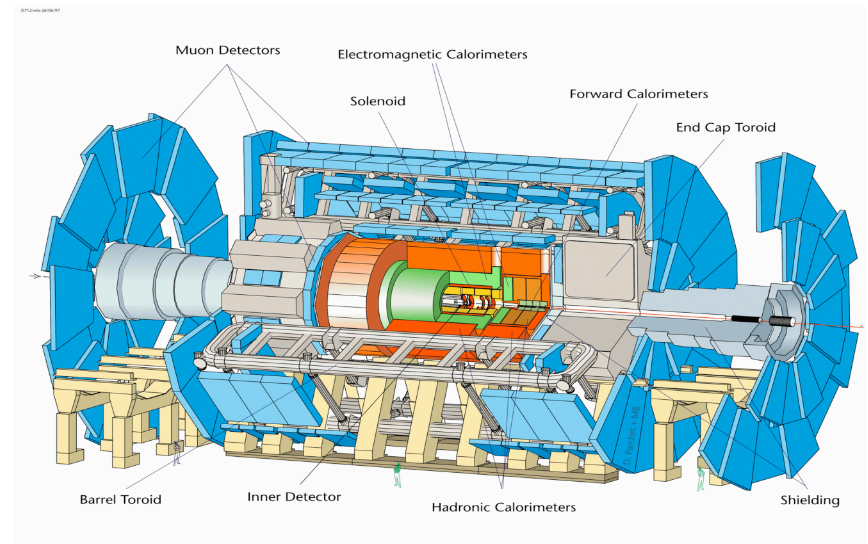


more to come: PHOWEG, B from VFNS

Addition of MC@NLO

CMS (Starodumov) & ATLAS (zur Nedden)





- Muon detection
- Calorimetry
- Silicon trackers
- **About (only) 5% of trigger bandwidth for B Physics**

CMS & ATLAS: B programmes

CMS

- B Physics
  - $b\bar{b}$ production x-section @ 14TeV (low p_T)
  - $b\bar{b}$ production mechanisms @ 14TeV
  - inclusive and exclusive B decays (CP, CKM, FCNC, NP ...)
  - HF spectroscopy
- b jets
  - $b\bar{b}$ production x-section @ 14TeV ($50\,\mathrm{GeV}/c < p_T < 1500\,\mathrm{GeV}/c$)
  - crucial ingredient in many physics studies and searches
    - $t\bar{t} \to W^+W^- b\bar{b}$
    - Higgs searches: $H \to b\bar{b}$, $t\bar{t}H$, $b\bar{b}H(A)$ etc
    - b jets in decays of SUSY particles

ATLAS

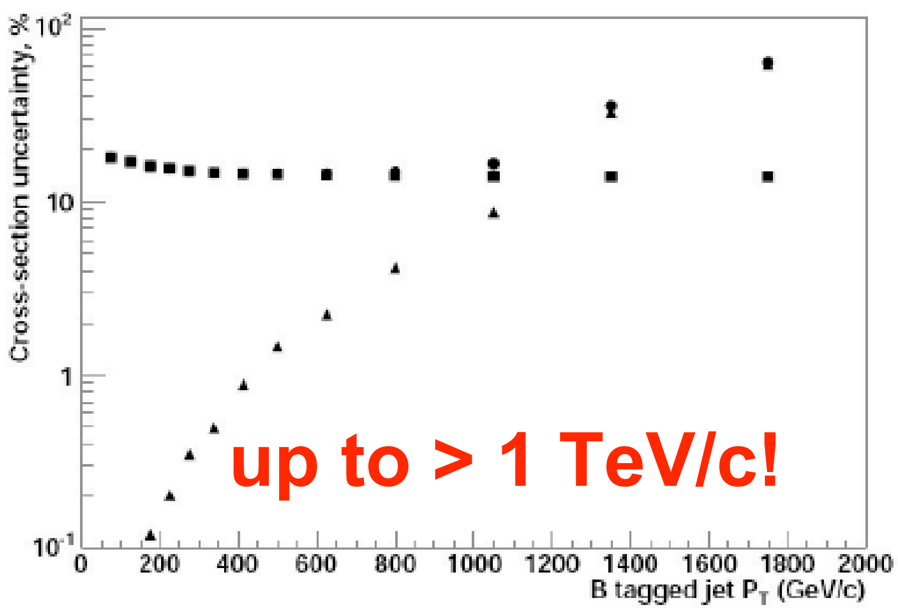
- **CP violation** (e.g. $B \to J/\psi(X)$, $B \to \mu\mu$)
- **B_s oscillations** (e.g. $B_s \to D_s\pi$, $B_s \to D_s a_1$)
- **Rare decays** (e.g. $B \to \mu\mu(X)$, $B \to K^*\gamma$)
- **Inclusive cross section measurement**

CMS & ATLAS: b-jet tagging

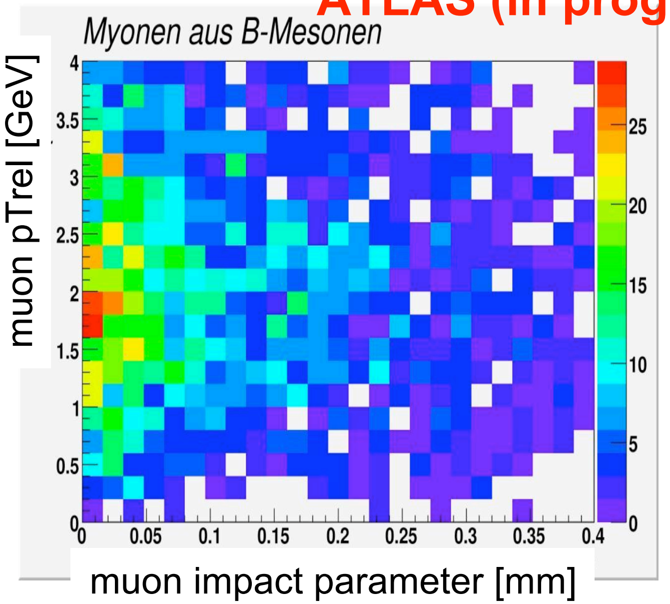
CMS

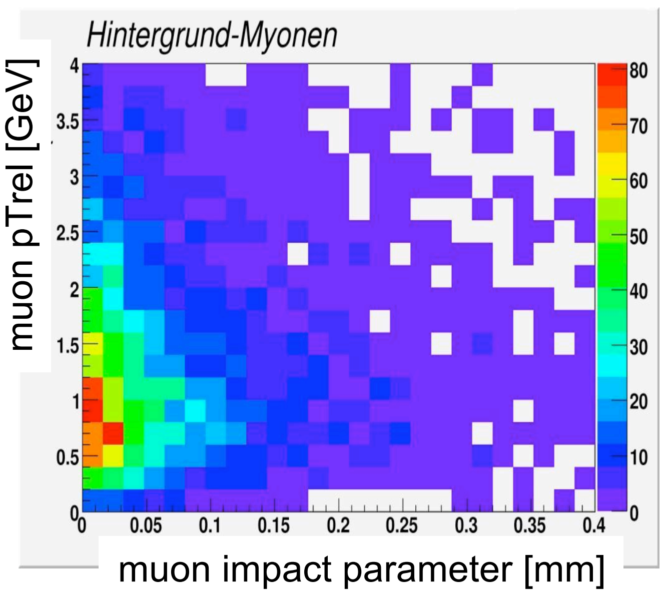
b x-section uncertainties:

stat (▲), sys (■), total (●)



ATLAS (in progress)

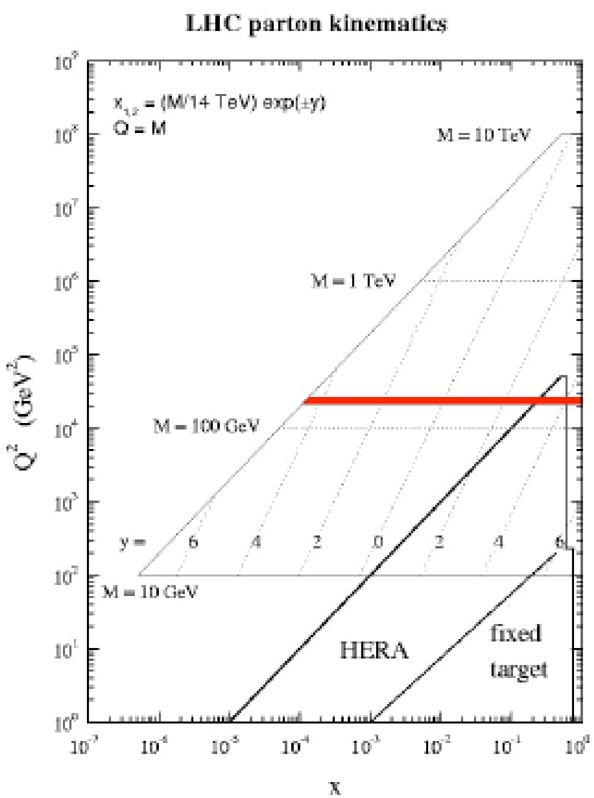


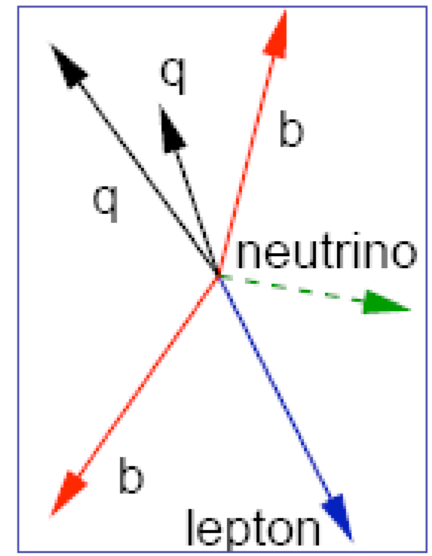


LHC vs HERA:
one heavy quark more (top!)

