The LHC: Experiments and First Physics (part III)

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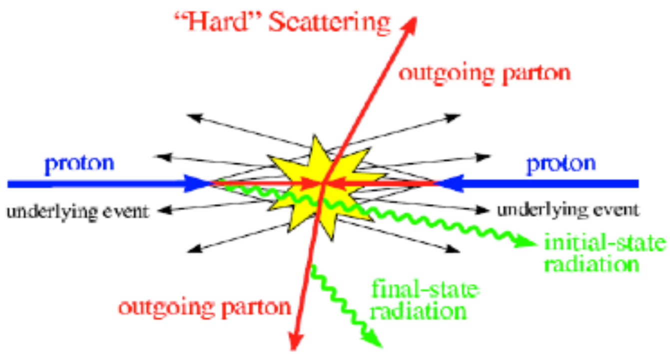
Lecture Plan

- Introduction
  - The LHC startup as seen from the experiments
- The experimental challenges at the LHC
  - The experimental solutions
- The “general purpose” experiments
  - The CMS experiment
  - The ATLAS experiment
- First performance results of ATLAS/CMS
- A tour on the other experiments and their performance
- First physics with the LHC experiments
  - QCD, B-physics
  - EWK/Searches and the outlook

Physics Results obtained so far:

- Studies of general characteristics of “minimum bias” events (our future pile-up)
- Study of the underlying event with a hard scattering
- Resonances/known particles
- Jet physics & QCD
- B-physics/charm physics
- W,Z boson production at 7 TeV
- Top quarks at 7 TeV
- Searches for new physics
- …



Underlying event

First Data: Study of the Strong Force

Motivations for QCD

Satisfactory model for strong interactions: non-abelian gauge theory SU(3)

$$U^\dagger U = UU^\dagger = 1 \quad \det(U) = 1$$

Hadron spectrum fully classified with the following assumptions

- hadrons (barions,mesons): made of spin 1/2 quarks
- each quark of a given flavour comes in N_c=3 colors
- SU(3) is an exact symmetry
- hadrons are colour neutral, i.e. colour singlet under SU(3)
- observed hadrons are colour neutral ⇒ hadrons have integer charge

$$\begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$

The QCD Lagrangian

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu} + \sum_f \bar{\psi}_i^{(f)} \left(i \not{D}_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)}$$

$$D^\mu_{ij} \equiv \partial^\mu \delta_{ij} + i g_s t^a_{ij} A^\mu_a \,, \qquad F^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu$$

⇒ covariant derivative ⇒ field strength

- only one QCD parameter g_s regulating the strength of the interaction (quark masses have EW origin)
- setting $g_s = 0$ one obtains the free Lagrangian (free propagation of quarks and gluons without interaction)
- terms proportional to g_s in the field strength cause self-interaction between gluons (makes the difference w.r.t. QED)
- color matrices t^a_{ij} are the generators of SU(3)
- QCD flavour blind (differences only due to EW)

LHC early physics

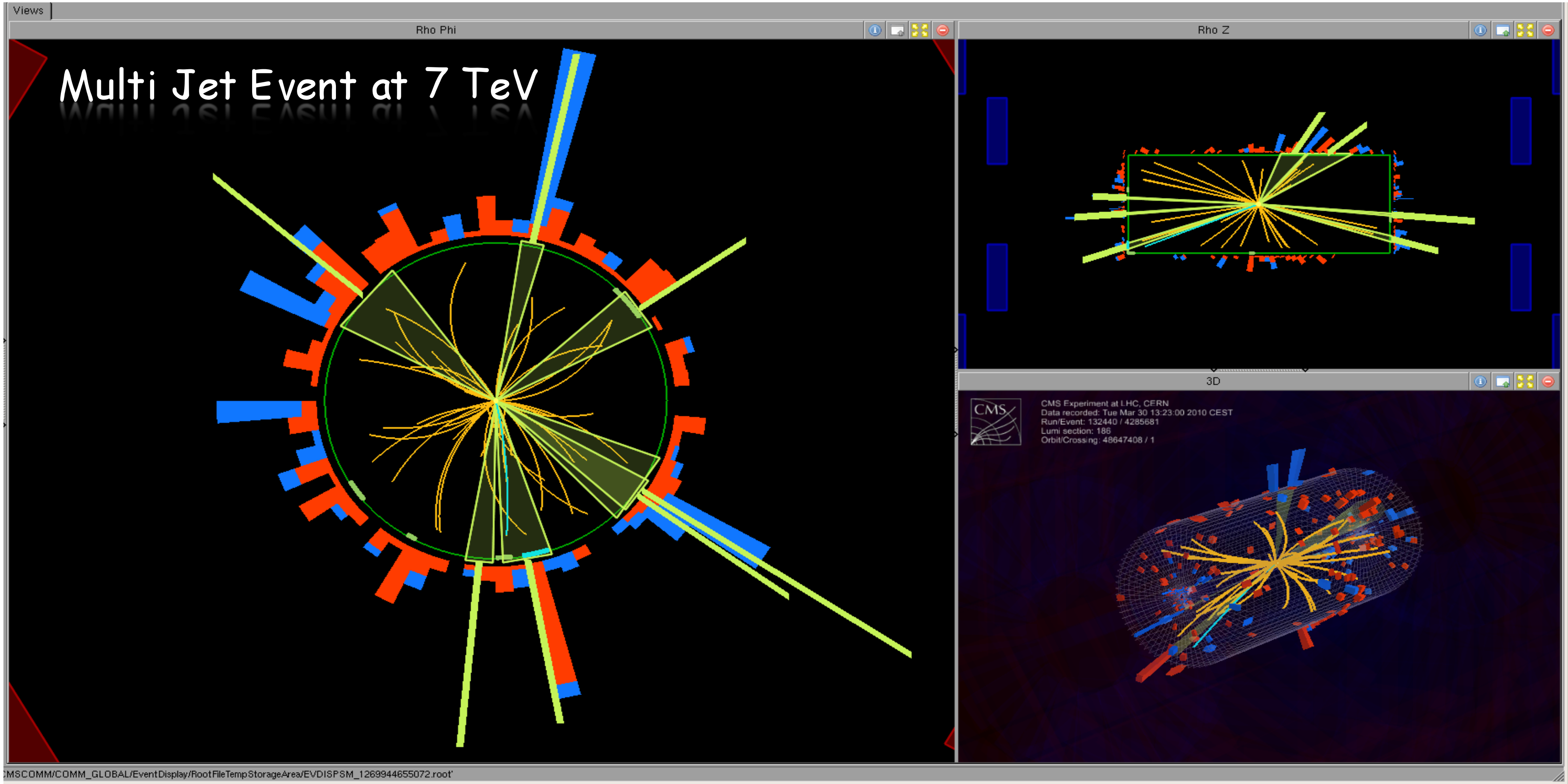
LHC

Highest energy & luminosity: operating regime such that even early data have a potential for many discoveries

One of today's most addressed question:
What one can do with early LHC data?

The answer to this question very much depends on beam control, detector understanding/performance and control over QCD

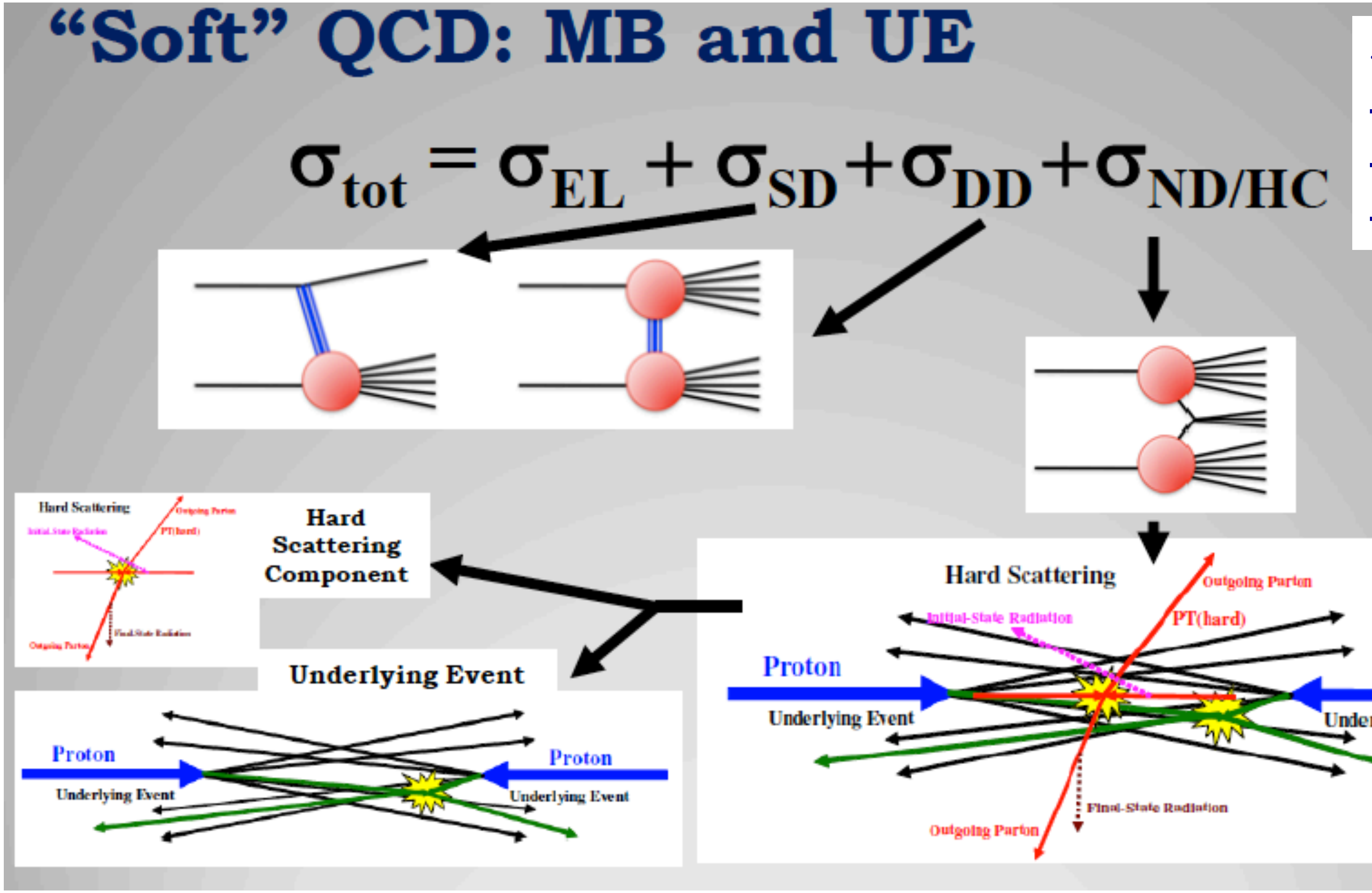
First Collisions at 7 TeV



What are the characteristics of events at 7 TeV

Number of particles? Correlations between particles? Jets? Heavy flavors?

Event Types



- -Elastic
- -Single diffraction
- -Double diffraction
- -Non-diffraction

We have models in terms of Monte Carlo programs to compare to data

- -PYTHIA
- -PHOJET
- -HERWIG
- -MadGraph
- -ALPGEN
- - …

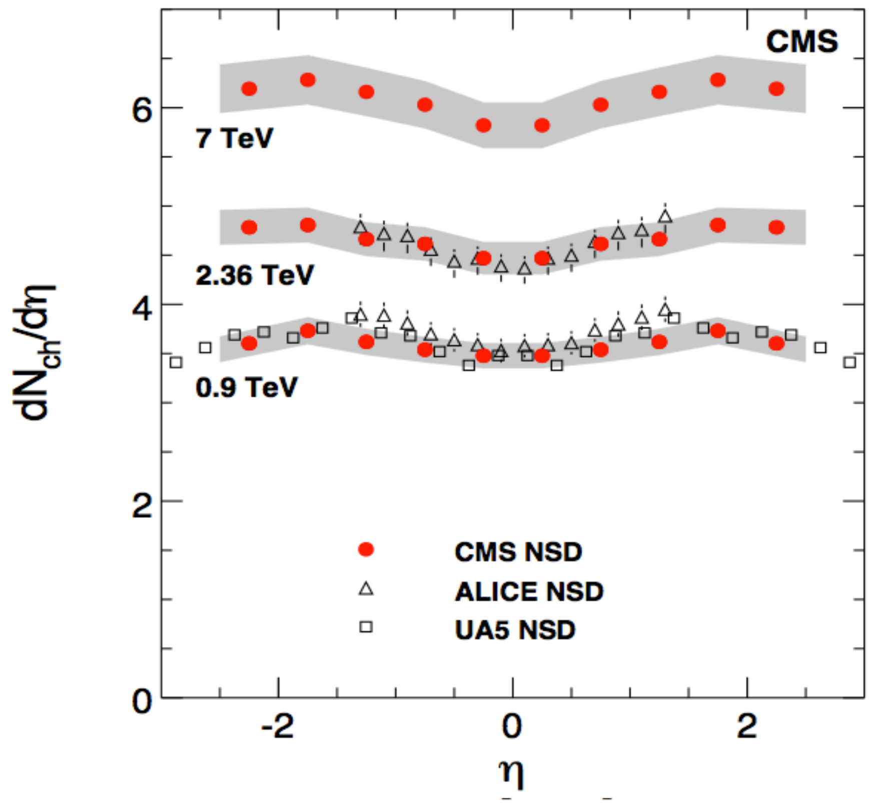
…Not always easy to classify individual events

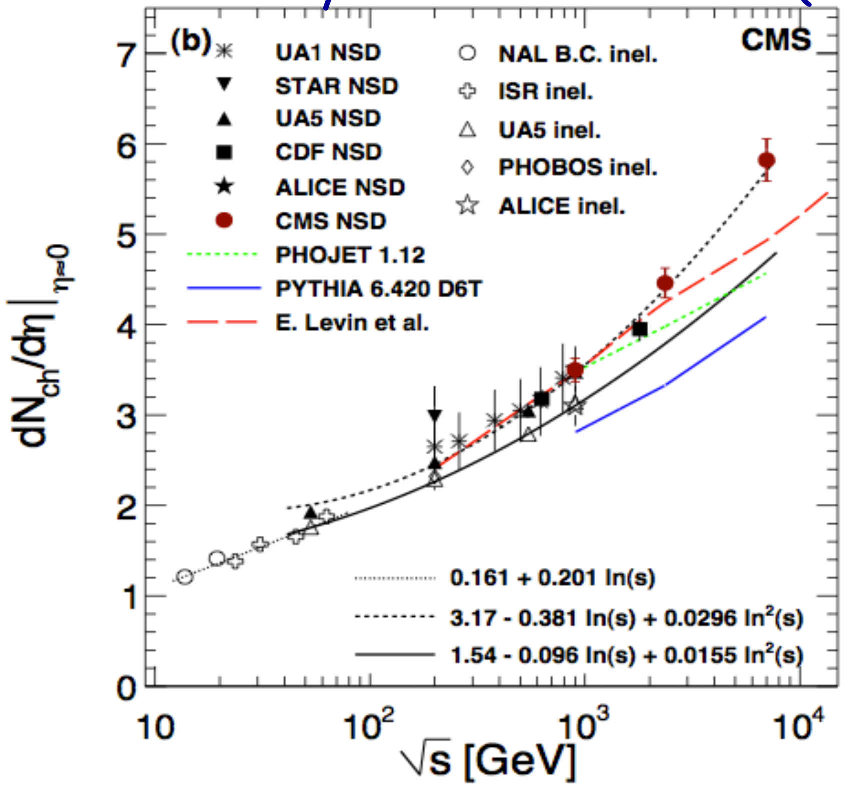
Charged Particles

pseudo-rapidity density of charged hadrons at √s = 7 TeV

Minimum bias events   Non-Single Diffractive event selection

Phys. Rev. Lett. : 105 (2010)



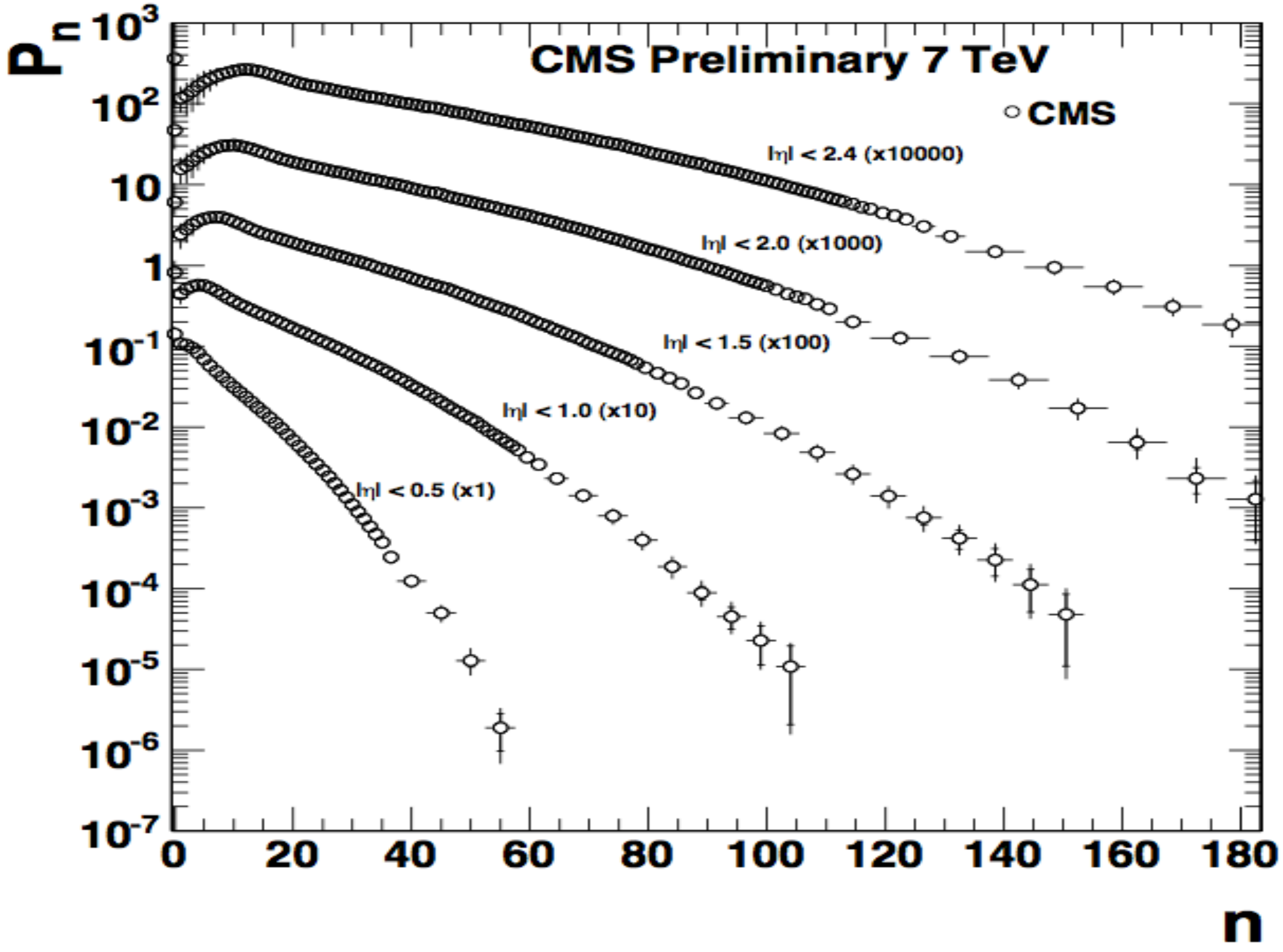


Rise of dN/dη in data stronger than currently used models

Multiplicity Distributions

Charged particle multiplicity of the events

- Minimum Bias event selection
- Unfolded charged particle multiplicity distributions (down to p_T = 0 GeV/c)
- <pT> versus multiplicity