Semileptonic $t\bar{t}$ decays – $t\bar{t} \rightarrow b\bar{b}q\bar{q}\ell\nu$

Rosemann)



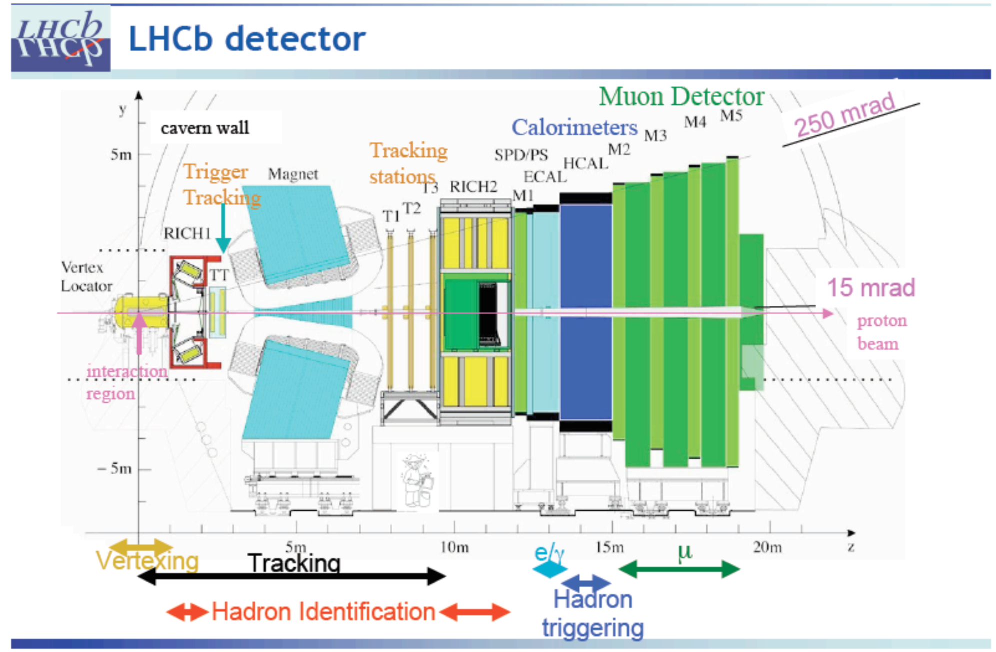


- Gluon pdfs of utmost importance
- Symmetric production threshold $x_0 = \frac{2m_{top}}{\sqrt{s}} = 0.025$
- Test of QCD
- In particular: experimental test at high Q^2 (> $2 \cdot 10^4$ GeV^2) DGLAP vs. CCFM vs. ?

- Powerful test of theory and experiment
- Currently promising results, e.g. small acceptance corrections
- 10% signal efficiency seem possible

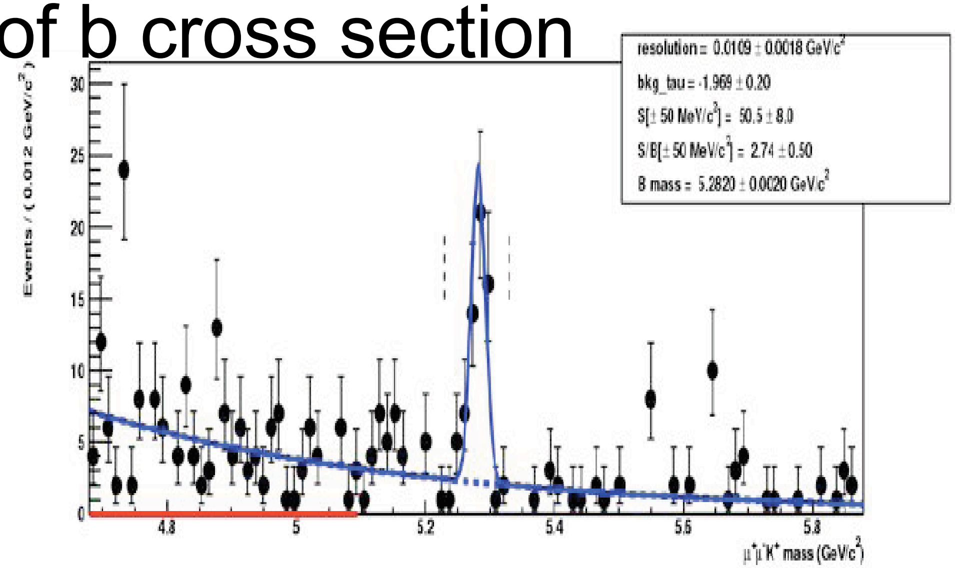
LHCb

Harrison



- dedicated to B Physics
  - CP violation
  - rare decays
  - B spectroscopy
- many complementary channels
- example: measurement of b cross section
  - inclusive displaced muons
  - inclusive displaced J/y & D's
  - exclusive B mesons

    e.g. $B^+ \rightarrow J/yK^+$

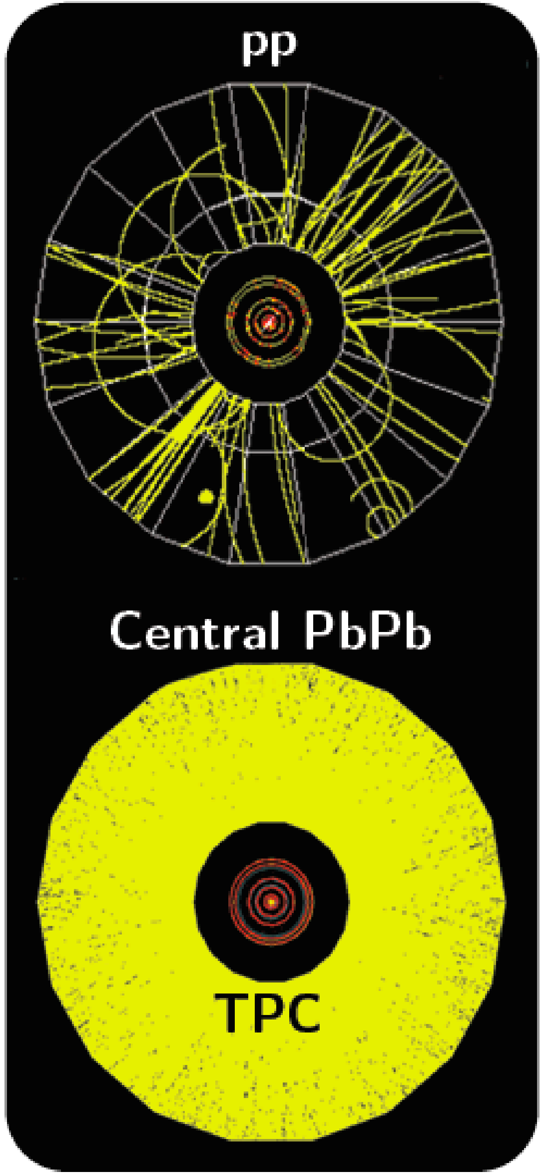


Guernane

Heavy flavour production at the LHC

Introduction

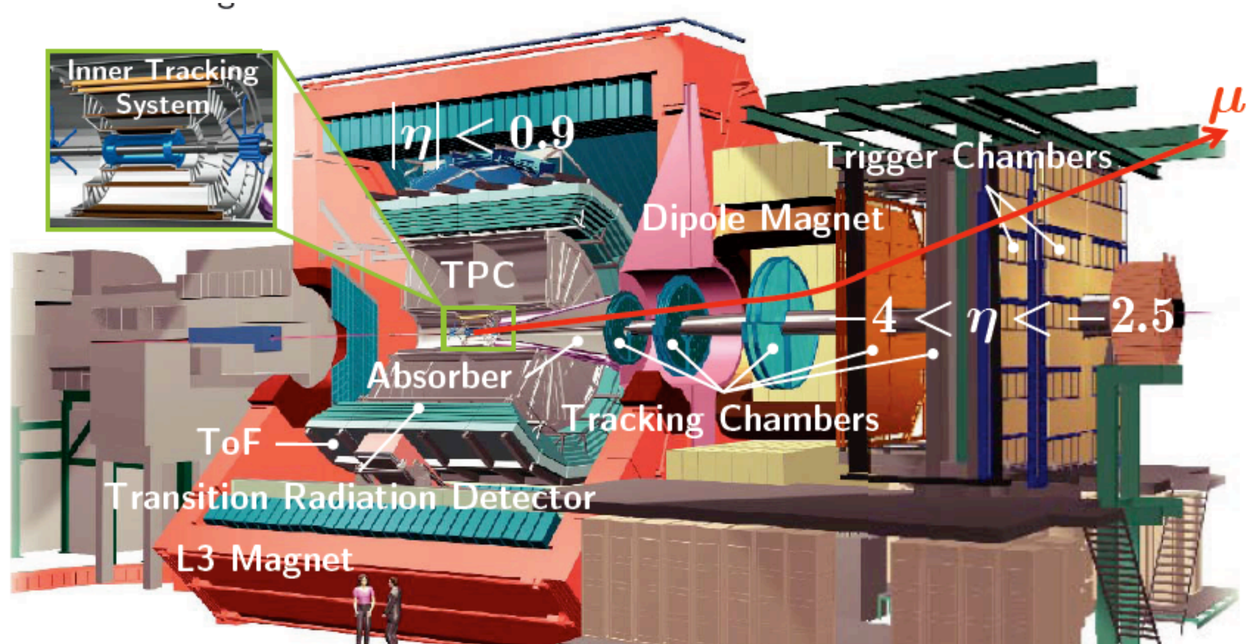
- What for?
  - heavy flavour production in hadron collisions provides a rich QCD phenomenology
    - pp $\rightarrow$ test reliability of pertubative calculations
    - pA $\rightarrow$ assess initial state effects
    - AA $\rightarrow$ probe the high colour-density medium
- LHC's novelties
  - hard cross section dominates
    - $\sigma_{hard} / \sigma_{tot} \sim 98\,\%$ VS $50\,\%$ at RHIC
    - copious production of both c & b quarks
  - large inelastic background
    - messy environnement with large combinatorics $\propto (dN_{ch}/dy)^2$ with $dN_{ch}/dy = 6000$ in central Pb-Pb!
- ALICE's plus points
  - muti-purpose $\rightarrow$ several heavy flavour measurements within the same experiment
  - precise tracking & vertexing $\rightarrow$ resolve D's & B's decay vertices
  - PID $\rightarrow$ π/K separation