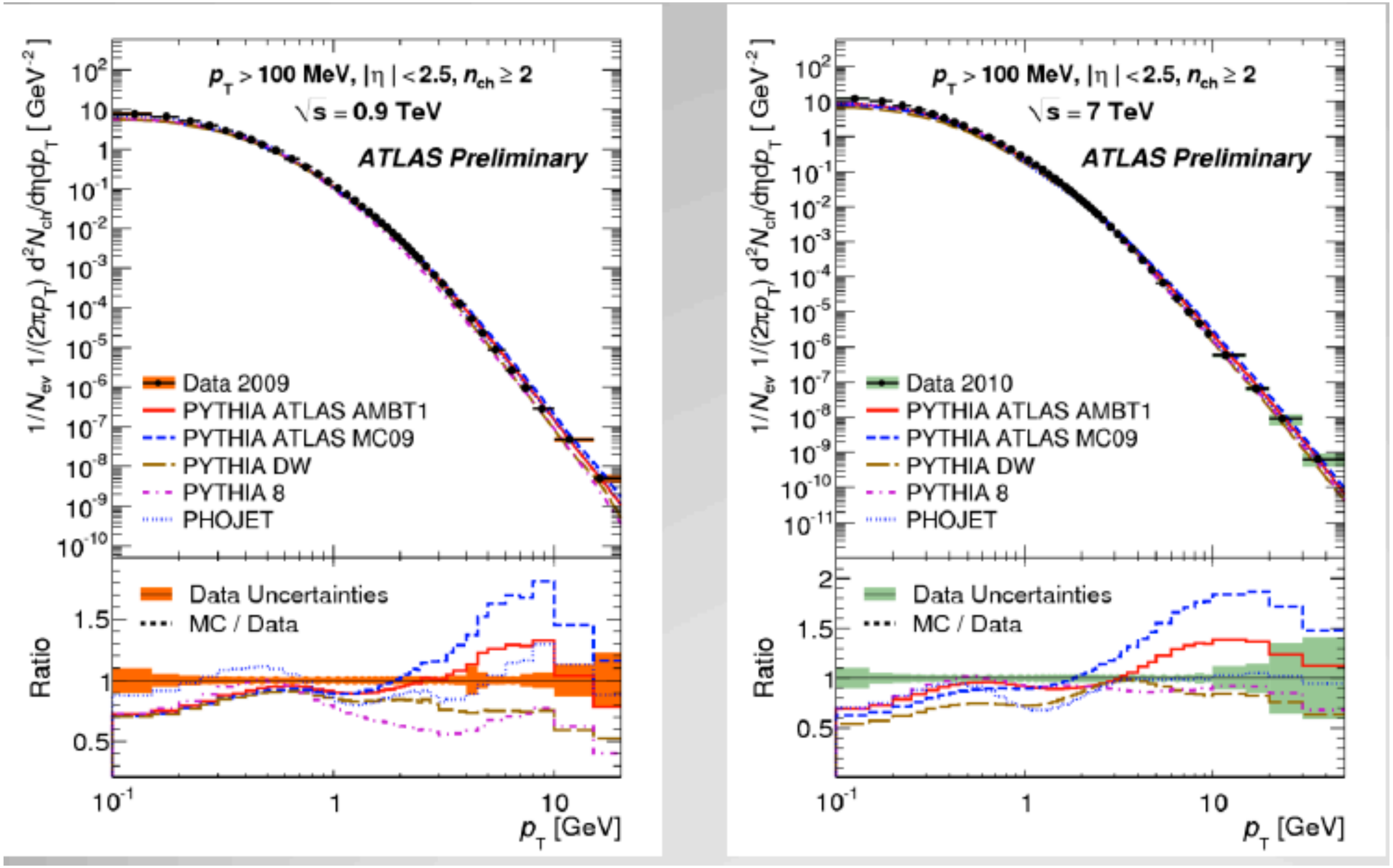


Comparison of the Experiments

- ATLAS selectes minimum bias events without separating diffractive components
  - Least Model dependend but hard to compare with other data as the measurement depends on the choosen phase space
  - Favoured by MC builders
- ALICE & CMS exclude single diffraction, which has a model dependence (in practice it is not large)
  - Favoured by model phenomenologists
- Future: we will release the measurements with both methods

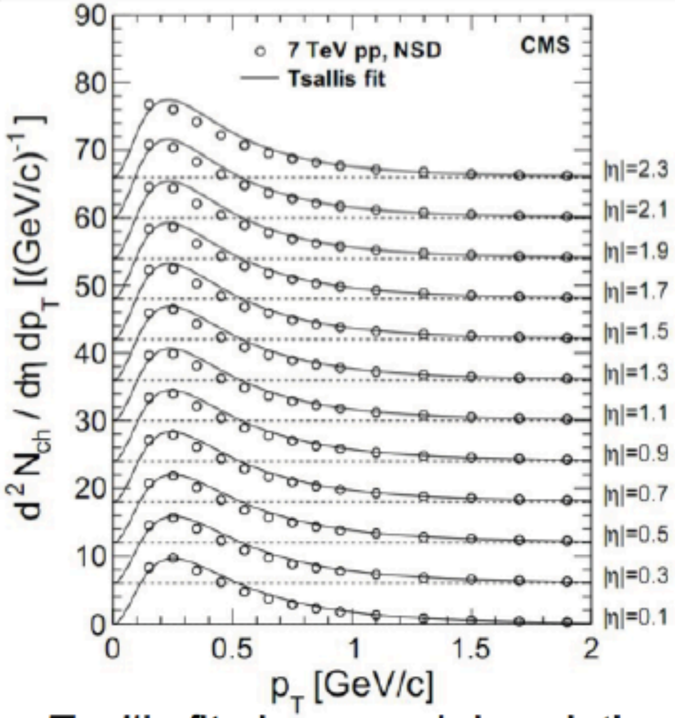
Charged Particles

P_T spectra & comparison with models



Momentum spectra

MinBias Trigger



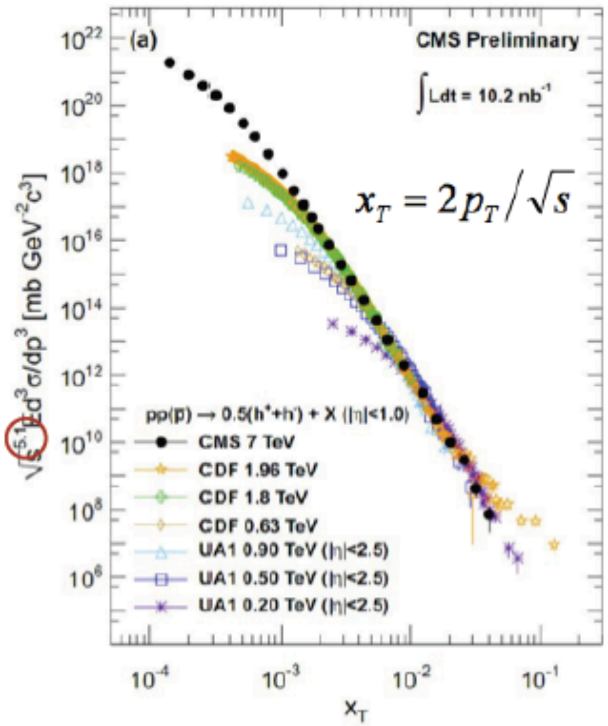
Tsallis fit gives good description

$$E\frac{d^3N_{\rm ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{\rm ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{\rm ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$

V. Khachatryan et al., JHEP 02 (2010) 041
V. Khachatryan et al., Phys. Rev. Lett. 105 (2010) 022002

Jet Trigger

QCD-10-008



Measured tracks up to 140 GeV/c

Expected power law scaling:

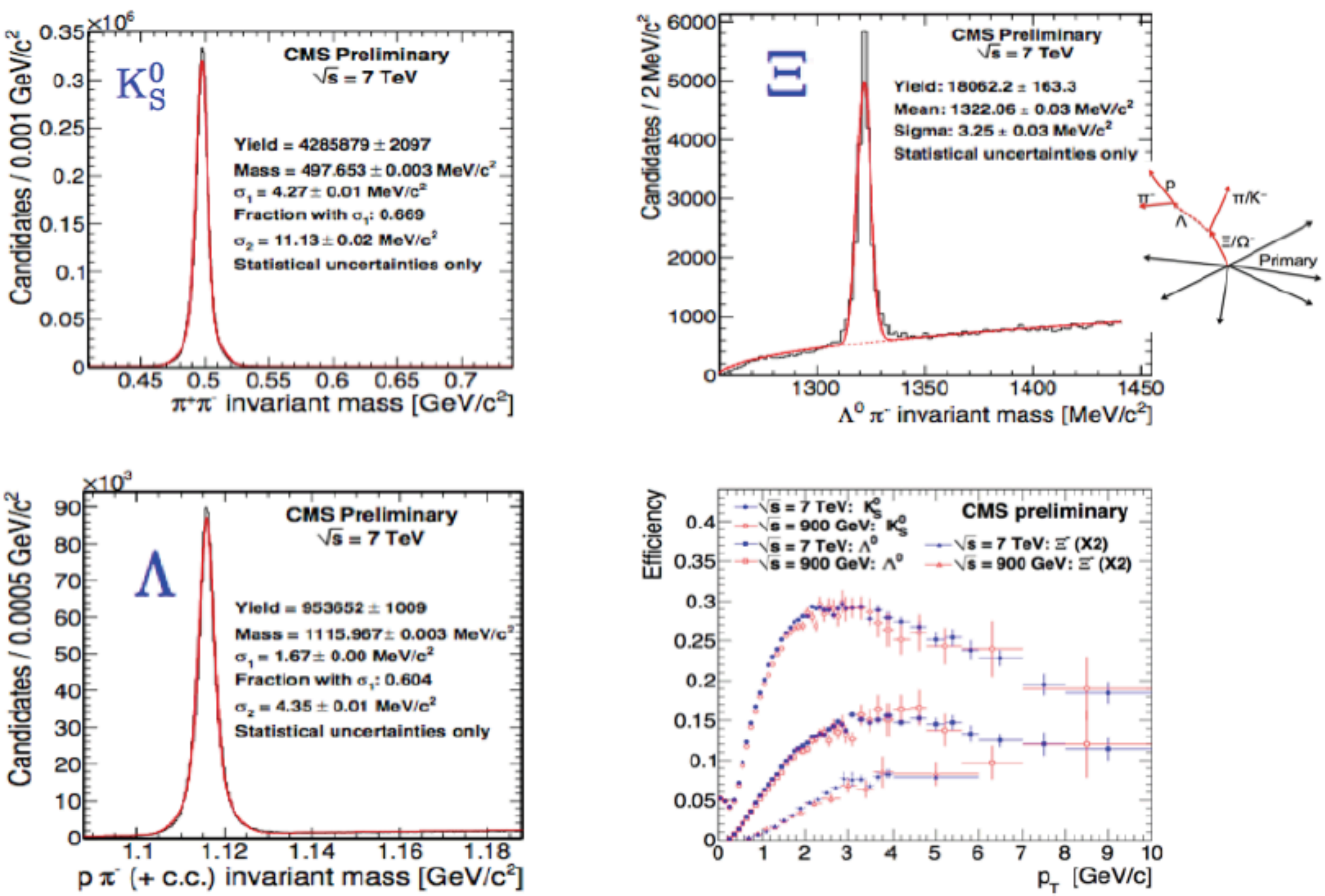
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/\sqrt{s}^{\,n(x_T,\sqrt{s})}$$

n≅5-6

CMS does not see a deviation from the power law scaling… (cfr CDF)