ALICE

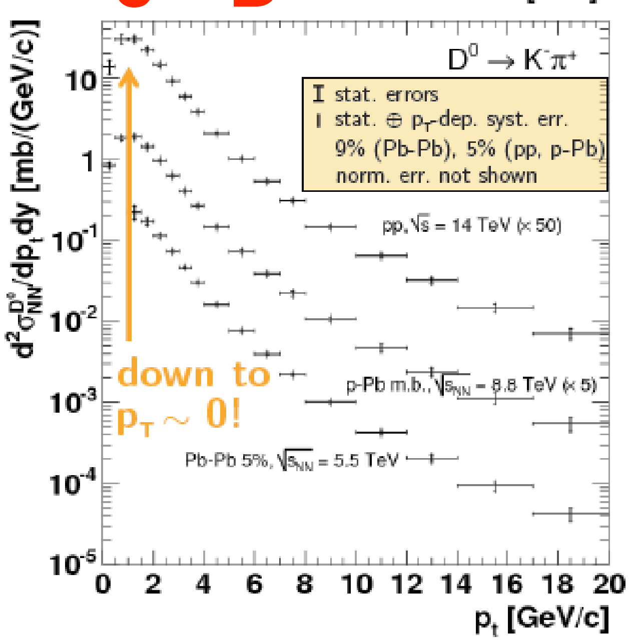
Guernane

Pb-Pb 5.5 TeV
pp 14 TeV
p-Pb 8.8 TeV

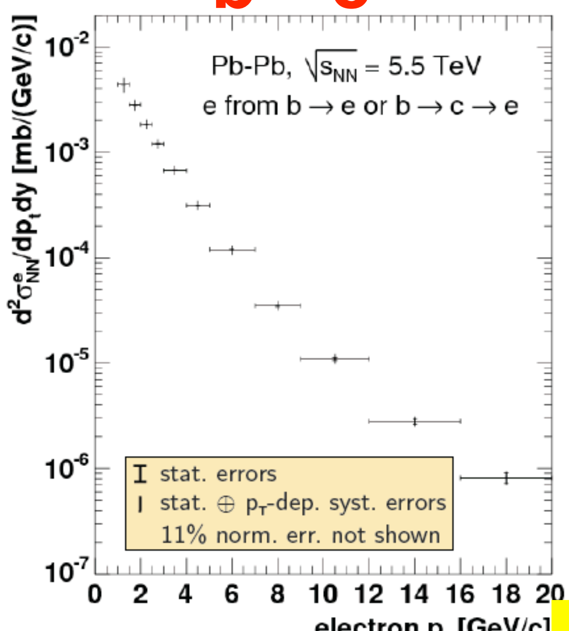


Size: 16 x 26 meters
Weight: 10,000 tons

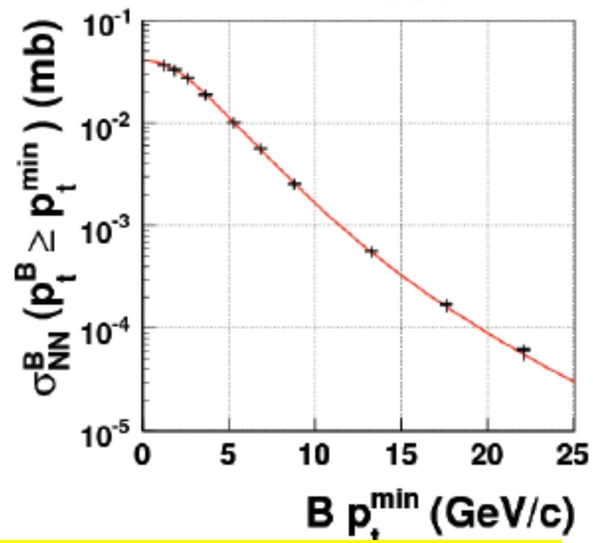
c→D⁰



b→e

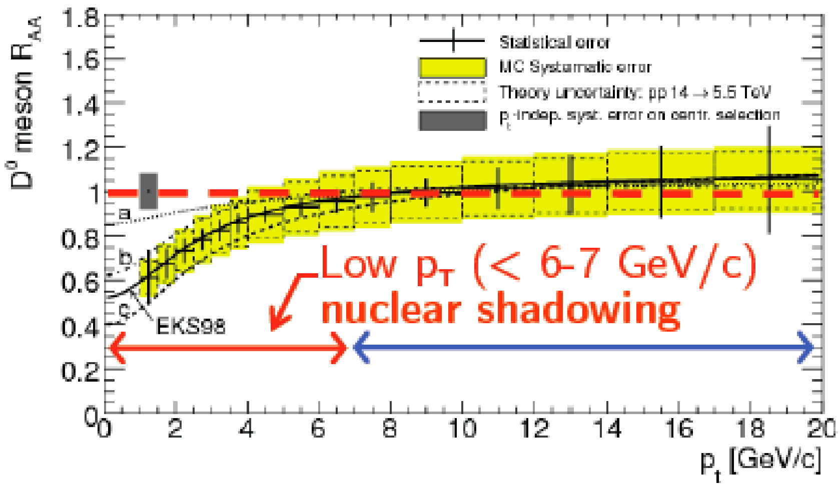


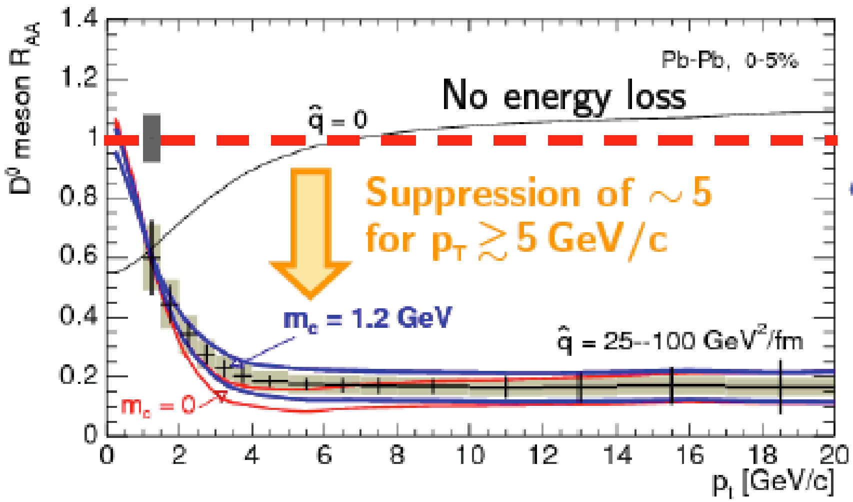
b→m

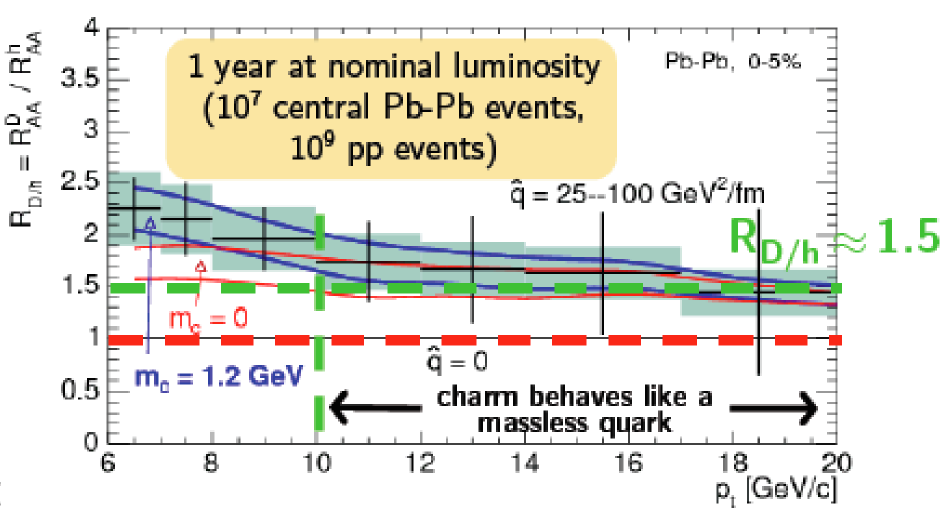


down to (almost) 0 pT!

Perspectives for the study of charm quenching







- The method
  - compare D^0 mesons p_T distributions in **pp** & **AA**

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

"High" p_T (> 6 - 7 GeV/c)

▷ here **energy loss** can be studied

▷ **only** expected effect?

in-medium hadronisation...

  - "heavy-to-light" ratios

$$\Delta E_g > \Delta E_q^{m=0} > \Delta E_q^{m\neq 0}$$

$$R_{D/h}(p_T) = R^D_{AA}(p_T) \,/\, R^h_{AA}(p_T)$$

test the **color-charge dependence** of QCD energy loss

$$R_{B/h}(p_T),\ R_{B/D}(p_T)$$

test the **masse dependence** of QCD energy loss

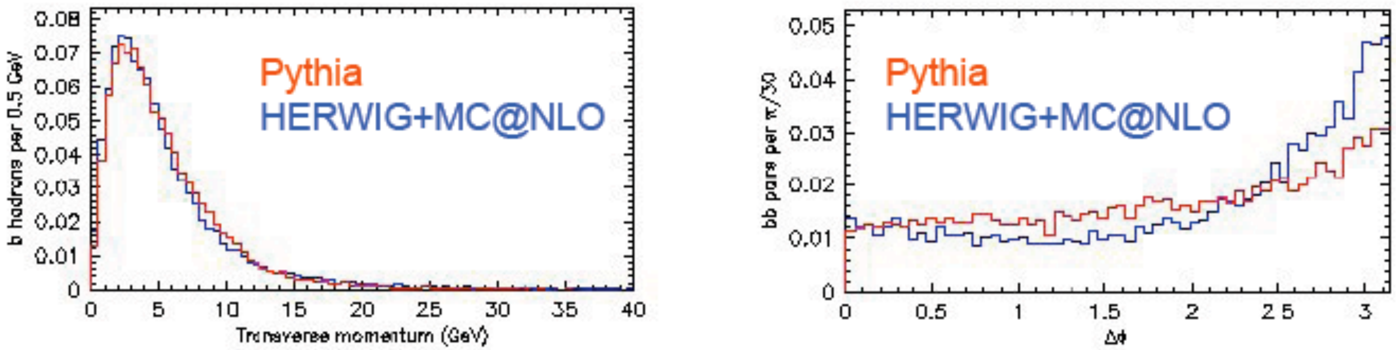
Warning: the LHC is unexplored territory (Hic Sunt Leones)

Important to use different MCs to perform corrections!

- example from LHCb. true for everybody -

Efficiency estimates

- Efficiency estimates rely heavily on simulation studies
- Most LHCb studies to date have used Pythia for particle production
- Studies for b production based on other packages also
  - HERWIG/MC@NLO/Jimmy, Sherpa, etc
  - Essential for understanding systematic uncertainties
    - Two generators can give same inclusive distributions, but different correlations
- Use EvtGen for particle decays, and Geant 4 for detector simulation



Timeline

- ☑ HERA
- ☑ LHC
- ☐ **Theory**
- ☐ Heavy quarks in PDF's

Kramer

Subject of this talk:

- One-particle inclusive production of heavy hadrons $H = D, B, \Lambda_c, \ldots$
- General-Mass Variable Flavour Number Scheme (GM-VFNS): [1]
  - Collinear logarithms of the heavy-quark mass $\ln \mu / m_h$ are subtracted and resummed
  - Finite non-logarithmic m_h/Q terms are kept in the hard part/taken into account
  - Scheme guided by the factorization theorem of Collins with heavy quarks [2]

Ongoing effort to compute all relevant processes in the GM-VFNS at NLO:

- $\gamma + \gamma \to D^{\star +} + X$: direct process [3]
- $\gamma + \gamma \to D^{\star +} + X$: single-resolved process [4]
- $\gamma + p \to D^{\star +} + X$ [5,6]
- $p + \bar{p} \to (D^0, D^{\star +}, D^+, D_s^+, \Lambda_c^+) + X$ [1,7]
- $p + \bar{p} \to B^+ + X$ [8]

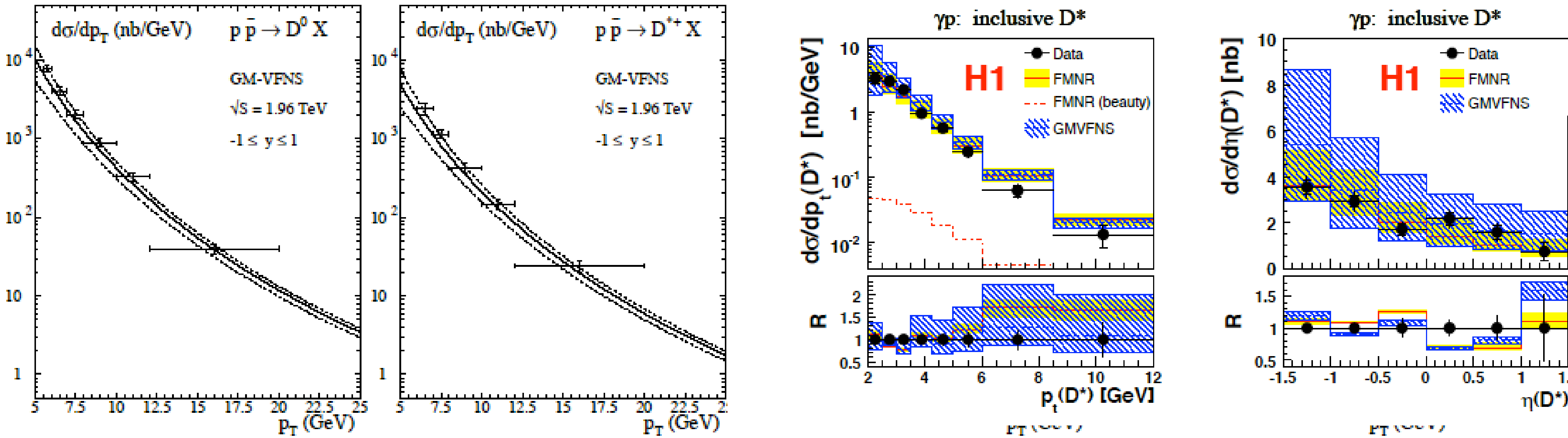
Development of a calculational framework which can interpolate between a fully massive calculation at small pT and a resummed one at large pT

Impressive amount of work ongoing on a huge number of processes

COMPARISON WITH CDF II DATA FOR $p\bar{p} \rightarrow (D^0, D^{\star +}, D^+, D_s^+)X$ [1]

Kramer

- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, GM-VFNS
- Uncertainty band: independent variation of $\mu_R, \mu_F, \mu'_F = \xi m_T$, $\xi \in [1/2, 2]$

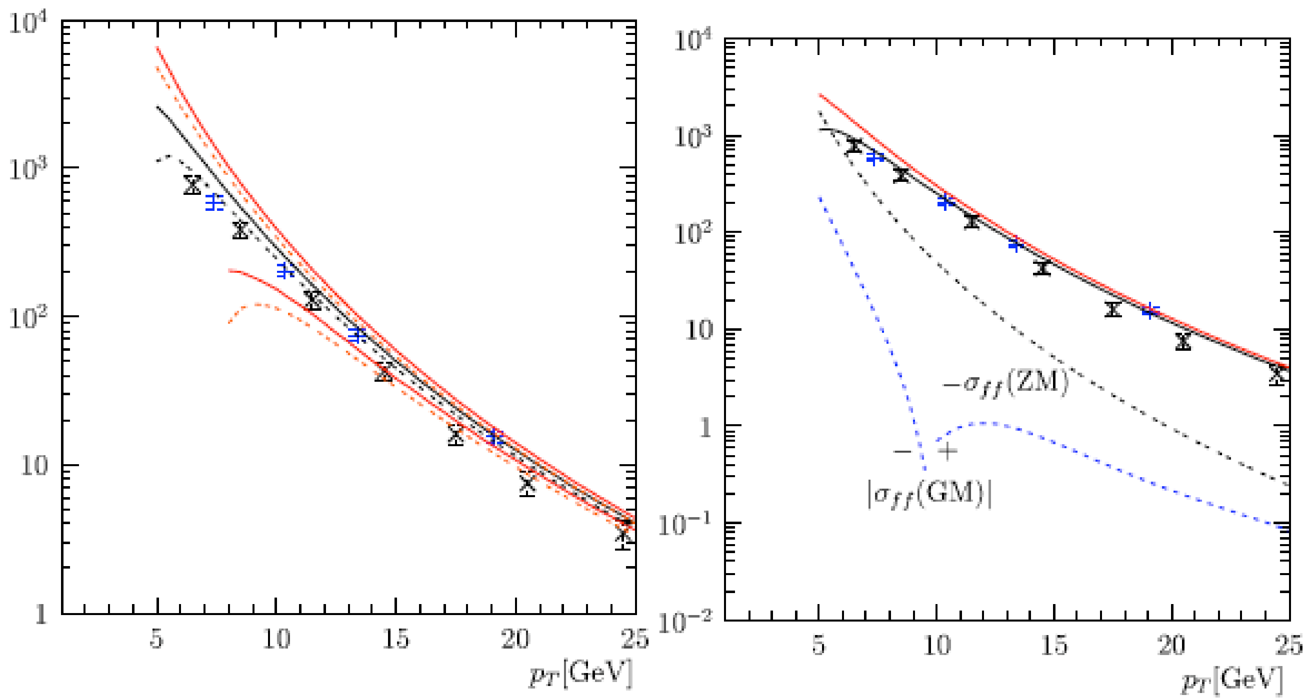


Good agreement with Tevatron data for D mesons production and with HERA data for photoproduction

COMPARISON WITH CDF II DATA FOR $p\bar{p} \to B^+X \to J/\Psi X'$ *and* $\to J/\Psi K$ [1

Kramer

- $d\sigma/dp_T$ (nb/GeV), $|y| \le 1$, GM-VFNS, four massless flavours, one massive
- Fragmentation function fitted to e^+e^- *data*
  $D_b^{B^\pm}(x) = Nx^\alpha(1-x)^\beta$ *at* $\mu = m_b = 4.5\text{GeV}$
- $\mu = \xi m_T,\ \xi_R = 1,$ *central* $: \xi_I = \xi_F = 1,$ *lower* $: \xi_I = \xi_F = 0.5,$ *upper* $: \xi_I = \xi_F = 2$



- Data described well by GM-VFNS in range of applicability: $p_T \gtrsim 10$ GeV, no agreement for small p_T
- GM-VFN (full lines) approaches ZM-VFN (dashed lines) at large p_T

Despite "GM" (general mass), problems at low pT. Reminder of complexity of issue. Possibly related to threshold issues discussed later on

An alternative approach: beyond the collinear limit

Saleev

The QMRK approach

$\mu \approx M_T = \sqrt{M^2 + |\mathbf{p}_T|^2}$

In the conventional Parton Model (PM): Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation, $\ln(\mu/\Lambda_{QCD})$.

$S > \mu^2 \gg \Lambda^2_{\rm QCD}$, and $q_T = 0$.

In the high-energy Regge limit the summation of the large logarithms $\ln(\sqrt{S}/\mu)$ in the evolution equation can be more important: Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation and $q_T \neq 0$ for *reggeized* t-channel gluons.

$x = \mu/\sqrt{S} \ll 1$

As the theoretical framework of high-energy factorization scheme we consider the quasi-multi-Regge kinematics (QMRK) approach [Lipatov, Kuraev, Fadin].

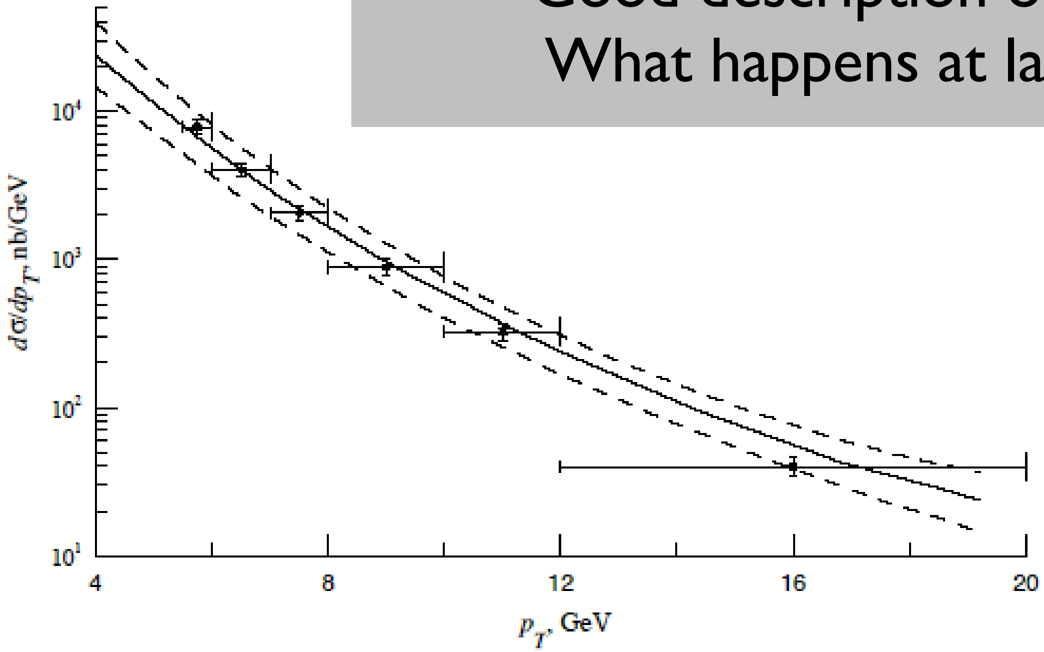
QMRK is based on effective quantum field theory implemented with the non-abelian gauge-invariant action, as was suggested a few years ago [Lipatov, 1995].

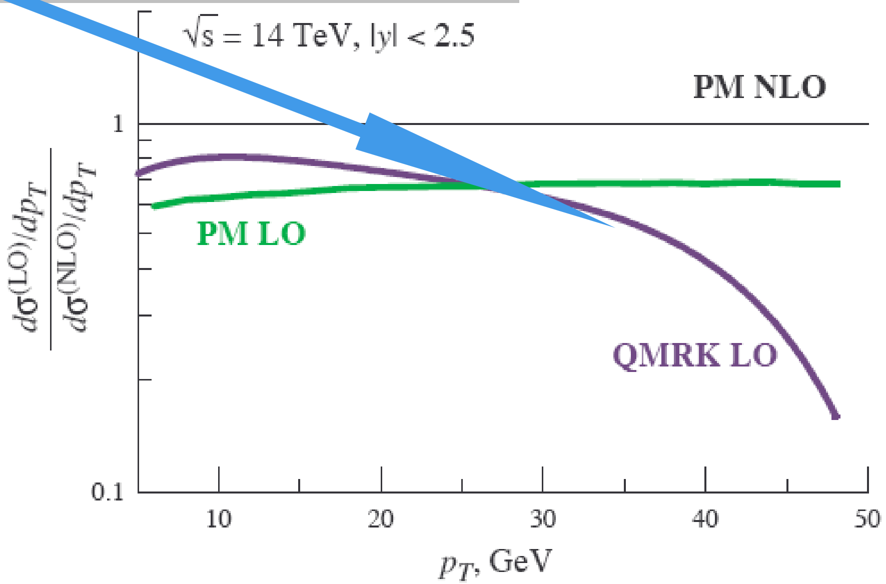
In the QMRK approach, $q^2 = q_T^2 = -|\mathbf{q}_T|^2 \neq 0$.