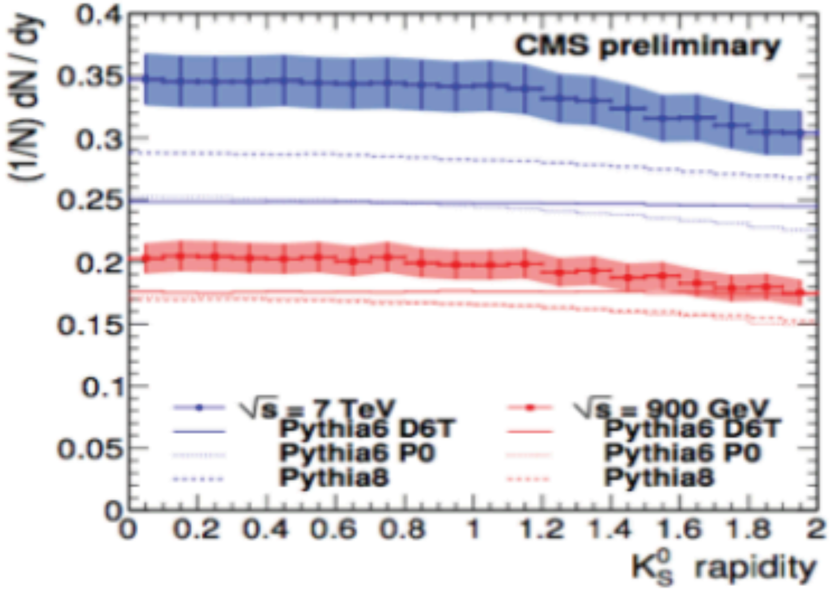
Resonances

QCD-10-007

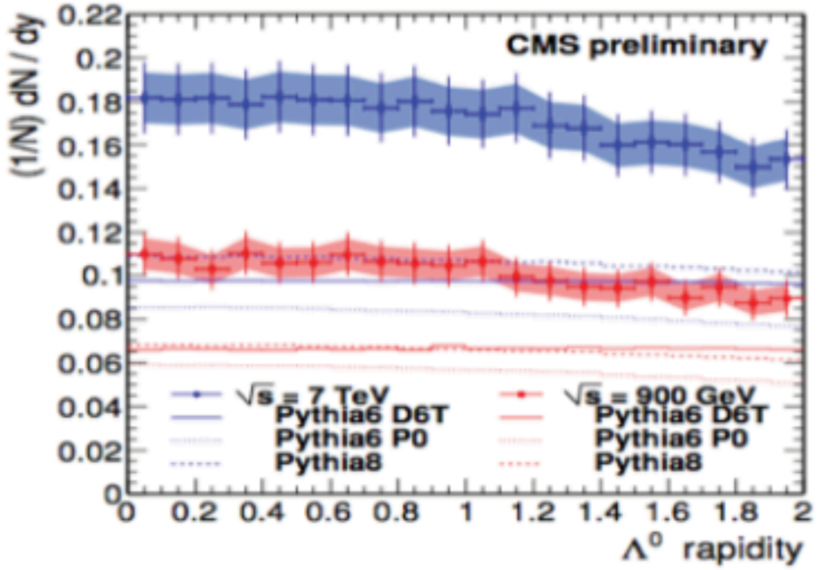


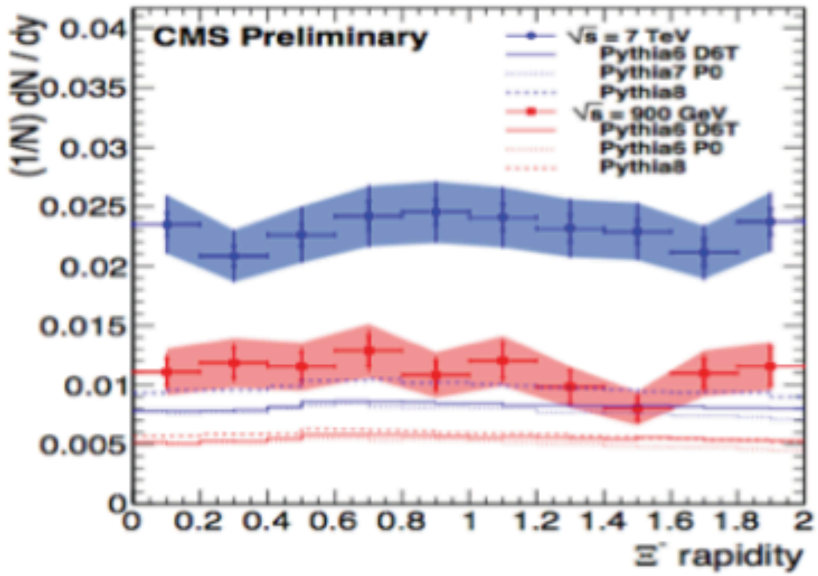
Strangeness Production

QCD-10-007

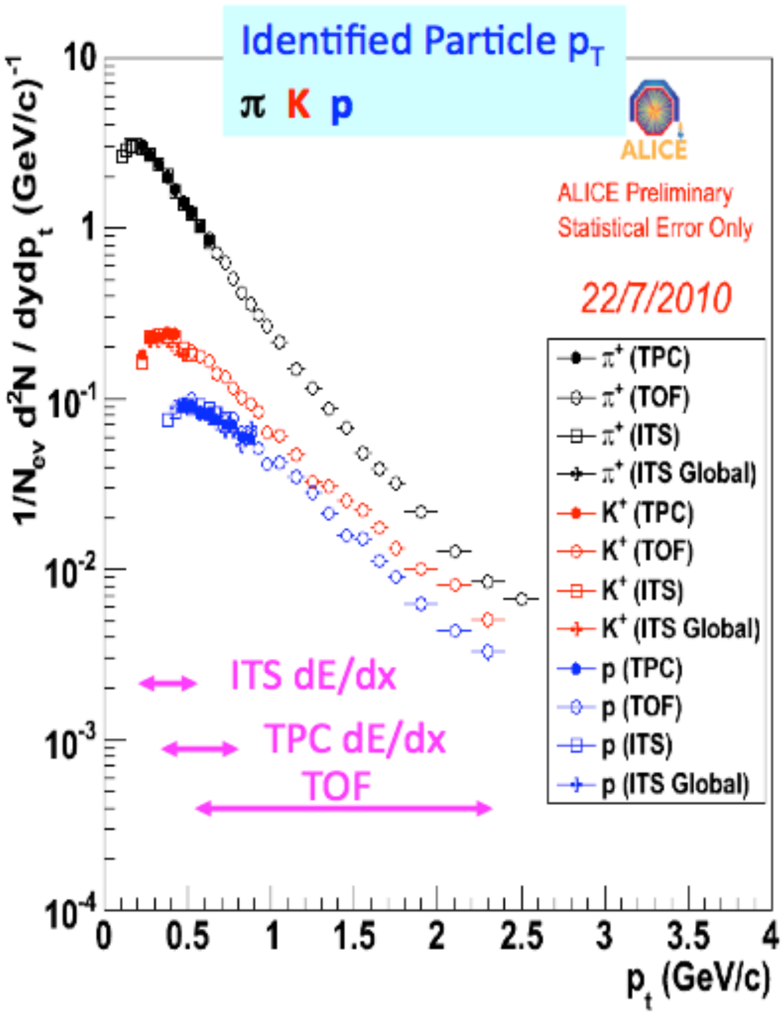


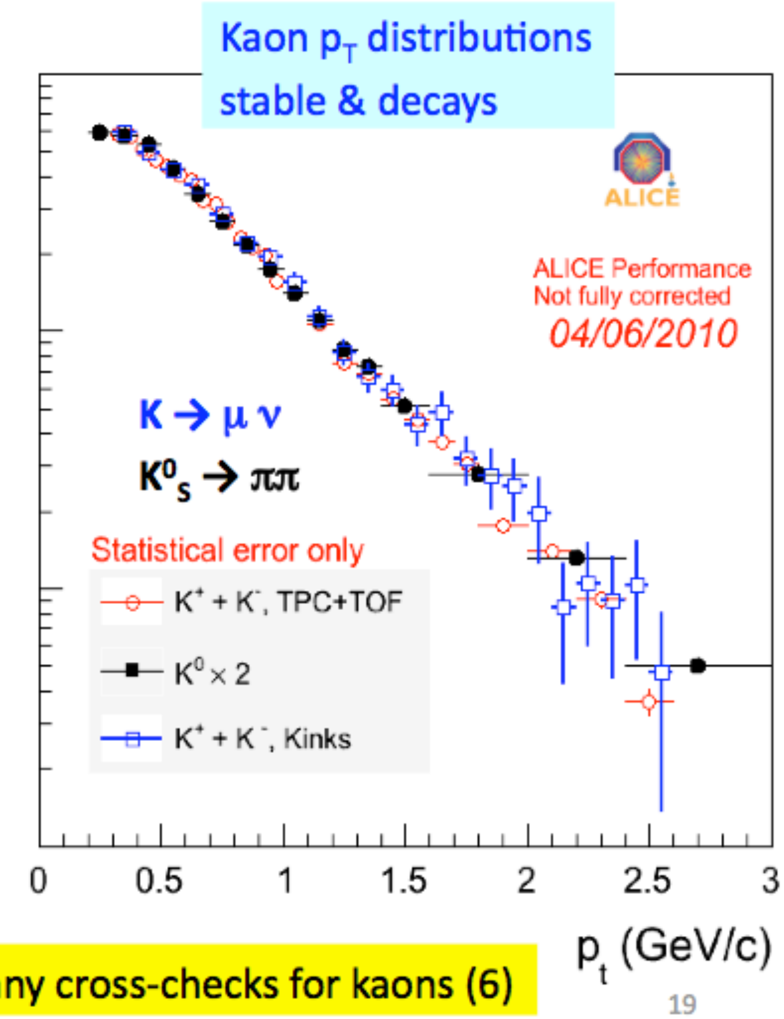
- All generators underestimate the amount of Strange Particles produces at both 0.9 and 7TeV





Particle Production



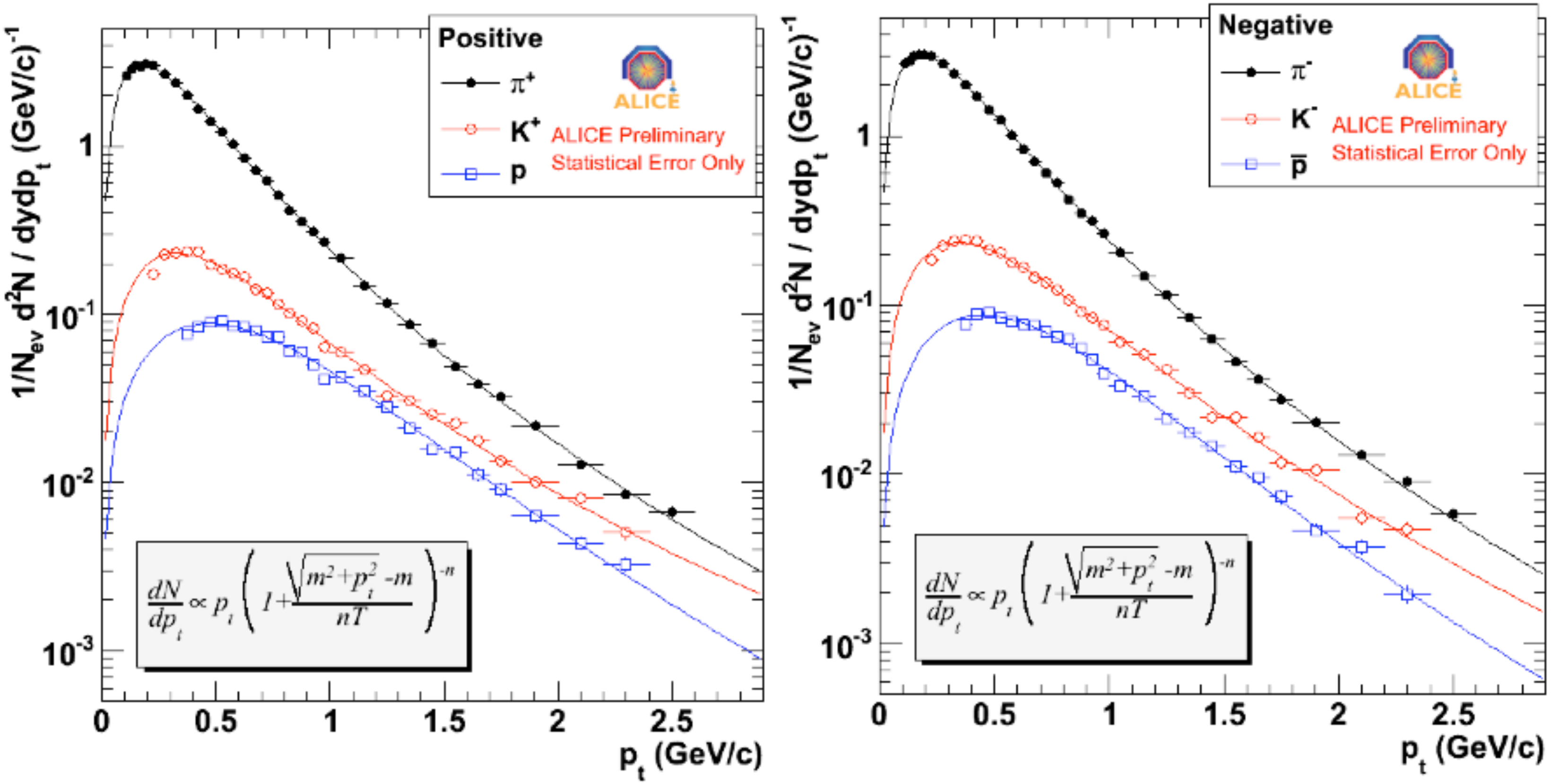


Many cross-checks for kaons (6)

Particle identification in ALICE

Particle Production

Charged π, K and p at √s = 900 GeV

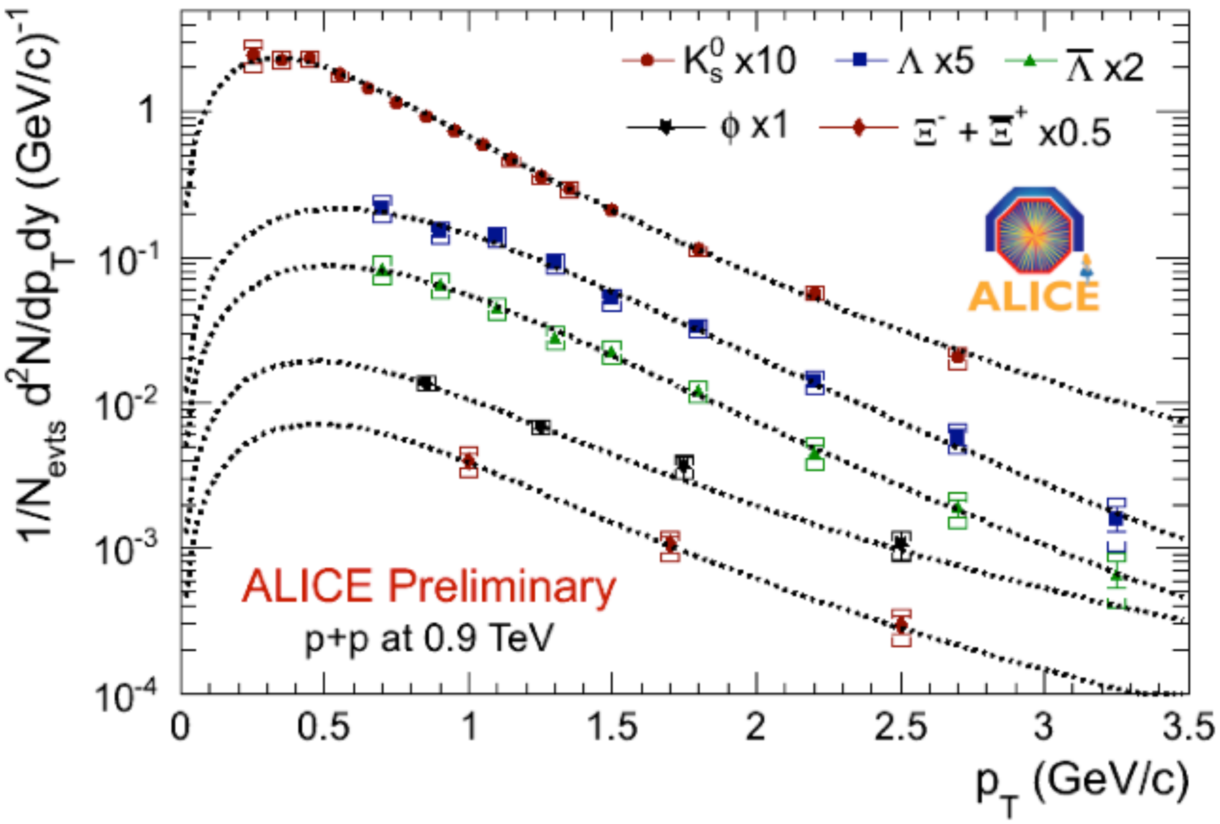


$$\frac{dN}{dp_t} \propto p_t \left(1+\frac{\sqrt{m^2+p_t^2}-m}{nT}\right)^{-n}$$

Spectra with statistical + systematic uncertainties
and Lévy function fits

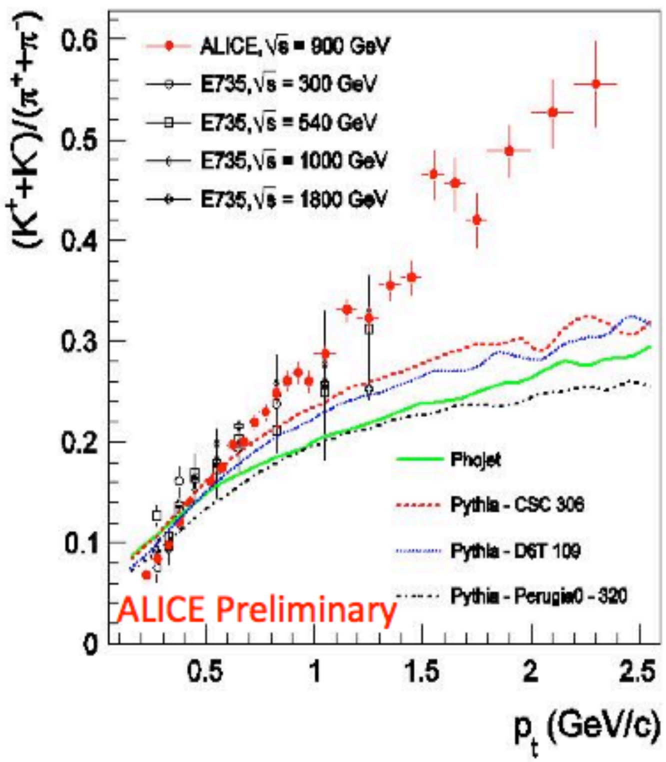
Particle Production

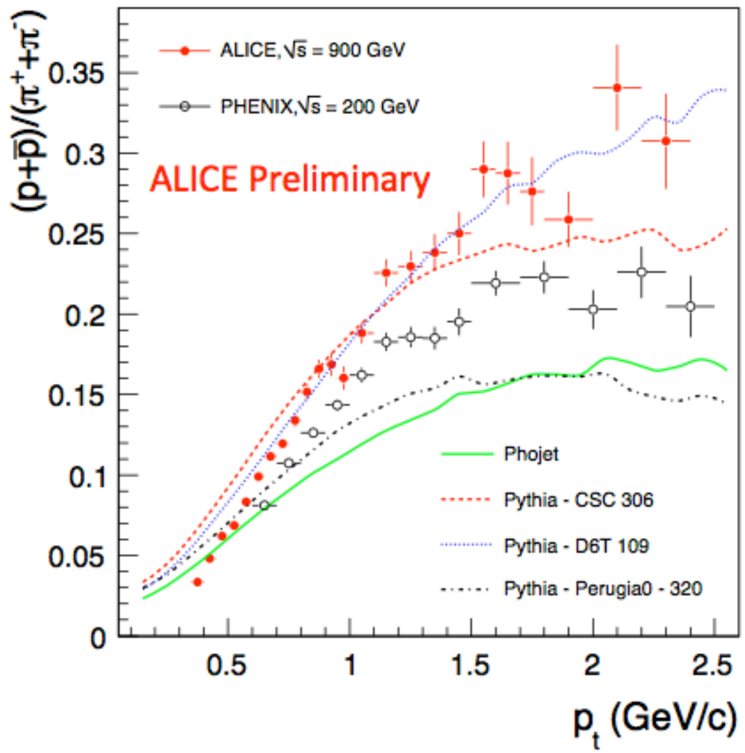
Neutral particles at √s = 900 GeV



Particle Production

Ratios vs p_T





Poor agreement with models,
but good agreement with other experiments …

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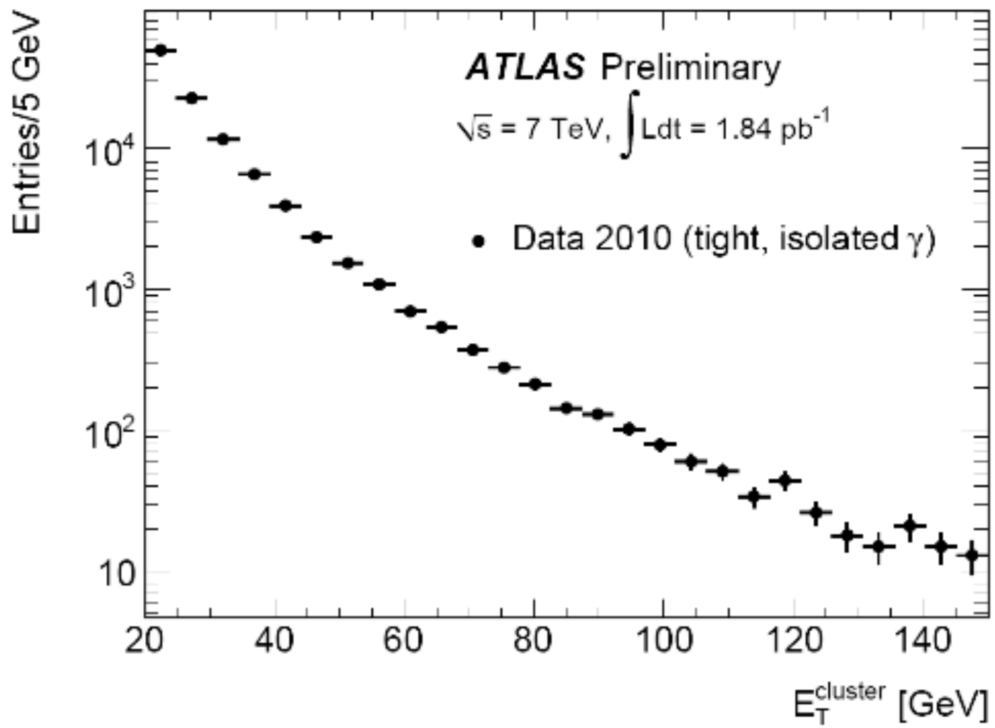
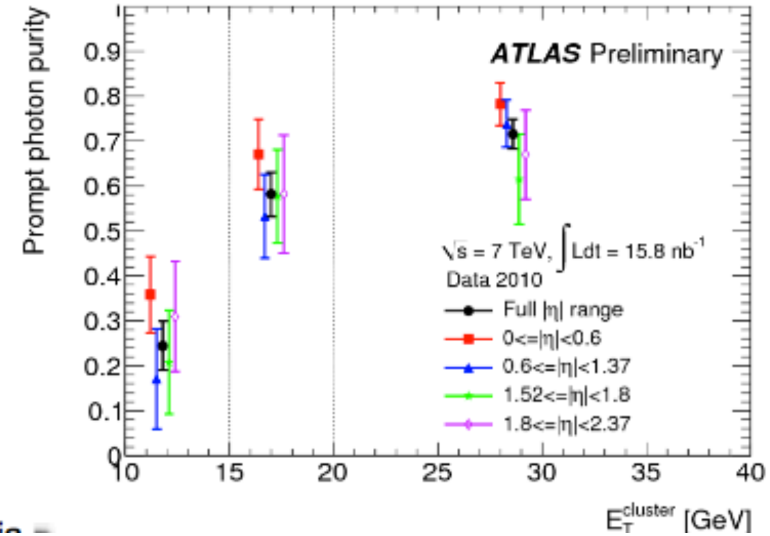
Photon spectra

- In principle, prompt photons are an excellent probe of the gluon density.
- Today, the major global fits avoid them:
  - A very large (2-3 GeV) intrinsic k_T is needed to fit the data.
- This is less of an issue here:
  - At the LHC, the same x_T is probed with p_T's 3.5 larger than the Tevatron
  - We operate at a typical p_T where a few GeV of intrinsic k_T doesn't matter as much.

The LHC kinematics helps here.



Photon purity measured almost entirely from data (small MC) corrections.



Beyond QCD, these are useful to set or check the JES via ...

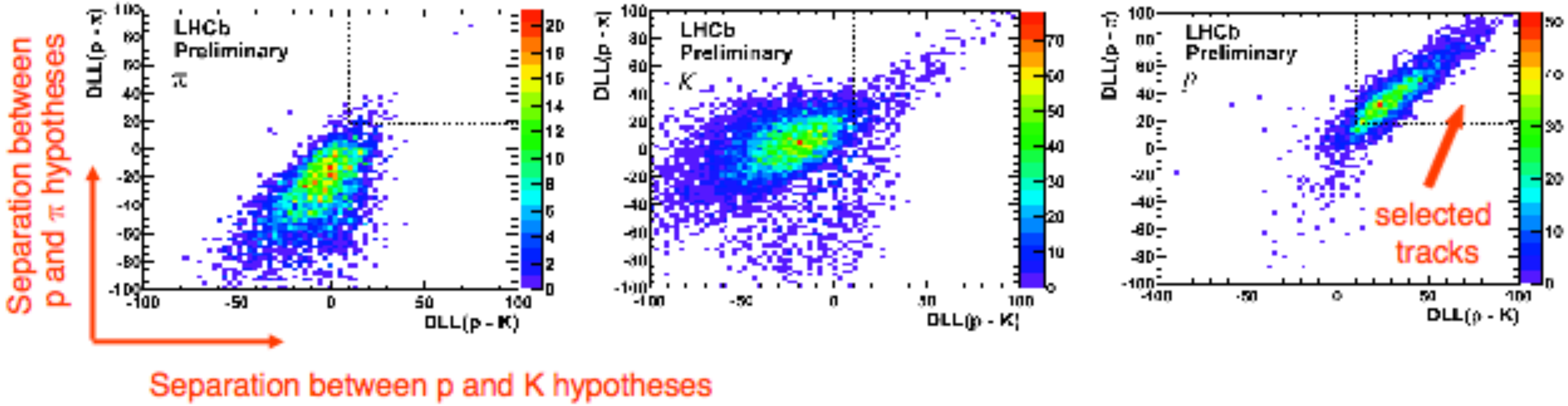
Particle/anti-particle ratios

Baryon number transport with $\bar{p}/p$

Baryon number conservation requires the destroyed beam particles in inelastic non-diffractive collisions must be balanced by creation of baryons elsewhere

Probe this baryon-number transport by measurements of antiproton/proton ratio as function of (pseudo)rapidity and p_t. Isolate pure samples with RICH likelihood ('DLL')

Performance calibrated in data using kinematically isolated samples of π, K and p



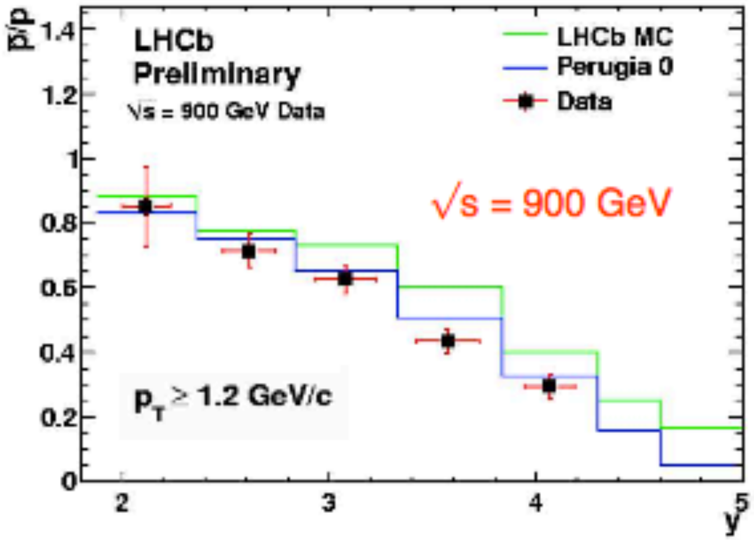
High purity (anti)proton samples of 90-95% obtained over full LHCb acceptance

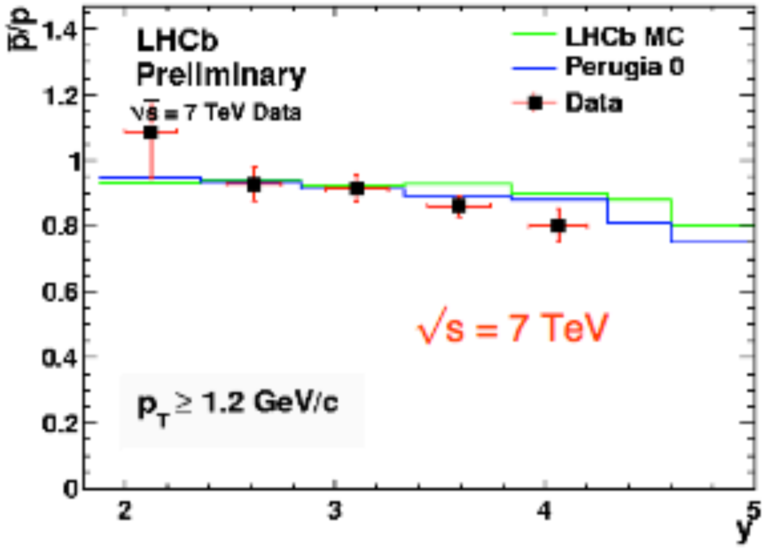
Particle/anti-particle ratios

$\bar{p}/p$ ratio vs y and p_t

Uncertainty dominated by finite statistics of calibration sample. Systematic effects eg. from difference in p-, p-nuclear cross-sections , from 'ghost' tracks etc small

Example results for $p_T > 1.2$ GeV/c (also measured at lower values):



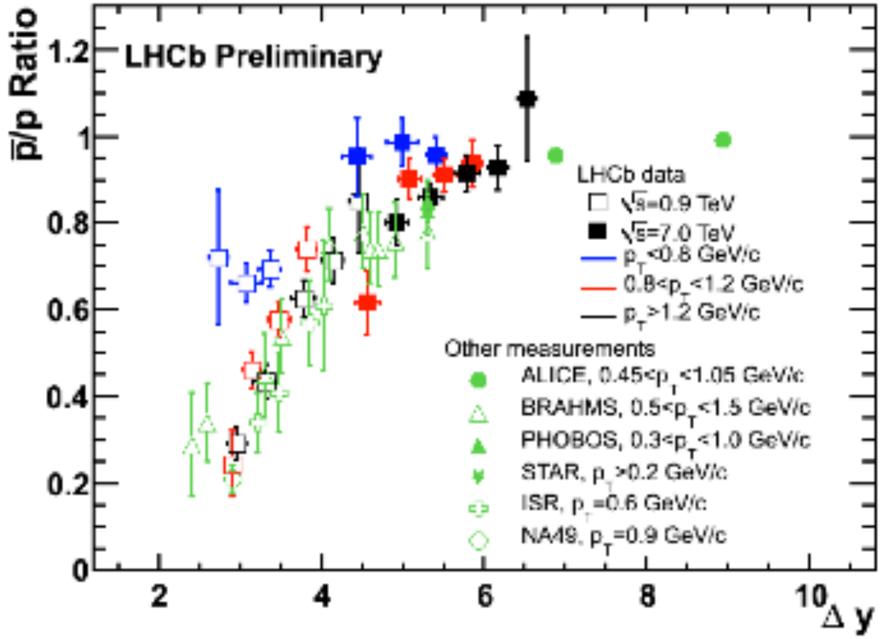


Big deviation in ratio from unity at low energy. Much less so at 7 TeV.
Reasonable agreement observed with Perugia 0 (some deviations at lower p_T)

Particle/anti-particle ratios

$\bar{p}/p$ ratio vs Δy ($\equiv y_{beam} - y_{proton}$)

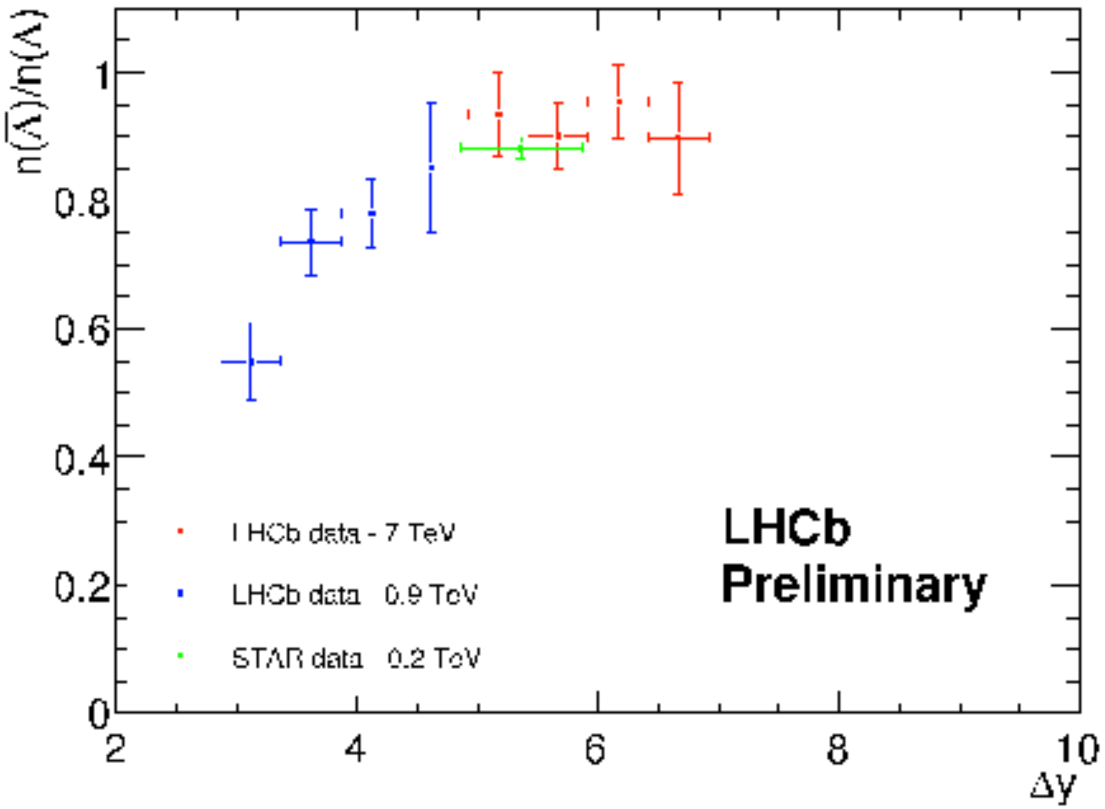
Can assemble results of previous measurements, and then compare with LHCb



Reasonable consistency exists.
For final results extend calibration dataset to achieve higher precision.

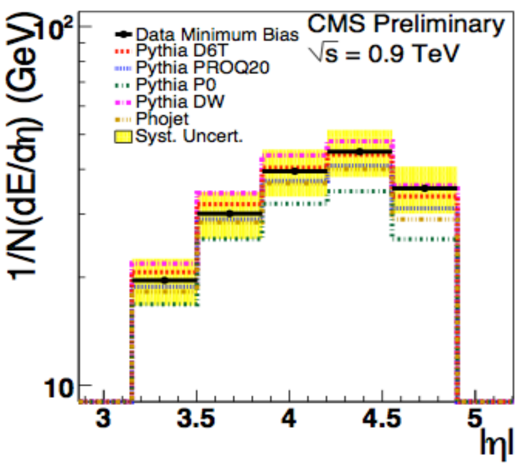
Particle/anti-particle ratios

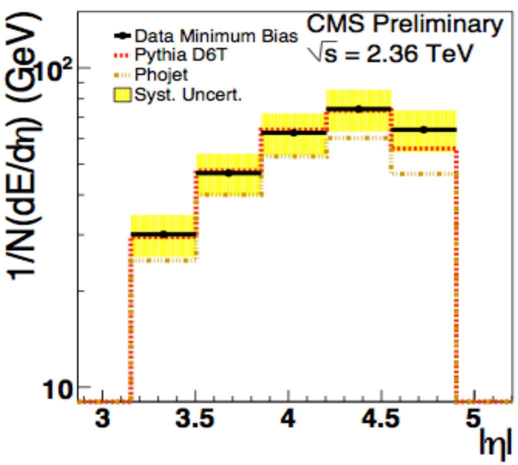
Baryon number transport with $\bar{\Lambda}/\Lambda$

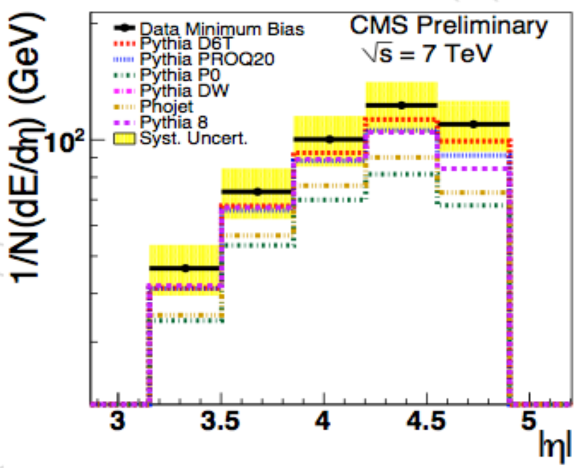


Forward Energy Flow

- MinBias event selection
- Energy flow at different CM energies

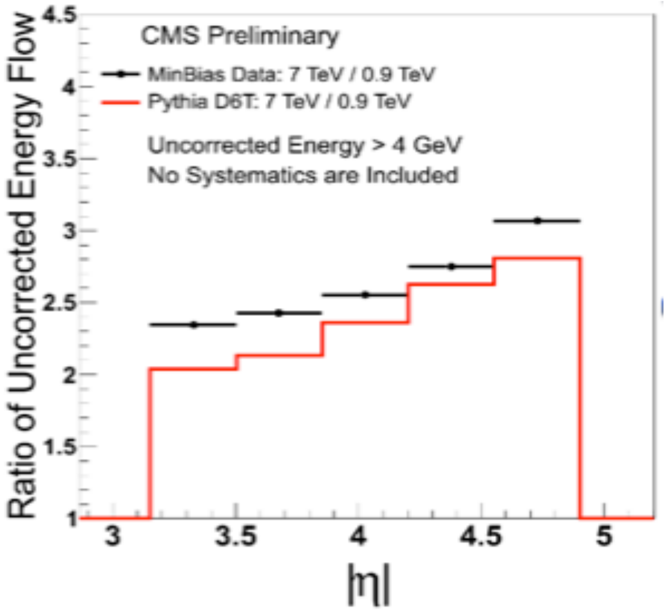






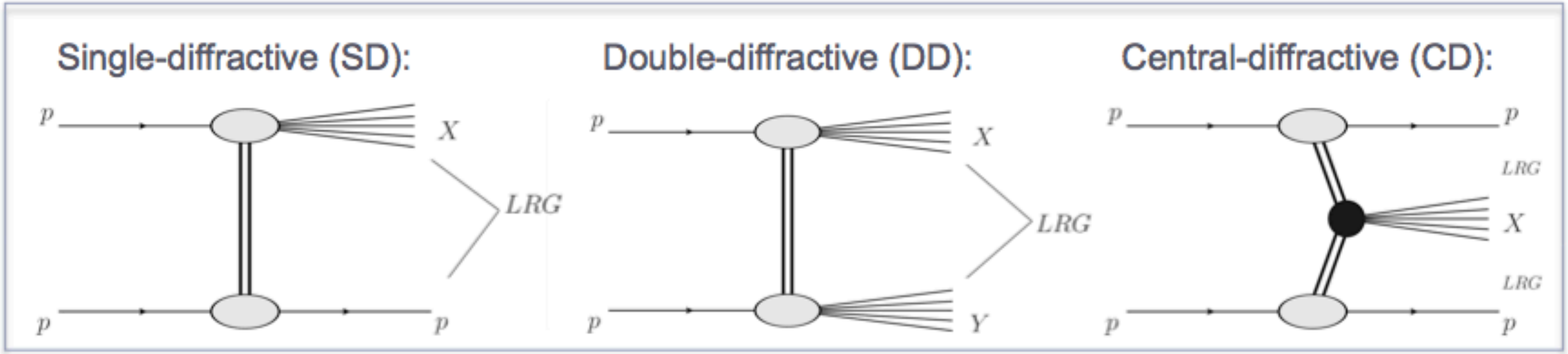
- Ratio of the energy flow at different energies

$$R_{Eflow}^{\sqrt{s_1},\sqrt{s_2}} = \frac{\frac{1}{N_{\sqrt{s_1}}}\frac{\Delta E_{\sqrt{s_1}}}{\Delta\eta}}{\frac{1}{N_{\sqrt{s_2}}}\frac{\Delta E_{\sqrt{s_2}}}{\Delta\eta}}$$

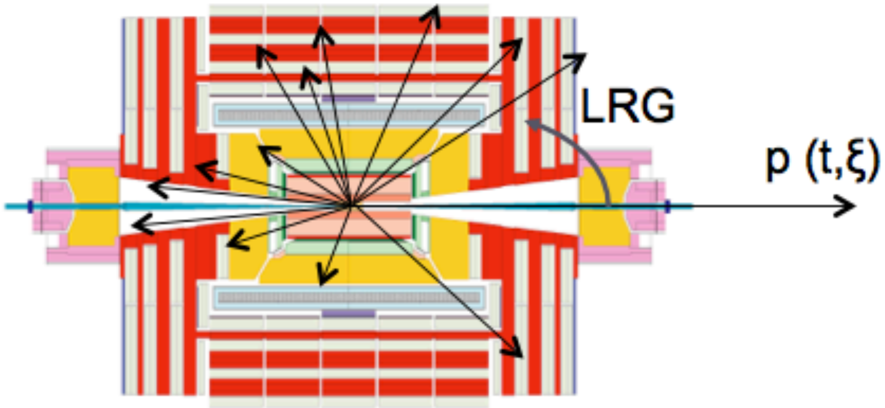


Similar rise with collision energy as seen in dN/dη analysis

The Diffractive Component

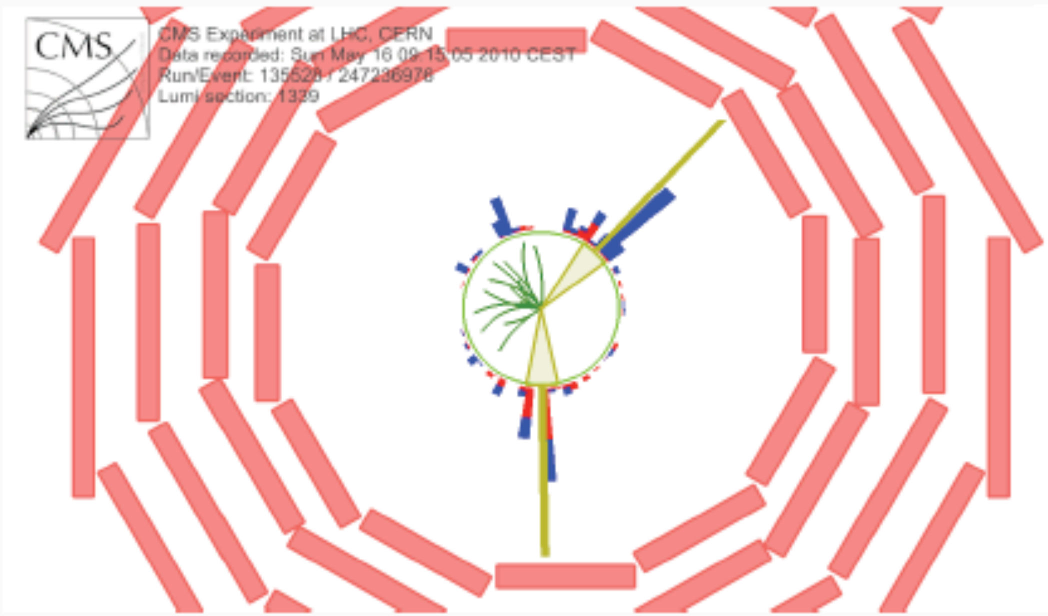


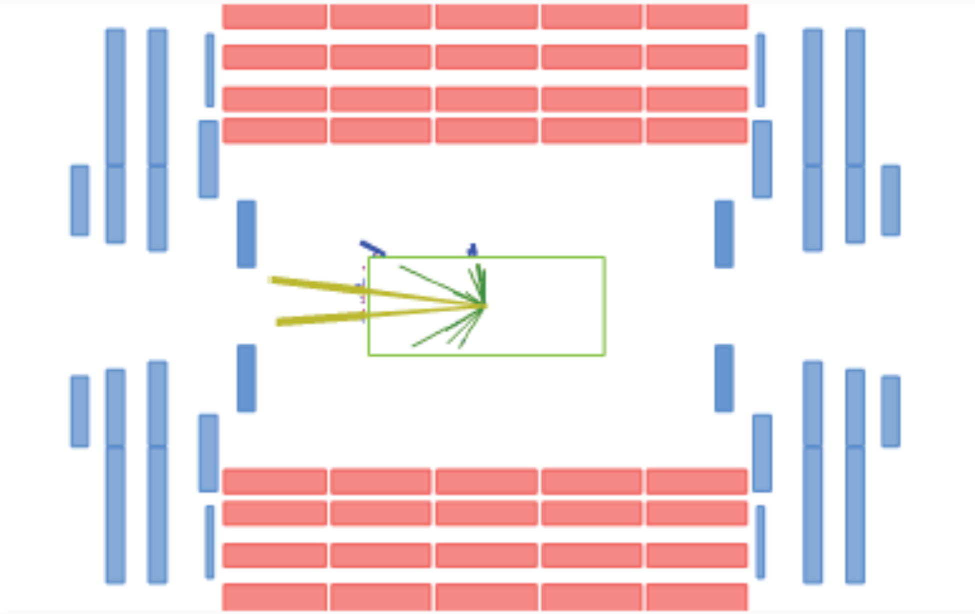
Sketch of single-diffractive event:

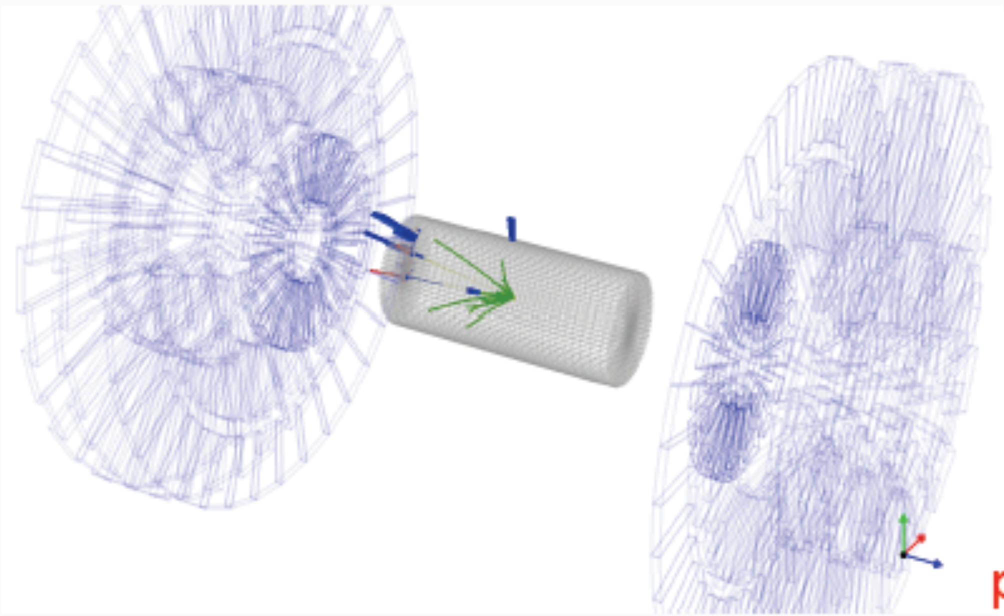


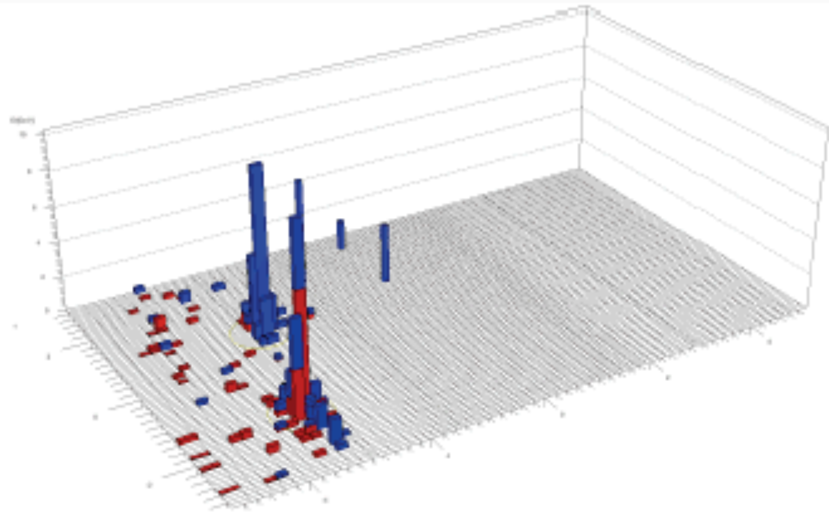
LRG: Large Rapidity Gap

- Diffractive events correspond to large fraction of the hadron-hadron cross section;
- Modeling of soft diffraction generator specific;
- Defining and constraining diffractive component (and their evolution with √s) important ingredient in the tuning of MC generators at the LHC.









$E(\eta < 3.0) > 1.5$ GeV $p_T(\text{track}) > 0.5$ GeV

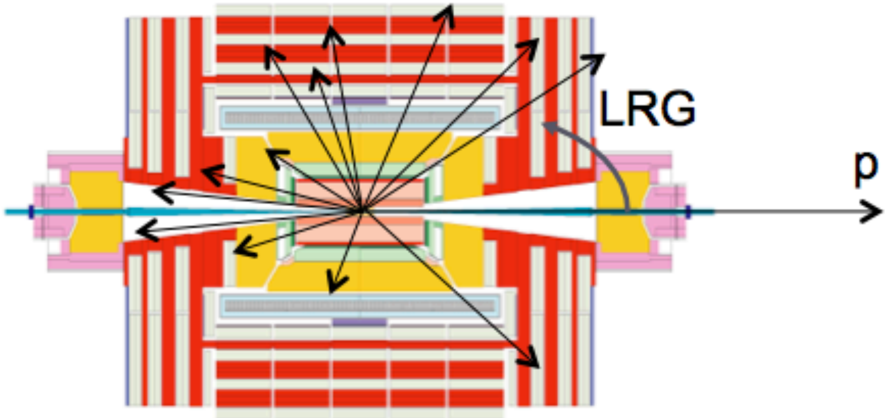
$E(\eta \geq 3.0) > 2.0$ GeV

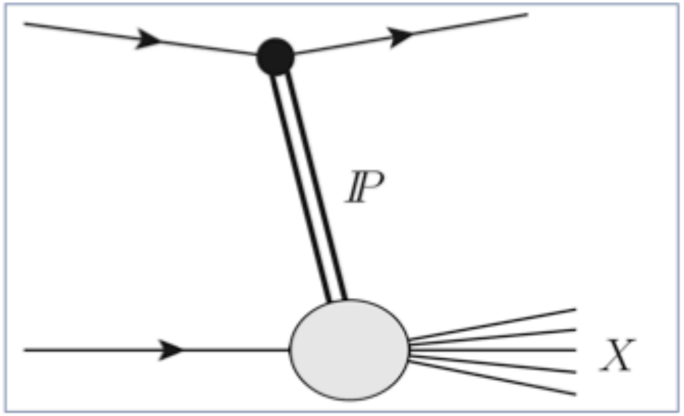
$p_T(\text{jet1}) = 41.2$ GeV, $p_T(\text{jet2}) = 31.9$ GeV

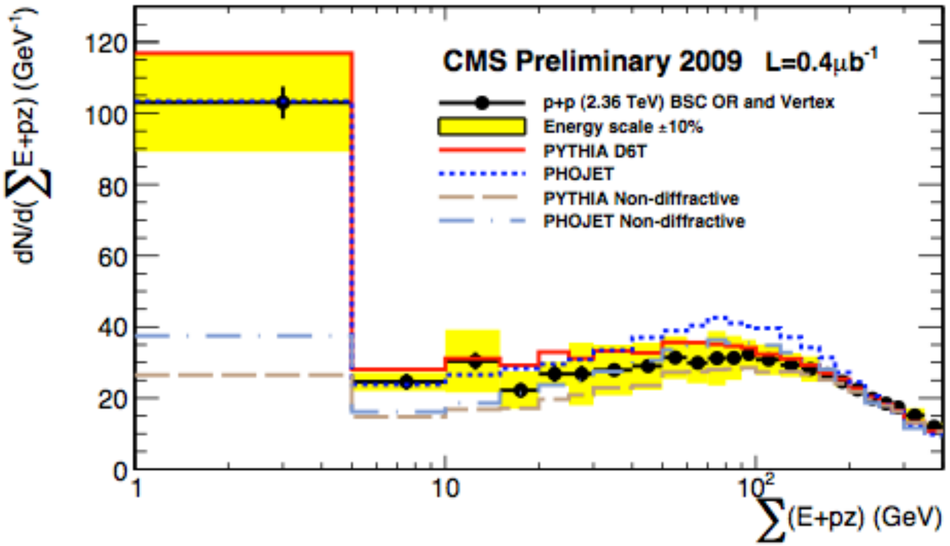
$\eta(\text{jet1}) = -2.8$, $\eta(\text{jet2}) = -3.3$

Diffraction in the data

Sketch of single-diffractive event:







$\Sigma(E \pm p_z)$ related to the momentum loss of the scattered proton. One expects a (diffractive) peak at low values of this variable ($\sigma \sim 1/\xi$).

Main systematic effect due to ±10% energy scale variation.

N.B. All plots are uncorrected

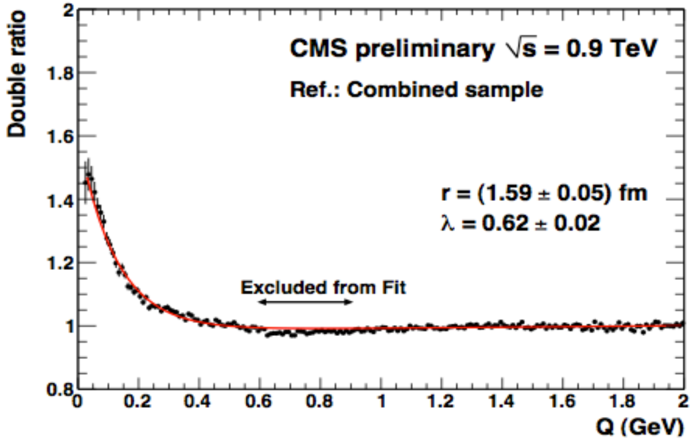
Bose Einstein Correlations

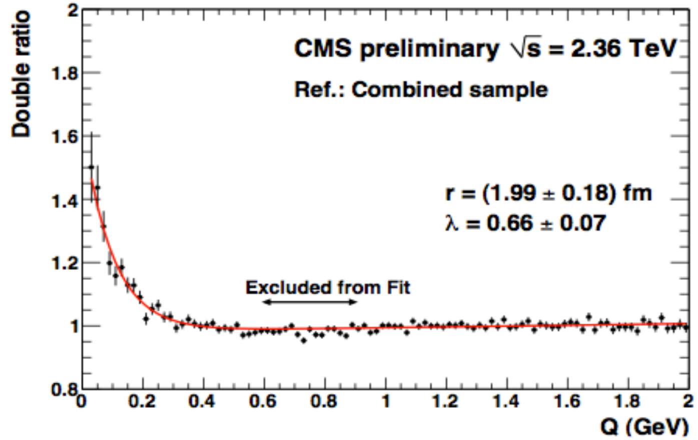
Correlations between two identical bosons (pions) √s = 0.9 and 2.36 TeV

$Q^2=-(p1-p2)^2$

$$R(Q) = C\,[1+\lambda\Omega(Qr)]\cdot(1+\delta Q), \qquad \Omega(Qr) = e^{-Qr},$$

- MinBias events
- Use 7 reference samples
- Combination of all ref. samples





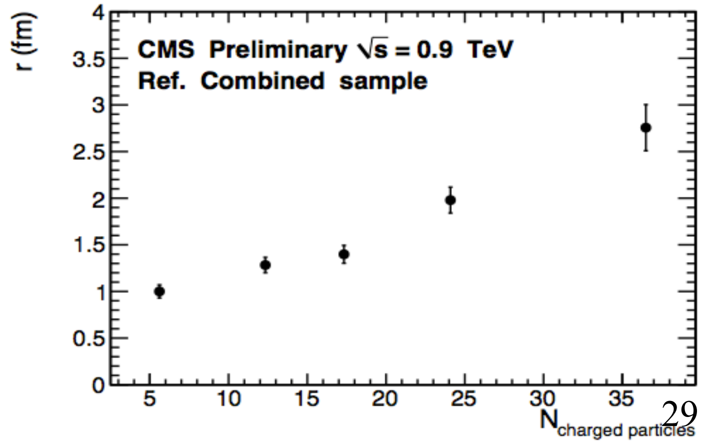
√s = 0.9 TeV $r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) fm and $\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.)

√s = 2.36 TeV $r = 1.99 \pm 0.18$ (stat.) ± 0.24 (syst.) fm and $\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.)

Multiplicity dependence

Results of fits to 0.9 TeV data

Multiplicity range	P-value	C	λ	r (fm)
2 - 9	9.7×10^{-1}	0.90 ± 0.01	0.89 ± 0.05	1.00 ± 0.07 (stat.)± 0.05 (syst.)
10 - 14	3.8×10^{-1}	0.97 ± 0.01	0.64 ± 0.04	1.28 ± 0.08 (stat.)± 0.09 (syst.)
15 - 19	2.7×10^{-1}	0.96 ± 0.01	0.60 ± 0.04	1.40 ± 0.10 (stat.)± 0.05 (syst.)
20 - 29	2.4×10^{-1}	0.99 ± 0.01	0.59 ± 0.05	1.98 ± 0.14 (stat.)± 0.45 (syst.)
30 - 79	2.8×10^{-1}	1.00 ± 0.01	0.69 ± 0.09	2.76 ± 0.25 (stat.)± 0.44 (syst.)



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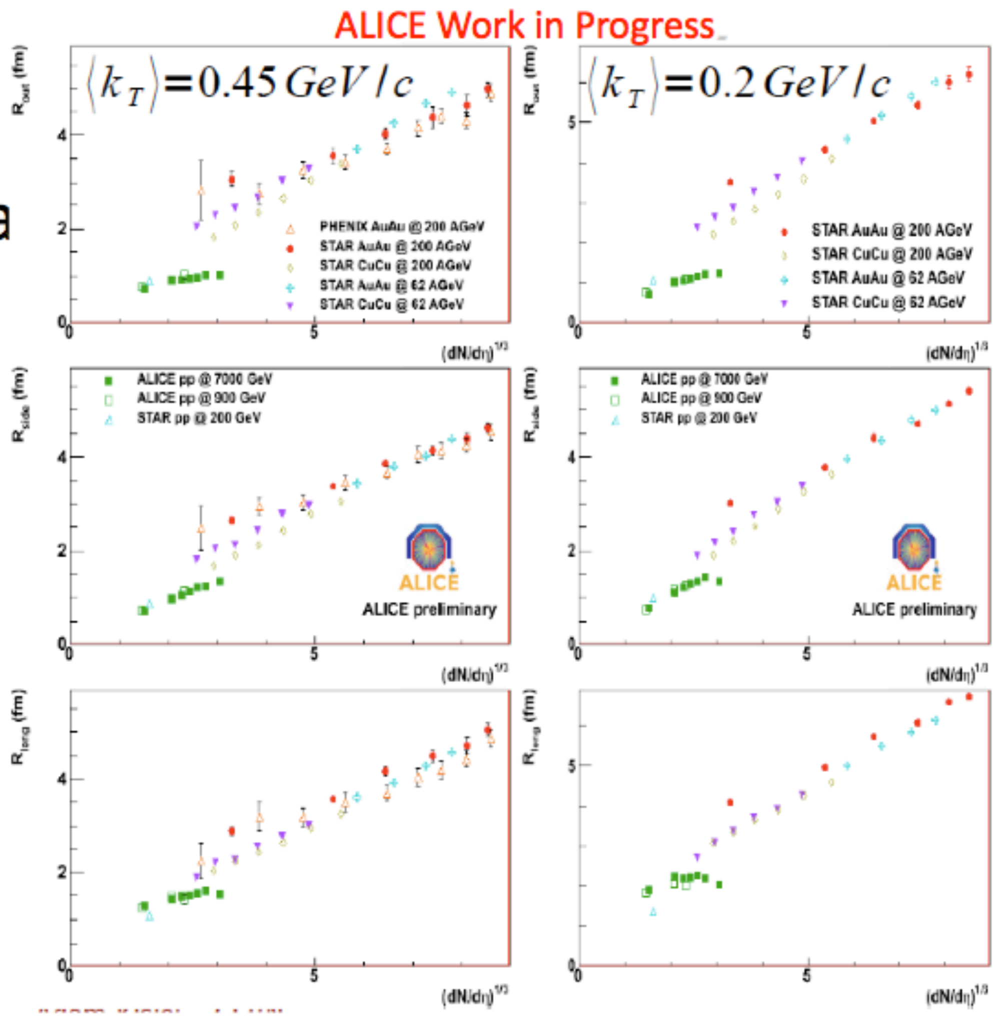
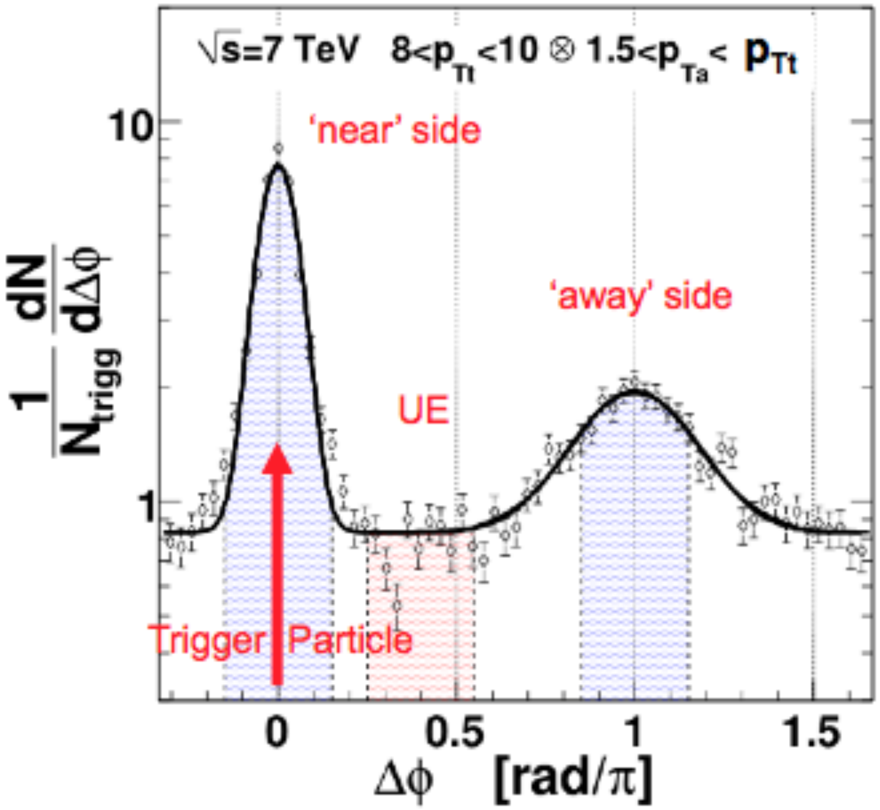
Correlations