The unintegrated gluon distribution function $\Phi(x, |\mathbf{q}_T|^2, \mu^2)$ is used.

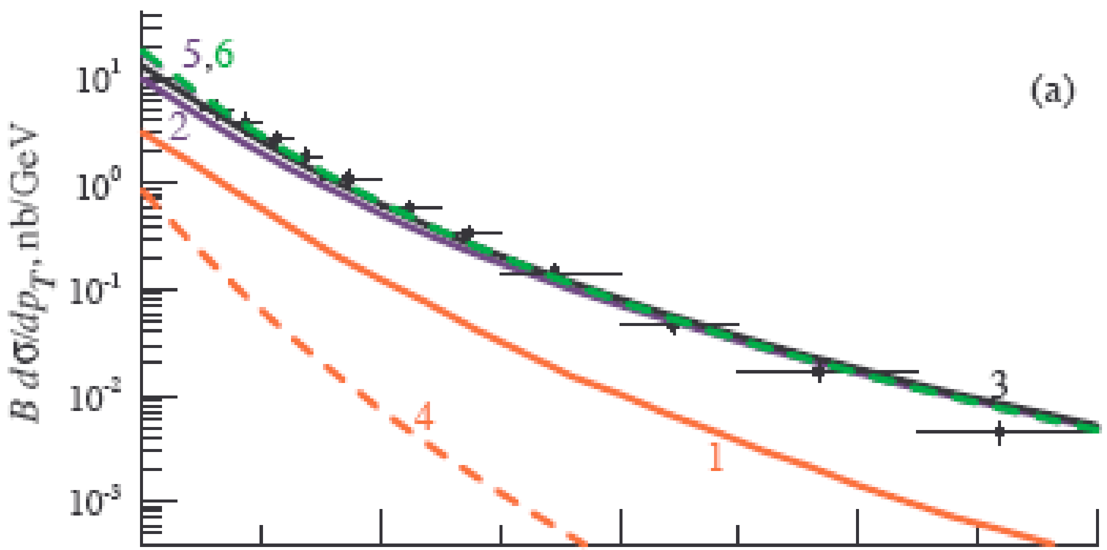
Saleev

Good description of D* @ Tevatron.
What happens at large pT @ LHC?





Allows for good fit of J/psi production @ Tevatron



Heavy quarks go next-to-next

Summary

Mitov

- b-spectrum
- QCD amplitudes
- massless case
- massive case
- massive case (2)
- massive case (3)
- massive case (4)
- checks
- relation to PFF
- applications

- I argued for the need of improved precision in the heavy flavor sector.
- Mostly b-production at NNLO and in the high energy limit. Phenomenologically relevant at the LHC.
- Related work on b-fragmentation at NNLO
- Structure of massive QCD amplitudes:
  - at the high energy limit,
  - beyond one loop.
- New results on the quark formfactor which I didn't discuss.
- Message I tried to convey:
  - We have tools to study massive problems of varying "inclusiveness" with purely massless means!
  - Work underway ...

Use factorisation to isolate universal behaviour of mass terms

Klein

Two–Loop Massive Operator Matrix Elements and Heavy Flavor Production in Deep–Inelastic Scattering

Sebastian Klein, DESY

in collaboration with I. Bierenbaum and J. Blümlein

1. Introduction
2. The Method
3. The Calculation
4. Results
5. Comparison to Previous Calculation
6. Conclusion

Refs.:
- J. Blümlein, A. De Freitas, W. L. van Neerven and S. K., Nucl. Phys. **B 755** (2006) 272.
- I. Bierenbaum, J. Blümlein and S. K., Nucl. Phys. Proc. Suppl. **160**, 85 (2006); Phys. Lett. B (2007) in print, [hep-ph/0702265].

Sebastian Klein HERA–LHC Workshop, Hamburg 13.03.2007

Issues way too complex to summarize in a few words. See talks

Ferrera

Parameter-free description of HQ fragmentation, using NNLL resummation and an **analytic coupling**

- Analytic QCD coupling: same discontinuity along the cut but analytic elsewhere in the complex plane [Shirkov & Solovtsov ('97)]:

$$\bar{\alpha}_S^{lo}(Q^2) = \frac{1}{\beta_0}\left[\frac{1}{\ln Q^2/\Lambda_{QCD}^2} - \frac{\Lambda_{QCD}^2}{Q^2-\Lambda_{QCD}^2}\right] , \quad LO \quad space-like$$

- b-quark fragmentation is a time-like process: the analytic coupling in the time-like region reads

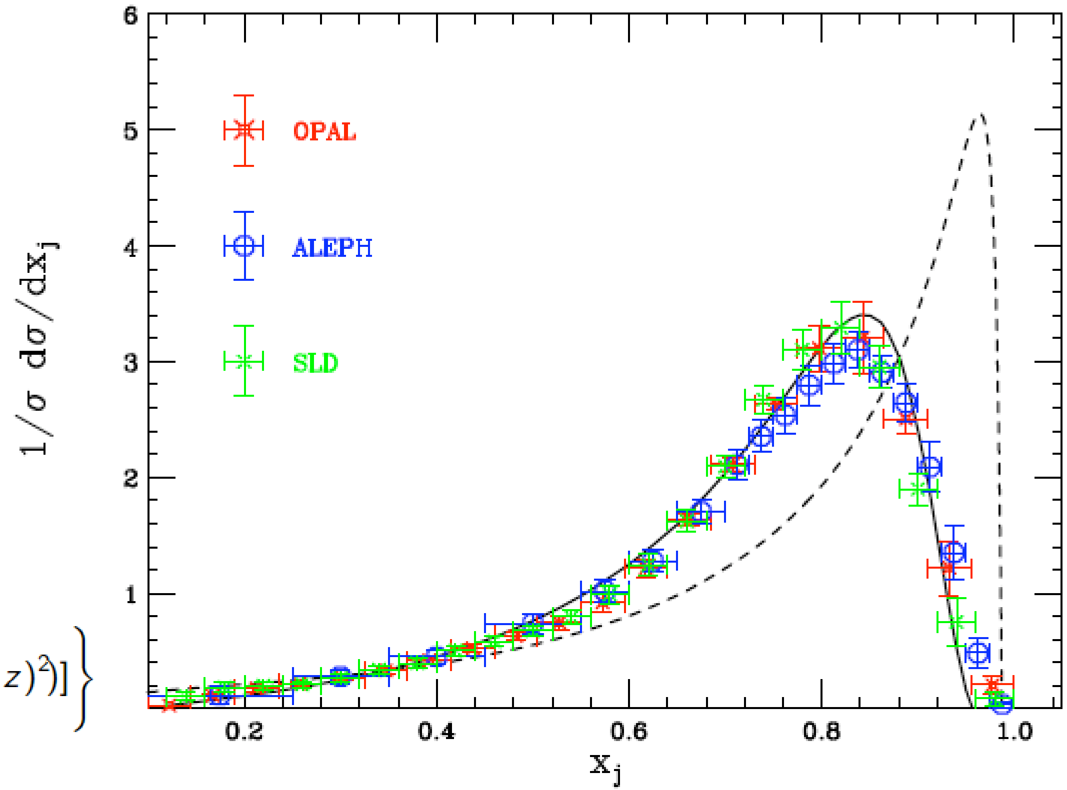
$$\tilde{\alpha}_S(k_\perp^2) = \frac{i}{2\pi}\int_0^{k_\perp^2} ds\, Disc_s \frac{\bar{\alpha}_S(-s)}{s}.$$

- At leading order we have:

$$\tilde{\alpha}_S^{lo}(k_\perp^2) = \frac{1}{\beta_0}\left(\frac{1}{2} - \frac{1}{\pi}\arctan\frac{\ln\frac{k_\perp^2}{\Lambda_{QCD}^2}}{\pi}\right) ,$$

Goes into resummation formula

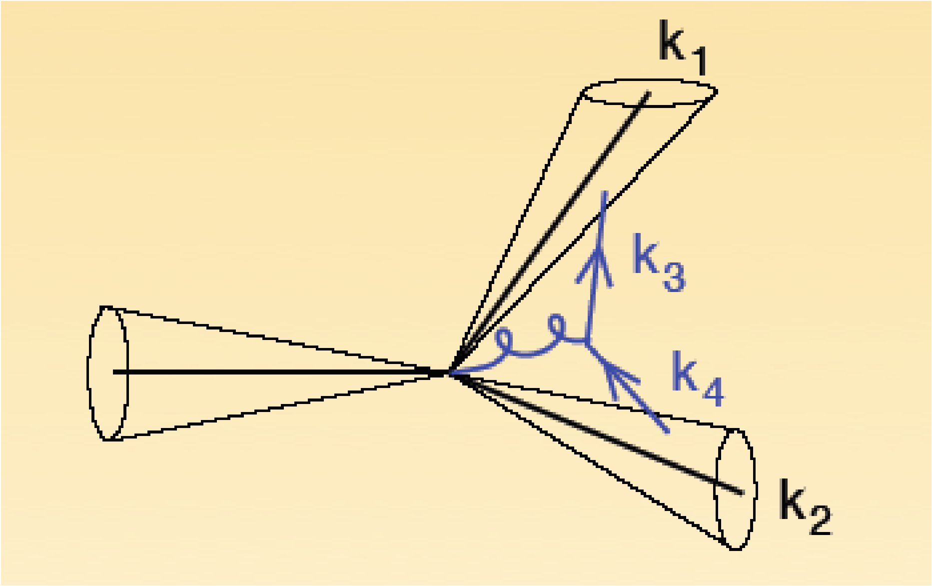
$$\ln D_N^{ini} = \int_0^1 dz \frac{z^{N-1}-1}{1-z}\left\{\int_{m_b^2(1-z)^2}^{\mu_{0F}^2}\frac{dk_\perp^2}{k_\perp^2}\tilde{A}\left[\tilde{\alpha}_S(k_\perp^2)\right] + \tilde{D}\left[\tilde{\alpha}_S(m_b^2(1-z)^2)\right]\right\}$$



Zanderighi

A better calculation of b-jets production using a new jet definition and a massless calculation

Some preliminary background:



The naive idea of "flavour of a jet" initiated by a given quark is **infrared-unsafe**: a soft gluon can change it

Typical consequence: bad convergence of perturbation theory

Solution: a new flavour jet algorithm

Infrared safe jet-flavour

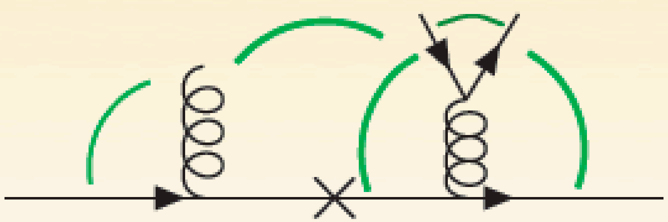
Zanderighi

To construct IR-safe flavour modify the distance measure for quarks so as to respect the divergences of QCD matrix elements

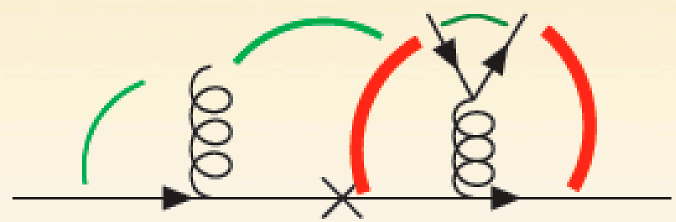
[Banfi, Salam & GZ '06]

$$d_{ij}^{(F)} = \frac{2(1-\cos\theta)}{Q^2} \times \begin{cases} \min(E_i^2, E_j^2) & \text{softer of } i,j \text{ is flavourless (gluon)} \\ \max(E_i^2, E_j^2) & \text{softer of } i,j \text{ is flavoured (quark)} \end{cases}$$

Normal k_t algorithm



Flavour k_t algorithm



small distance

large distance

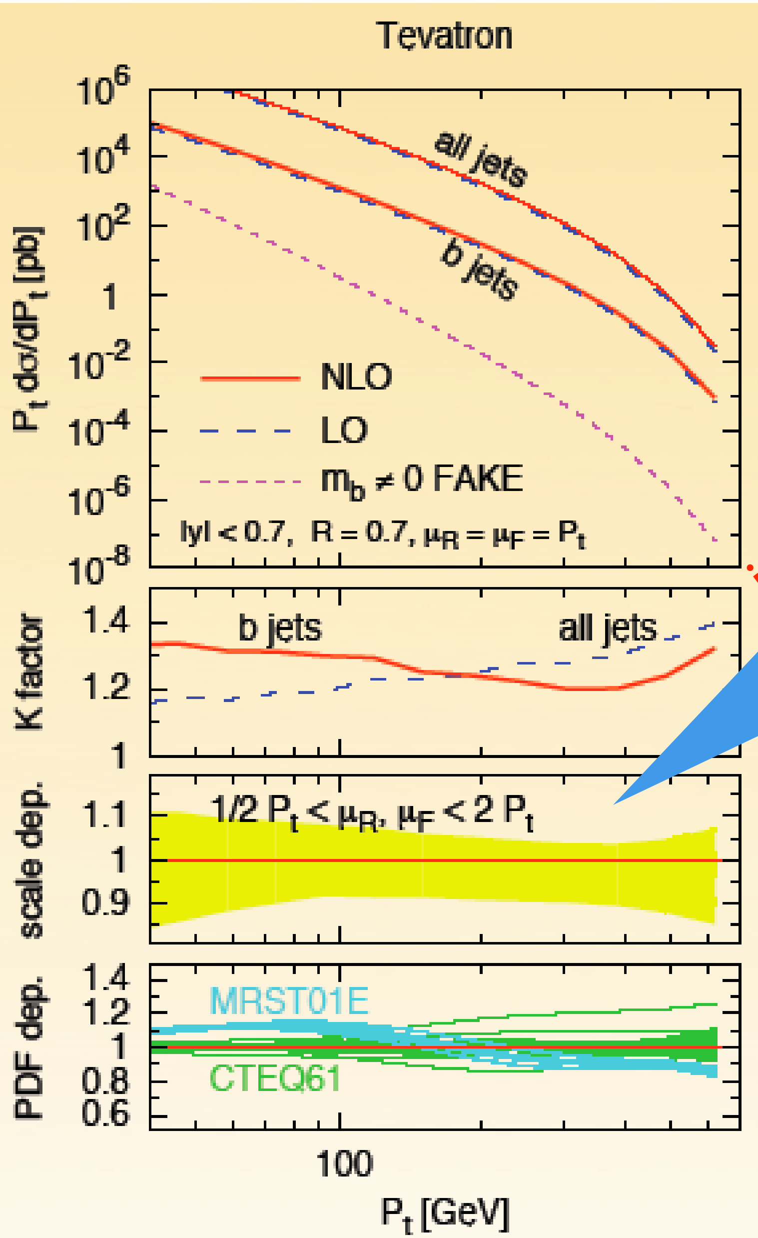
Recombination depends on angle

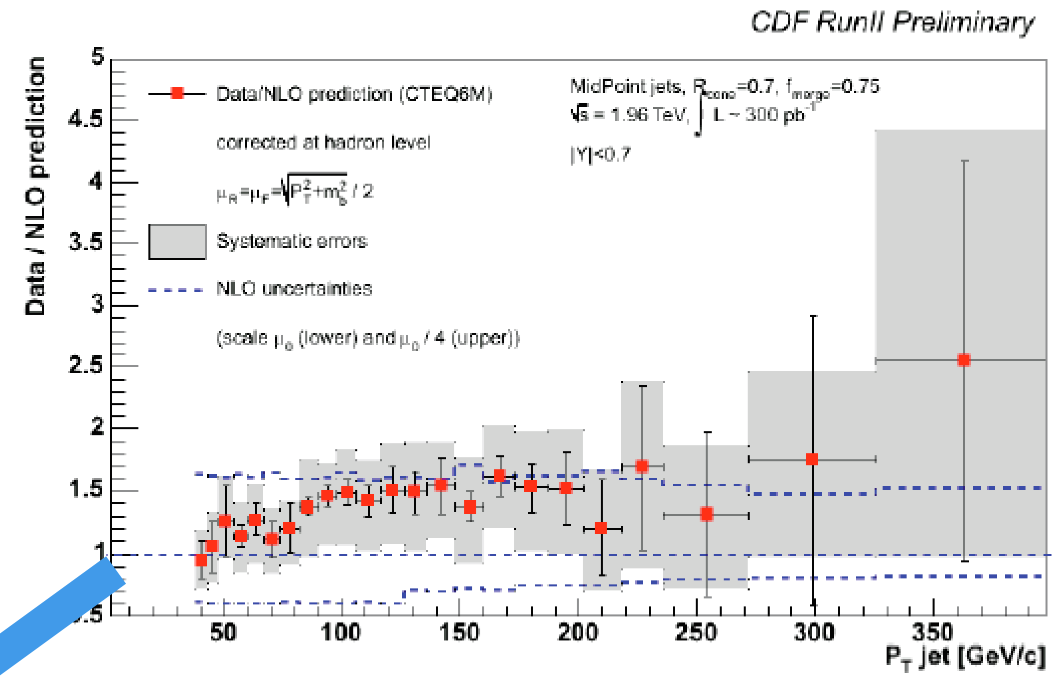
Bad recombinations strongly suppressed

To run the algorithm you need to tell a gluon from a quark. Hard in a detector. Except, perhaps, for a b quark.....