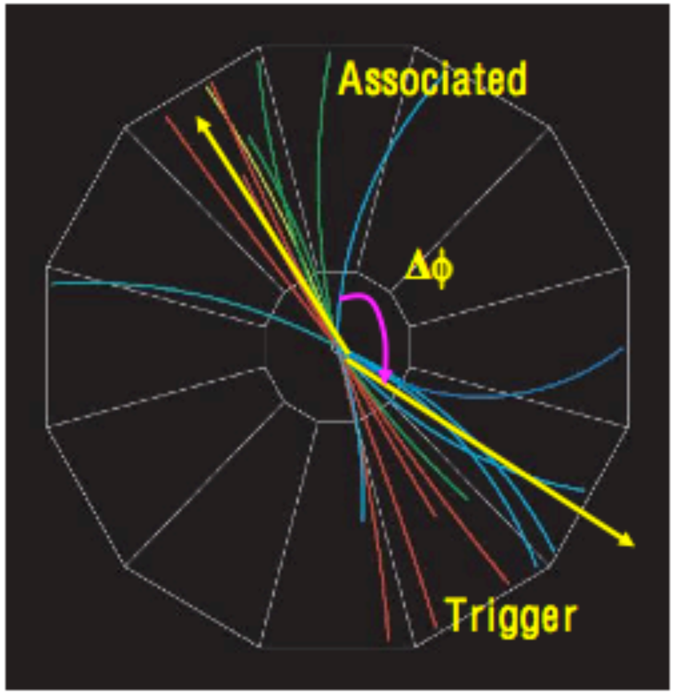
Bose-Einstein Correlations (HBT)

- Preparation for HI
- Similar phenomena in pp and HI?
- M overlapp pp and HI.
- Scaling with M similar to STAR but different from HI
- pp sizes smaller than HI at same M



Particle Correlations

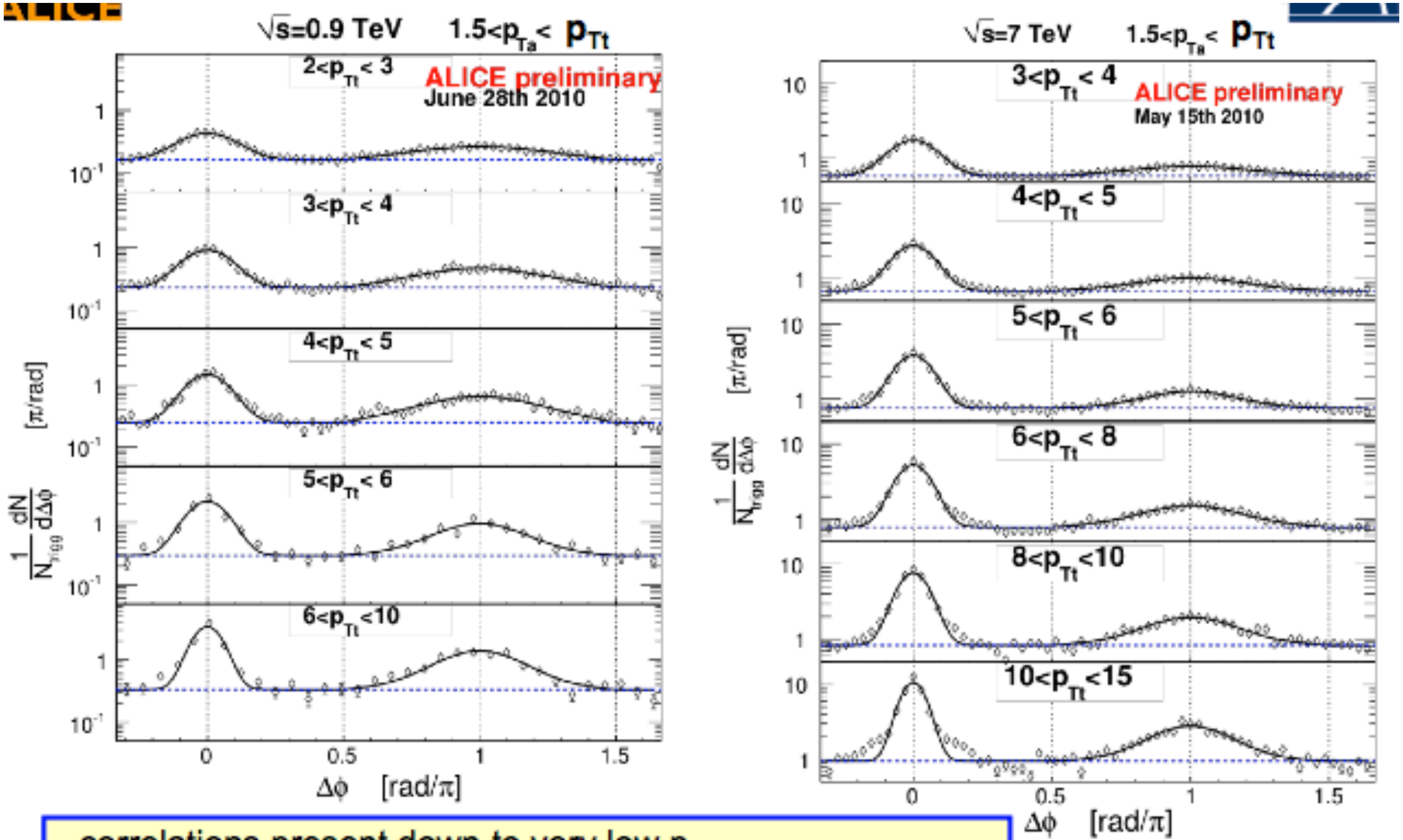




Trigger Particle: highest p_T particle in event (p_{Tt})

Associate Particle: all the others (p_{Ta})

Particle Correlations



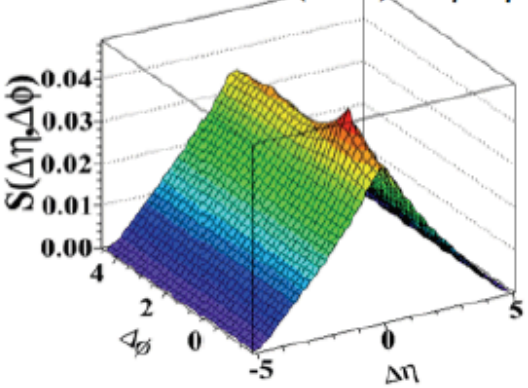
- correlations present down to very low p_T
- study ‘mini-jet region (difficult with fully reconstructed jet ?)

Two Particle Correlations

Two particle angular correlations

Signal distribution:

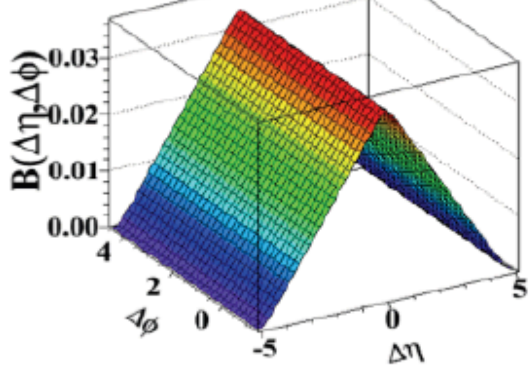
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



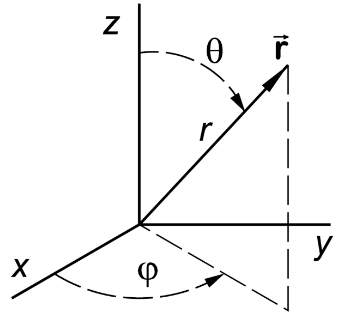
Same event pairs

Background distribution:

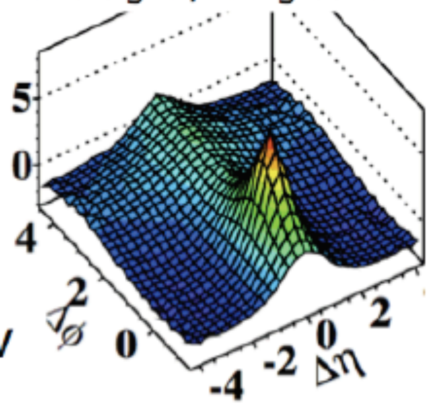
$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



Mixed event pairs



Ratio Signal/Background



$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

$$\Delta\eta = \eta_1 - \eta_2$$

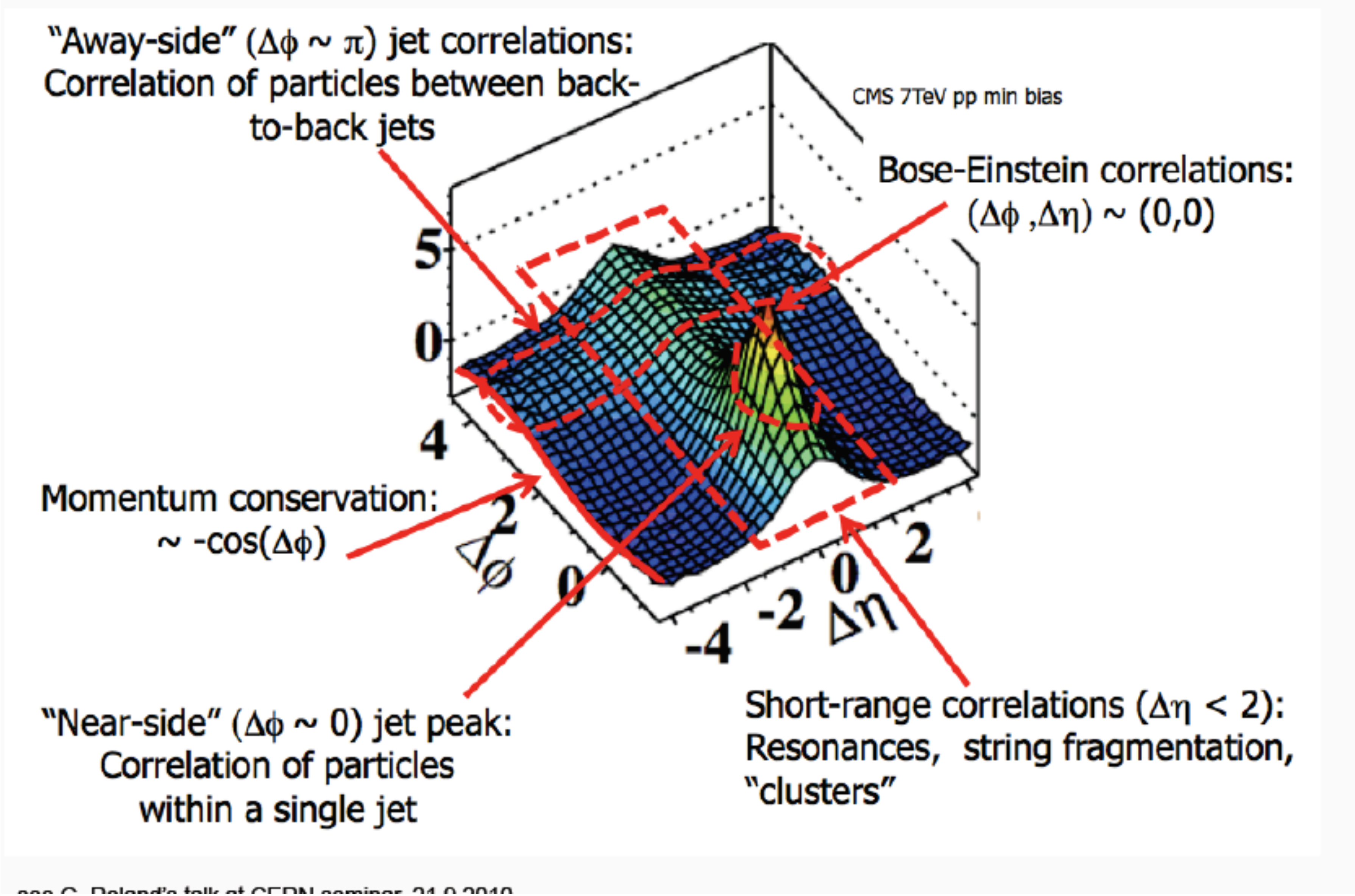
$$\Delta\varphi = \varphi_1 - \varphi_2$$

CMS pp 7TeV

p_T-inclusive two-particle angular correlations in min bias collisions

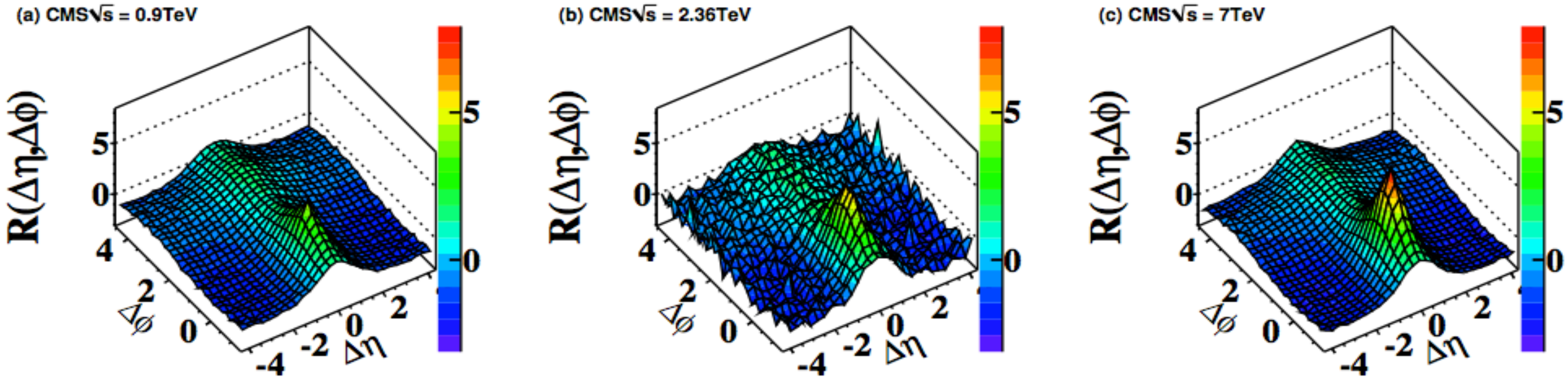
see G. Roland's talk at CERN seminar, 21.9.2010

Two Particle Correlations



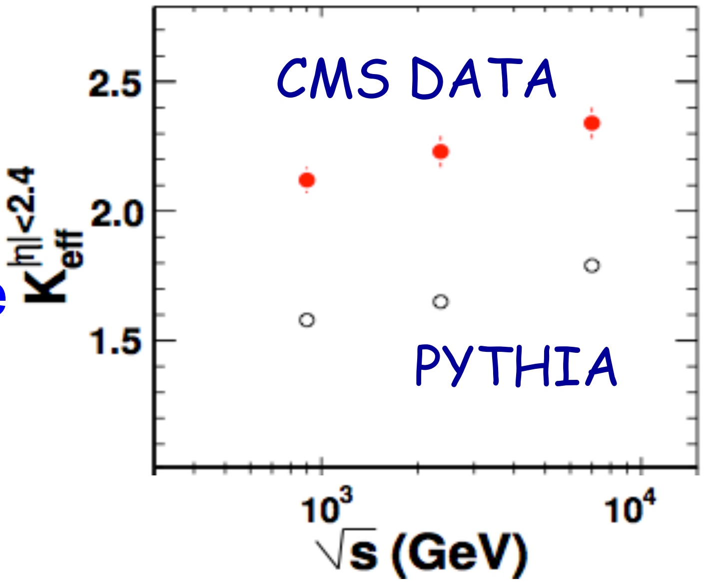
Two Particle Correlations

Two particle angular correlations



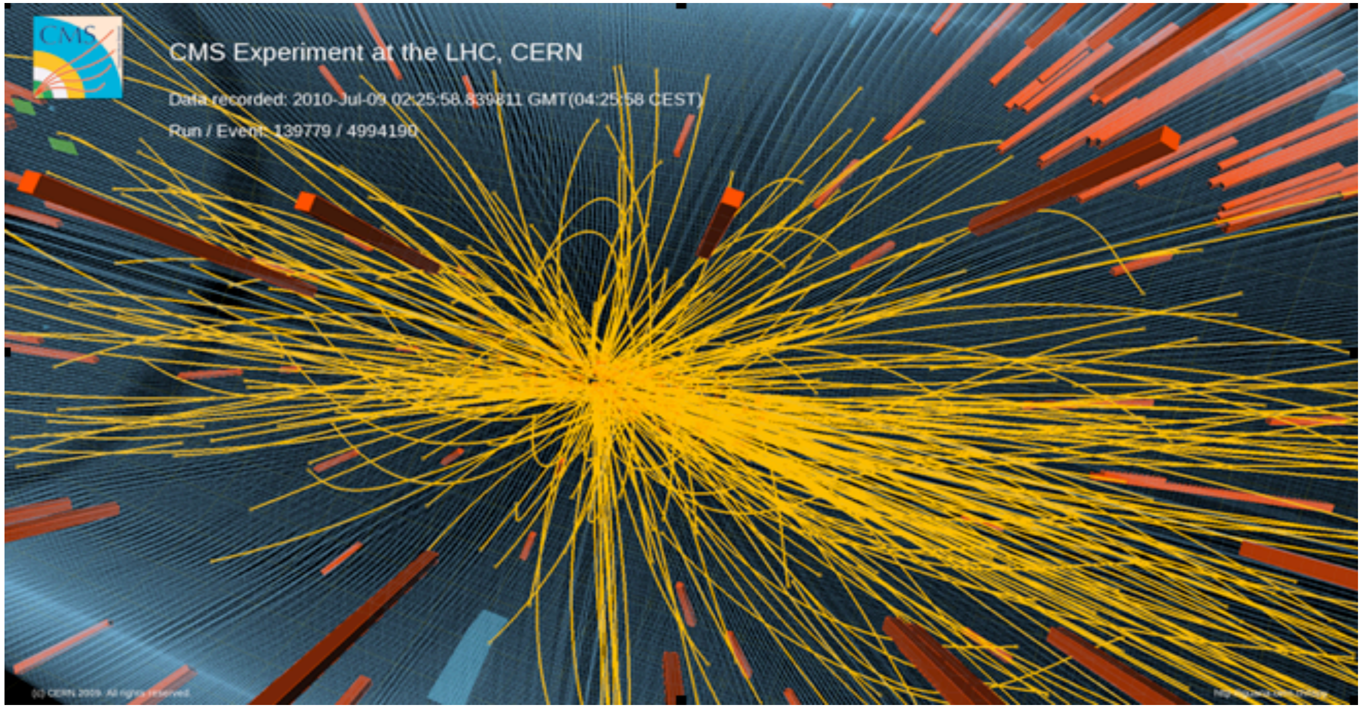
$$R(\Delta\eta, \Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta, \Delta\phi)}{B_N(\Delta\eta, \Delta\phi)} - 1\right)\right\rangle_N$$

Effective cluster size



Short range correlations
Cluster size not described by eg PYTHIA

…and correlations can be interesting ☺



Collisions at 7 TeV with very high
charged particle multiplicity (> 100)

Two Particle Correlations

CMS Collab.. arXiv:1009.4122, accept. for publ. in JHEP!