Trick: use a **massless** calculation to evaluate b-jets cross section (it's IR safe now)
Result: reduce K factor, theoretical uncertainty down from 50% to 20%

Zanderighi





improvement

Standard algorithms (IR unsafe):

- cross-sections have large logarithms $\alpha_s^2 \cdot \alpha_s^n \ln(P_t/m_b)^{2n-1}$ due to gluon splitting (GSP)
- cross-sections have large logs $\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n$ due to initial state collinear branchings (FEX)
- must keep finite m_b in PT calculation, FEX and GSP at LO

Flavour algorithms (IR-safe):

- no large logs from gluon splitting, because gluon jets do not contribute to b-jet spectra
- logarithms from initial state gluon branchings to $b\bar{b}$ can be resummed in b-PDFs
- full NLO massless QCD calculation (much simpler)

Timeline

- ☑ HERA
- ☑ LHC
- ☑ Theory
- ☐ **Heavy quarks in PDF's**

Talks by

Wu-Ki Tung

CTEQ6.5M and ACOT-chi prescription

Robert Thorne

MRST prescription

Mandy Cooper-Sarkar

Effect of inclusion of charm in fits

Talks used to bootstrap discussion.
Mainly discuss results of the latter

Issue: treatment of heavy quarks in PDF fits

Done differently by CTEQ/MRST. Does it matter?

But first: why do they not agree?

In the following: what I understood from the discussion

CTEQ and MRST agree on the way partons are evolved, and change through heavy quark thresholds.

They differ in the way they construct cross sections like F_2 and F_{2c}, F_{2b}

Why can they differ?
They wish to describe both the threshold region ($Q \sim m$) and the asymptotic region ($Q >> m$)

The first one needs a massive fixed flavour number calculation (FFN)

The second a massless (zero mass) resummed calculation (ZM)

Naive merging:

$$F_2 \quad = \quad \text{FFN} \quad + \quad \text{ZM} \quad - \text{ double counting}$$

Matching

In an ideal world the matching would be smooth

$$F_2 \;=\; \mathrm{FFN} \;+\; \mathrm{ZM} \;-\; \text{double counting}$$

At Q ~ m these two cancel,
leaving only the FFN

At large Q these two terms cancel,
leaving the resummed ZM one

However, the devil is in the details

The devil

$$F_2 \quad = \quad \text{FFN} \; + \; \text{ZM} \; - \text{double counting}$$

This terms starts one order higher than FFN.
A priori, it **does not** contain the correct mass effects

Its naive behaviour is usually unphysical: we need a prescription

(This is the same kind of issue that makes the GM-VFNS calculation in hadro-production difficult in the threshold region)

How to include such mass effects, which are **not known** from an explicit calculation, is precisely the source of the ambiguity between different approaches

The different choices

CTEQ focuses on F2.
For the heavy quark component, it chooses the simplest prescription compatible with a physical threshold behaviour and the order it is working at (NLO).

MRST tries to include higher (NNLO) orders.
This can give a better description of the charm/bottom structure functions.
Not being complete, the addition of higher order terms amounts to a prescription (and a further prescription à la CTEQ is also present)

Can they agree on a single choice?

Does it matter?

Can they agree on a single choice?

Don’t even think about it

Does it matter?

Probably not yet

The numerically effect is small, the charm contribution to F2 is limited and subject to large experimental uncertainties

Mandy Cooper-Sarkar has shown that including the charm in the fit does not change the partons significantly.
Hence, an ambiguity on the charm itself will have virtually no effect.

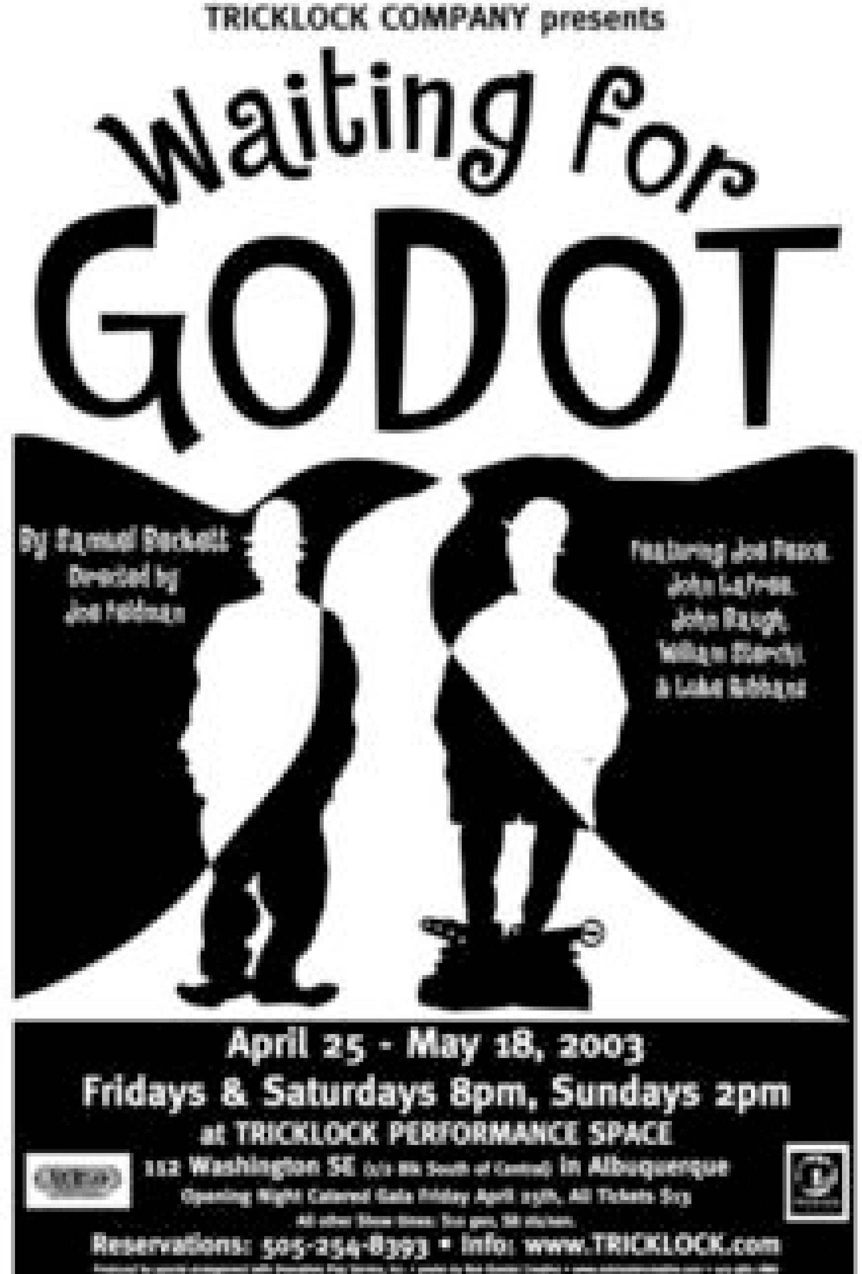
[Though, of course **NOT** treating the charm threshold at all can have quite some sizeable effects, see CTEQ6.1 → 6.5 change]

For the time being, we can live with this situation.

Conclusions

- ☑ Plenty of new HERA data, and of preparations for LHC analyses
- ☑ Theory also moving forward. Work on treatment of heavy quark mass effects, first glimpses of NNLO
- ☑ Issue of different prescriptions for treating heavy quarks in PDF fits starting to be clarified. Probably nothing to worry about. Downside: heavy quark HERA data unlikely to play a significant role in the determination of the partons
- ☑ Heavy quarks at HERA have given the push for considering matched calculations: useful at the LHC. Moreover, they have allowed to test pQCD in a number of different regimes

Expectations



"The LHC will start soon, and of course we expect to discover the Higgs.... since we have already found so many fundamental scalar bosons."

Rocky Kolb

Two wonderful machines, LEP and HERA, set out to revolutionise physics. Which they did, just perhaps not in the way we expected

Let us be ready for all contingencies