Intermediate p_T: 1-3 GeV/c

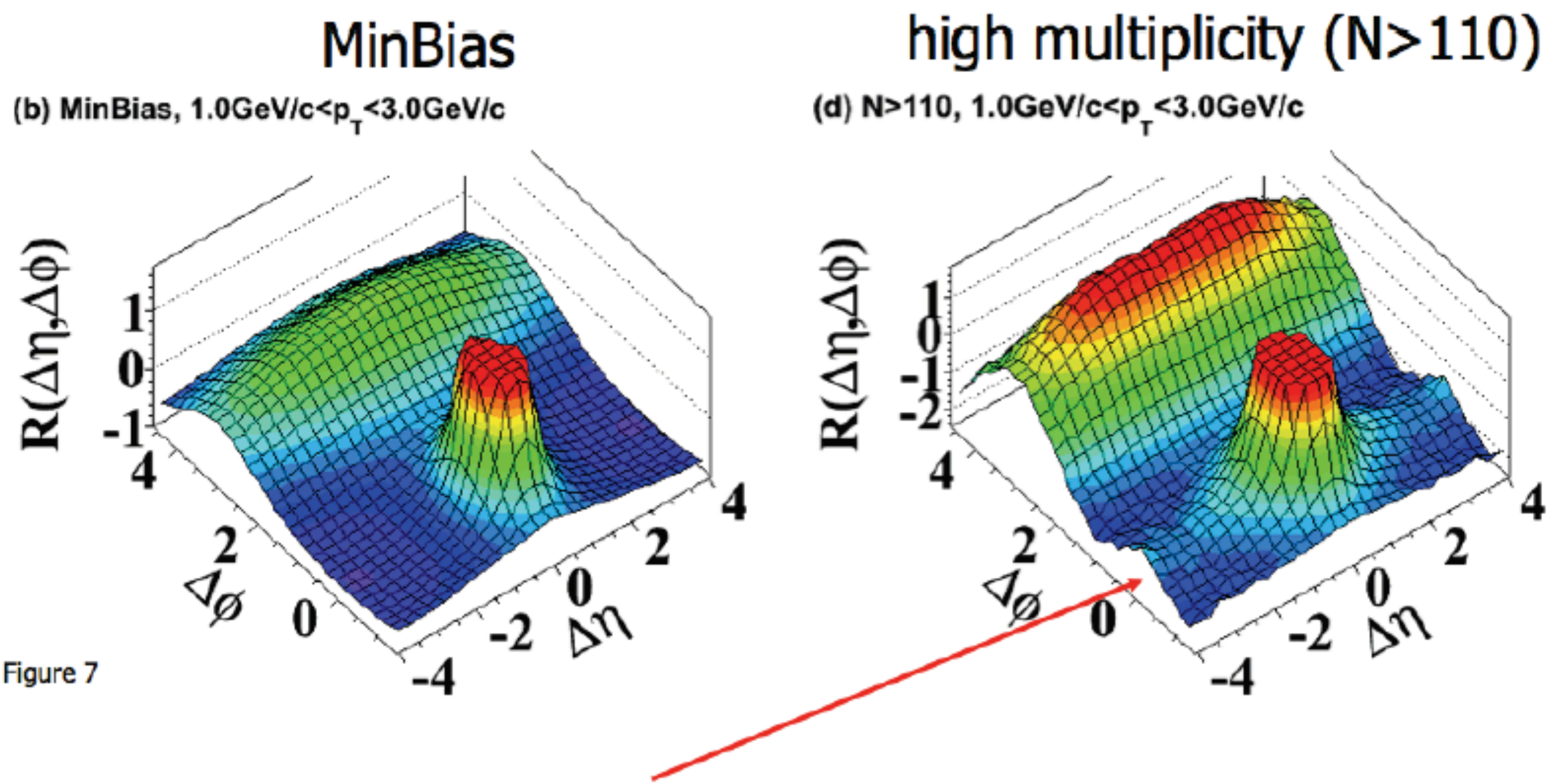
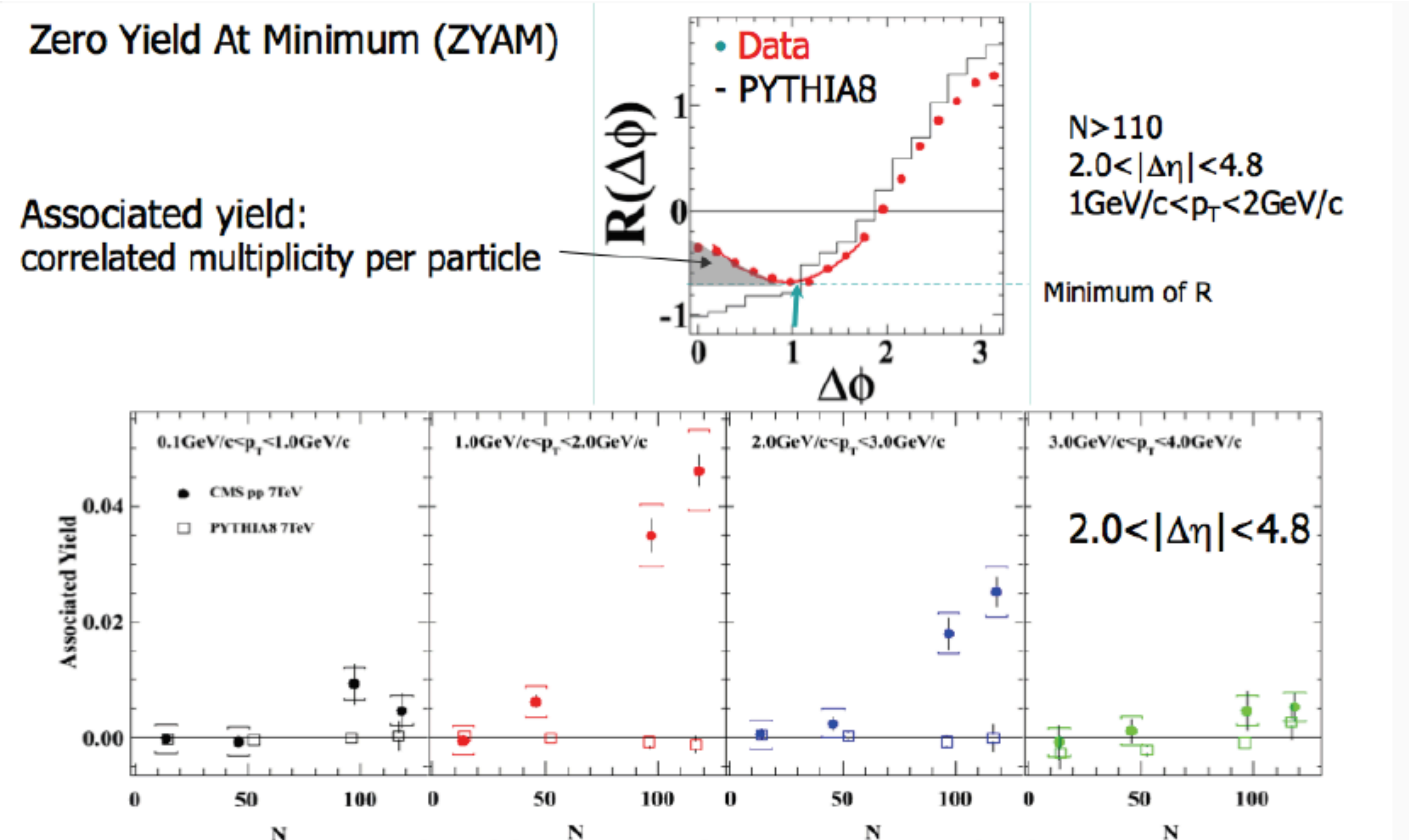


Figure 7

Pronounced structure at large δη around δφ ~ 0 !

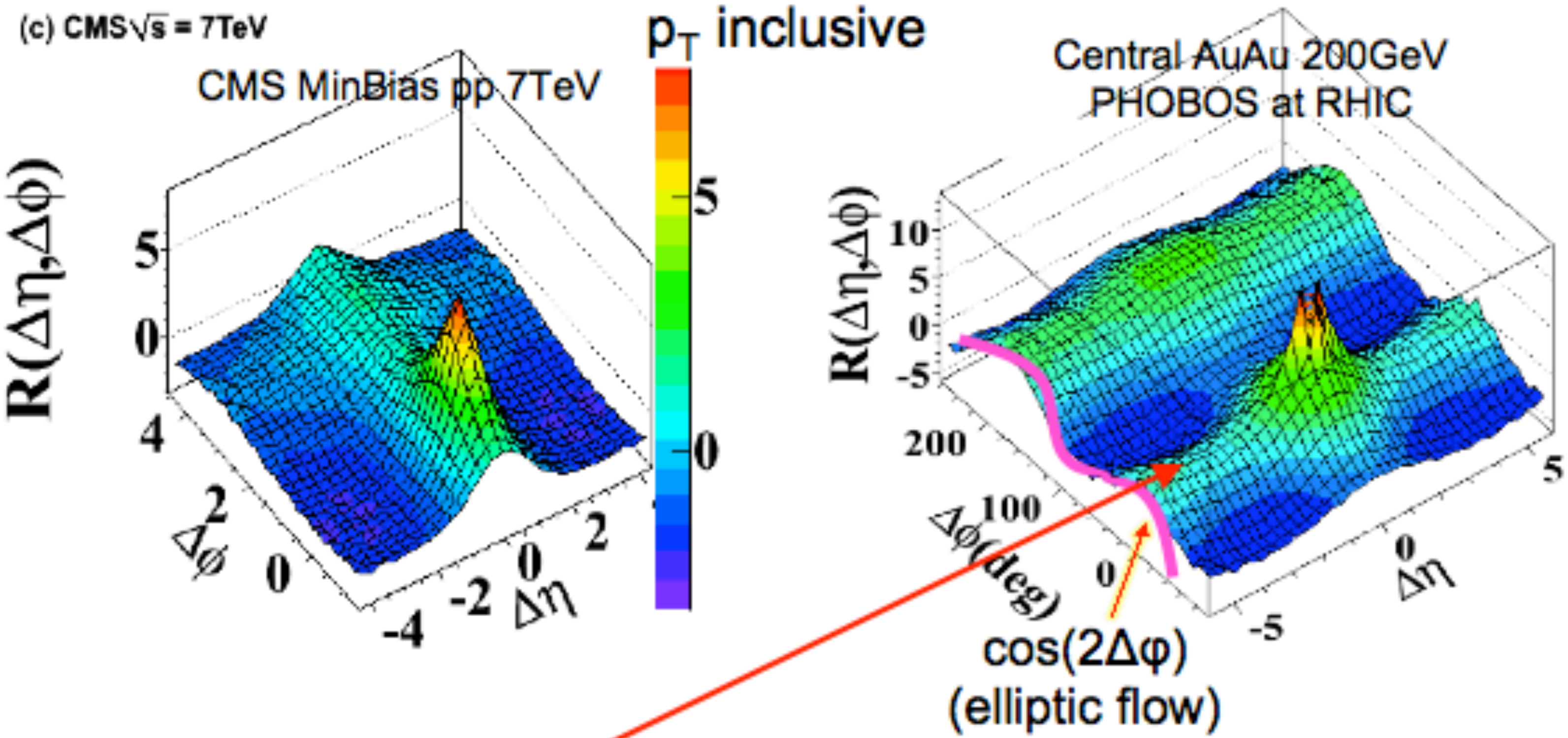
see G. Roland's talk at CERN seminar 21.9.2010

Two Particle Correlations



Associated yield grows with increasing multiplicity

Correlations in Heavy Ion Collisions



Long-range "Ridge"-like structure in Δη:

- Believed to be mainly hydrodynamic flow from "Perfect Liquid"
- Most important HI results in the past 10 years
- Several papers (exp. and theo.) with 400-700 citations

Simularity with the effect now seen in pp

Two Particle Correlations

- Observation of long-range, near-side correlations in high multiplicity events
  - Signal grows with event multiplicity
  - Effect is maximal in the $1 < p_T < 3$ GeV/c range
- Long-range, near-side correlation is not seen in low multiplicity events and generators, but resembles effects seen in heavy-ion collisions at high energies
- Very extensive systematic checks performed
  - we are confident in the measurement as such
- This is a subtle effect in a complex environment – careful work is needed to establish physical origin

The origine of this correltion is presently not known
Does it have to do with hot dense matter?

Theory Response..

Comments on the CMS discovery of the "Ridge" in High Multiplicity pp collisions at LHC

Edward Shuryak

(Submitted on 23 Sep 2010)

A very recent paper by the CMS collaboration \cite{cms_ridge} has created large discussion in the media, which call it important but did not explain why, in some places even calling it "unundestandable". While it is of course too soon to know what causes the correlations in question, a very similar observation in heavy ion collisions at RHIC has rather simple explanation related to explosion of high energy density matter. Perhaps this observation is the first hint for an explosive behavior in pp, which was anticipated and looked for for decades, yet never been seen.

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)
Cite as: **arXiv:1009.4635v1 [hep-ph]**

Submission history
From: Edward Shuryak [view email]
[v1] Thu, 23 Sep 2010 15:25:49 GMT (15kb,D)

The ridge in proton-proton collisions at the LHC

Adrian Dumitru, Kevin Dusling, Francois Gelis, Jamal Jalilian-Marian, Tuomas Lappi, Raju Venugopalan

(Submitted on 27 Sep 2010)

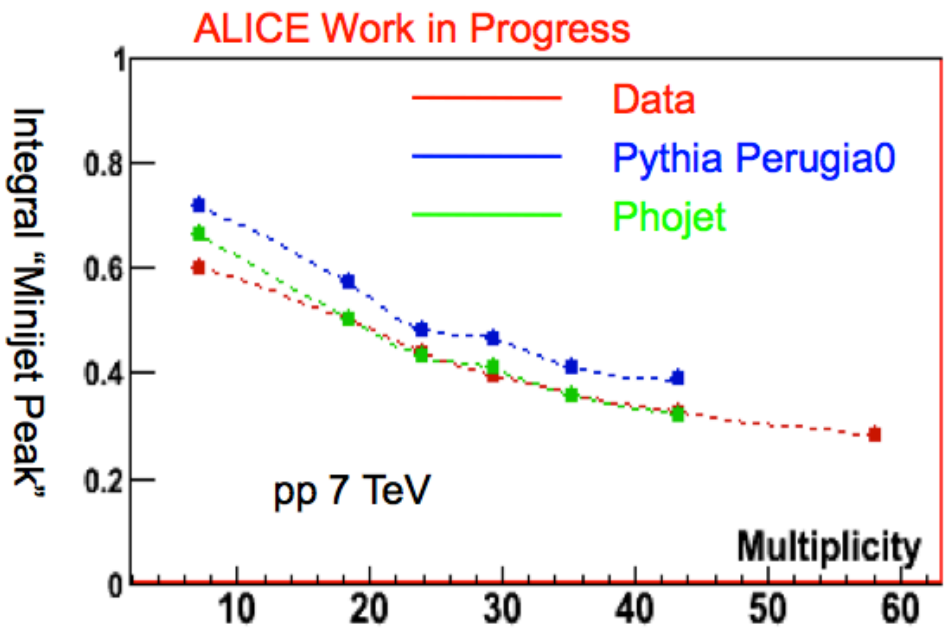
We show that the key features of the CMS result on the ridge correlation seen for high multiplicity events in sqrt(s)=7TeV proton-proton collisions at the LHC can be understood in the Color Glass Condensate framework of high energy QCD. The same formalism underlies the explanation of the ridge events seen in A+A collisions at RHIC, albeit it is likely that flow effects may enhance the magnitude of the signal in the latter.

Comments: 6 pages, 7 figures, ReVTEX4
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Nuclear Theory (nucl-th)
Report number: INT-PUB-10-051, BCCUNY-HEP/10-03, BNL-94103-2010-JA, RBRC-858
Cite as: **arXiv:1009.5295v1 [hep-ph]**

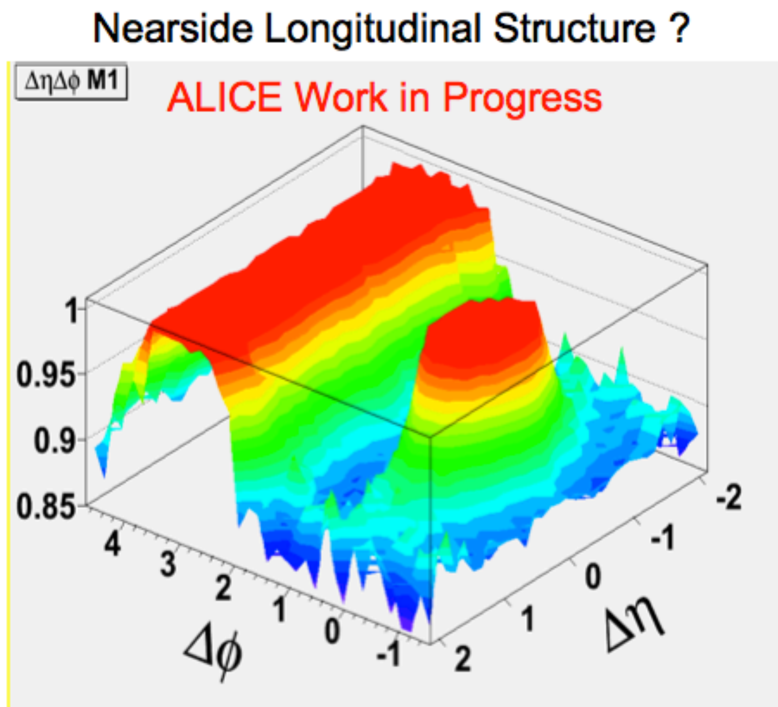
..and a few more

What do the other experiments say?

Quick analysis of ALICE



No p_T cut



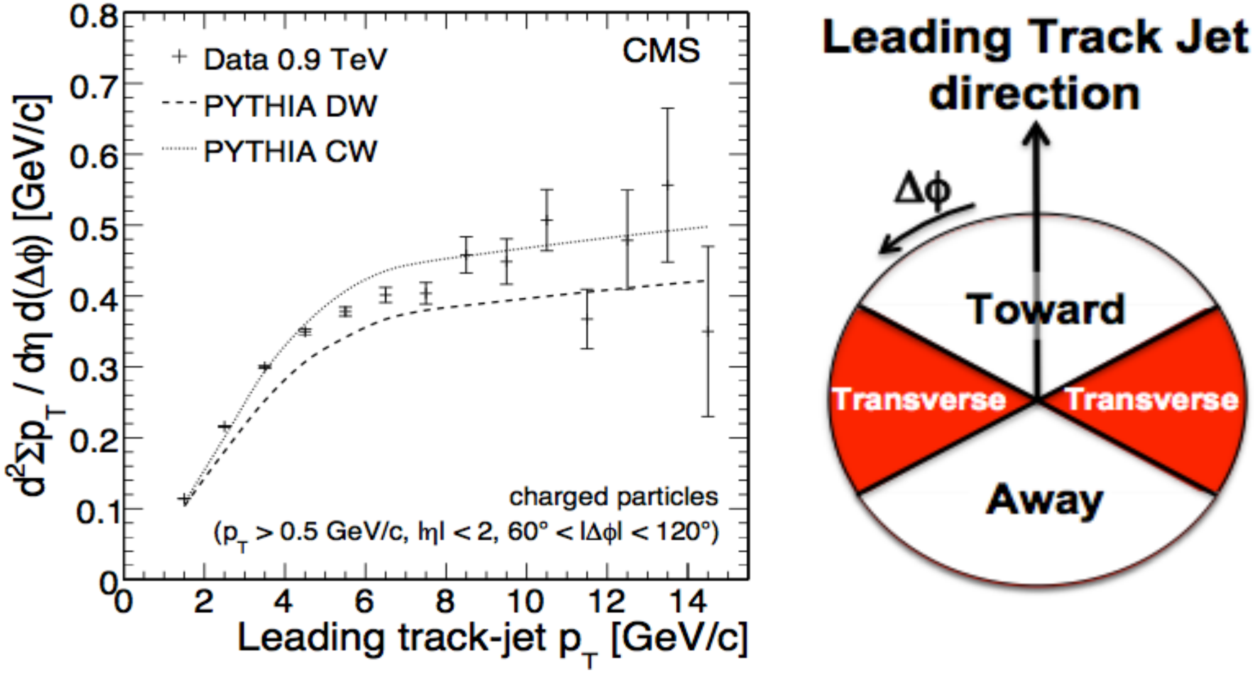
$5 - 6 \times \langle M \rangle$, $p_T > 1.5$ GeV

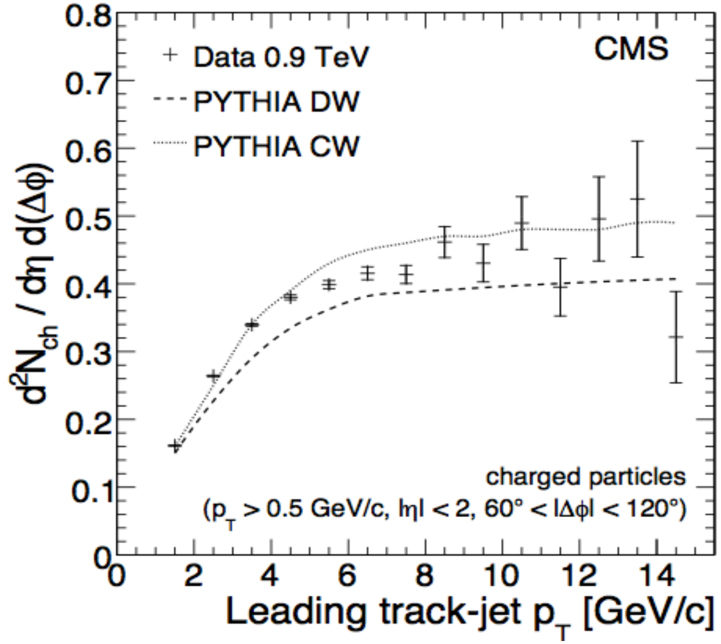
Not conclusive yet

Underlying Event Studies

Underlying event activity at √s = 0.9

- MinBias event selection, with additional requirement of a 'hard' scattering via a track jet with p_T > 3 GeV
- Study the particle density and scalar p_T sum in the transverse region, for particles with |η| < 2 and p_T > 0.5 GeV (uncorrected data)





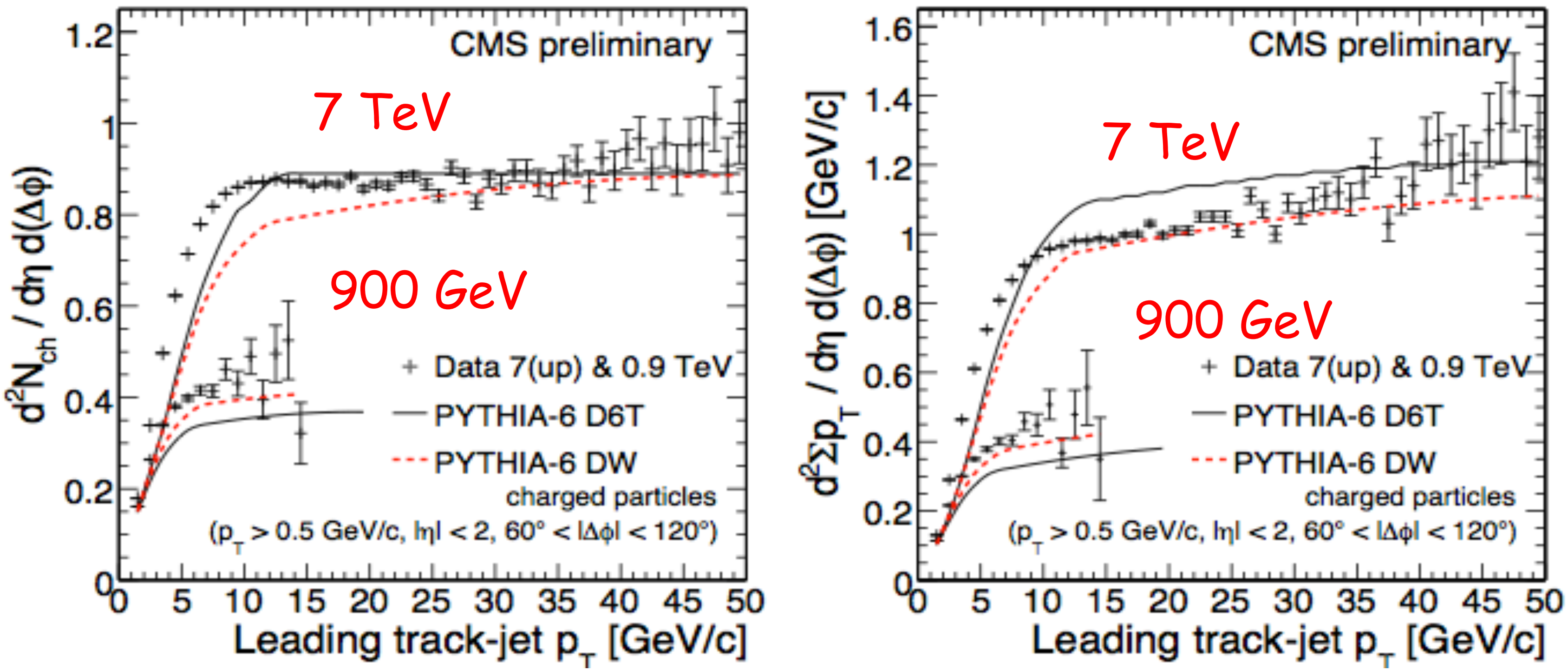
Model Comparison: DW = Standard Tune CW = New Tune (p_{T0}= 1.8 GeV, ε= 0.3)

More food for MC model tuning…

Underlying Event Studies

•MinBias event selection

• Analysis of the 7 TeV data

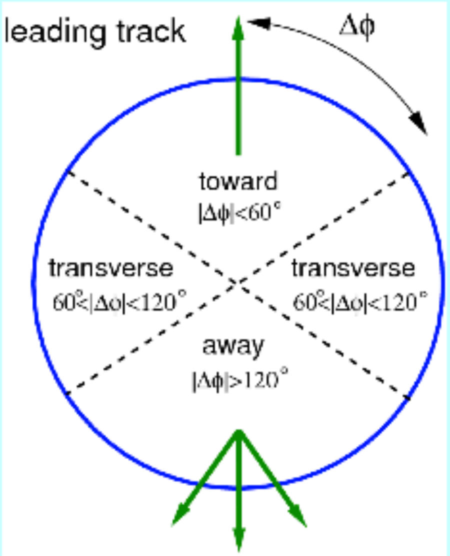


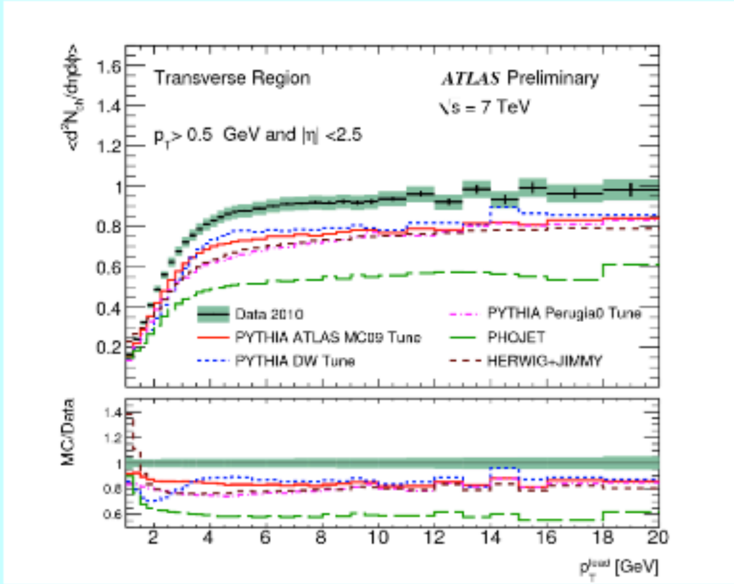
•Also: Jet Area/Median Approach Analysis

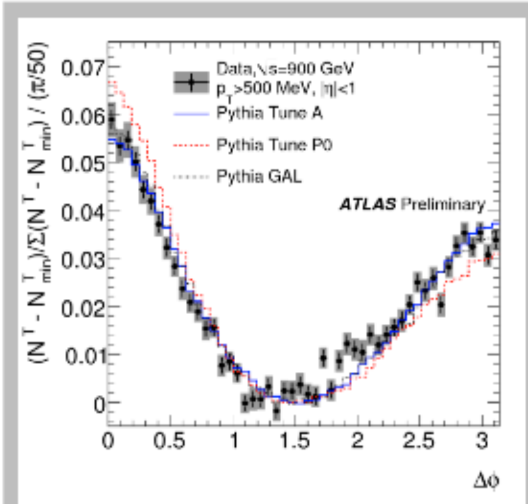
Underlying event activity increases with factor ~2 at 7 TeV
Significant increase of multi-parton interactions?

Underlying Event Studies

Underlying event: properties of tracks in selected regions relative to the leading track





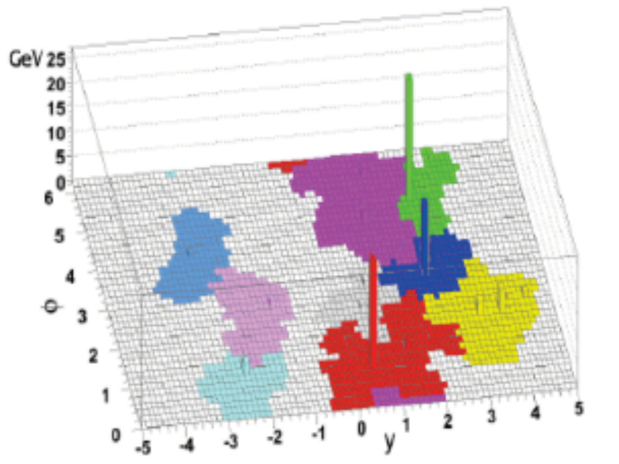


Angular difference ( ) between leading track and other tracks in the event.

(A more "continuous" version of the above measurement)

- Overall ATLAS strategy for soft QCD : report what we measure
  - Corrected for detector effects, of course
- Instead of (e.g.) correcting for diffraction, we have released measurements of diffraction-enhanced and diffraction-suppressed samples.

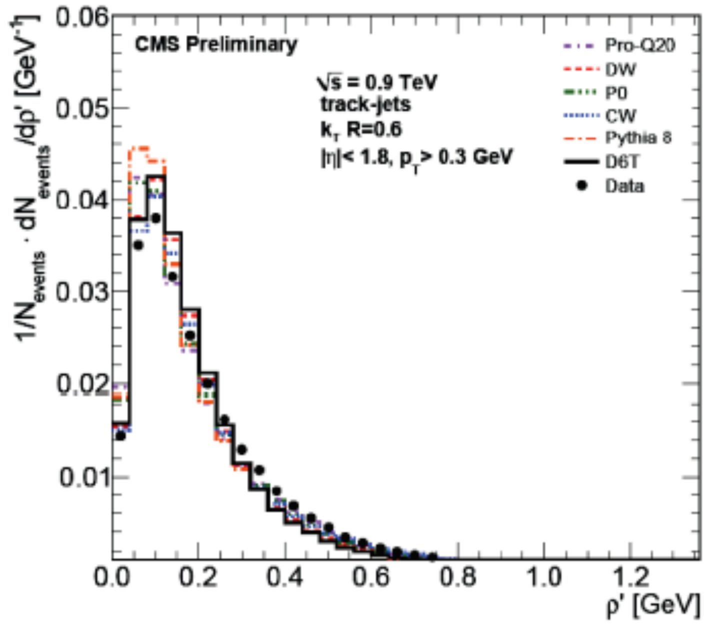
Underlying Event Studies

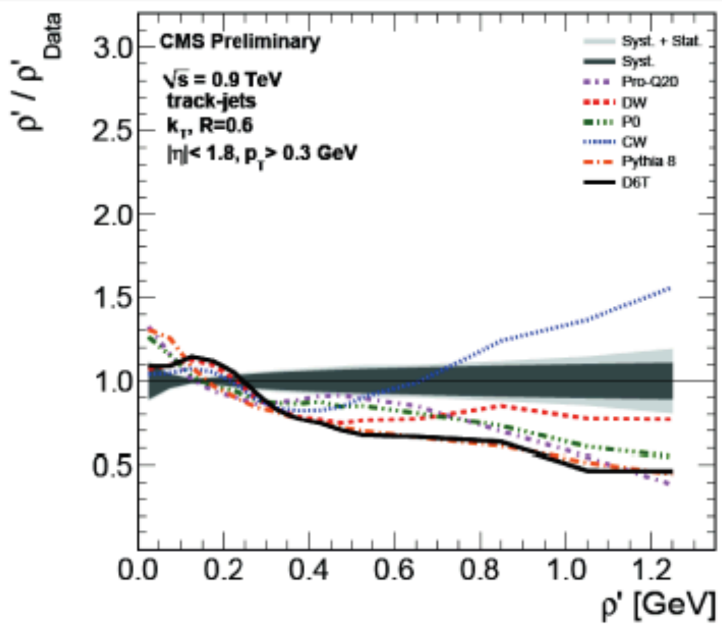


New Approach: Jet Area/Median

- Discussed in JHEP 04 (2010) 065 on generator level
- Median of pt/area of all jets in an event is a measure for UE activity → new observable ρ
- Supresses influence of hard objects
- Suitable for different event topologies

$$\rho' = \underset{j \in \text{physical jets}}{\text{median}} \left[\left\{ \frac{p_{Tj}}{A_j} \right\} \right] \cdot C \qquad C = \frac{\sum_{j \in \text{physical jets}} A_j}{A_{tot}}$$





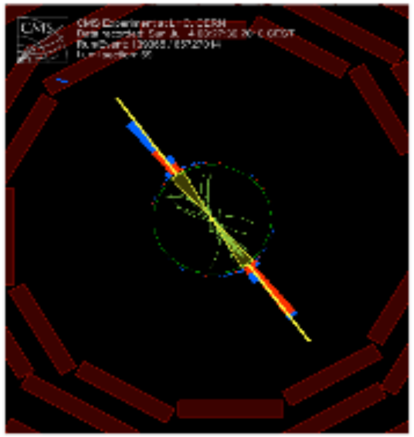
Event Shapes

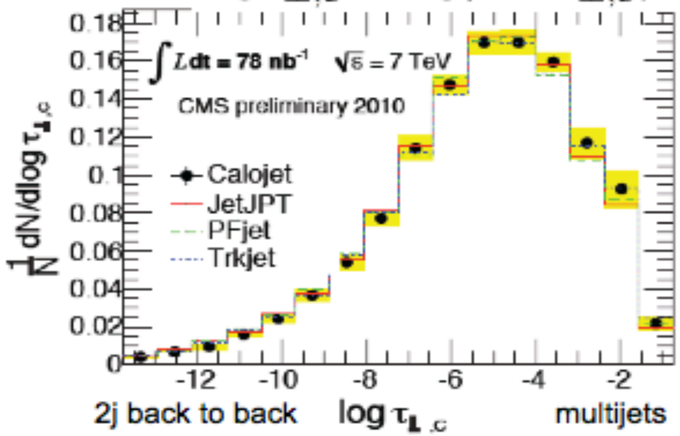
Hadronic Event Shape

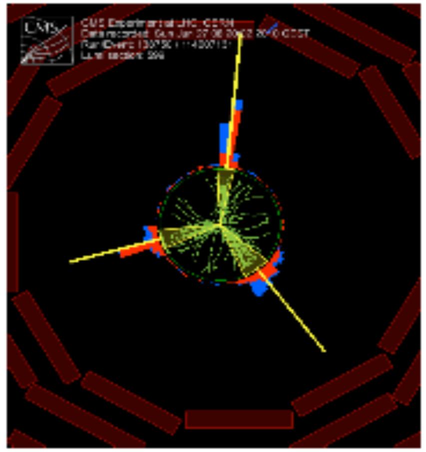
- **Central transverse thrust**

$$T_{\perp,C} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\cdot\vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

$$\log\tau_{\perp,\mathcal{C}} = \log(1 - T_{\perp,\mathcal{C}})$$

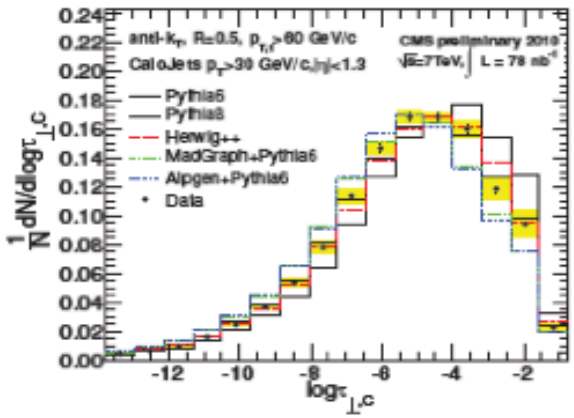






- $\textcolor{blue}{\text{4 jet types}}$ in very good agreement
- $p_T^{leading}$>60 GeV, $|\eta_{j1j2}|$<1.3, p_T>30 GeV, $|\eta|$<1.3,

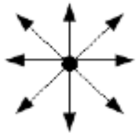
  → JES dominant syst, JER and position resolution (±10%)



Event Shape

Event shape analysis

small $S_\perp$: 

large $S_\perp$: 

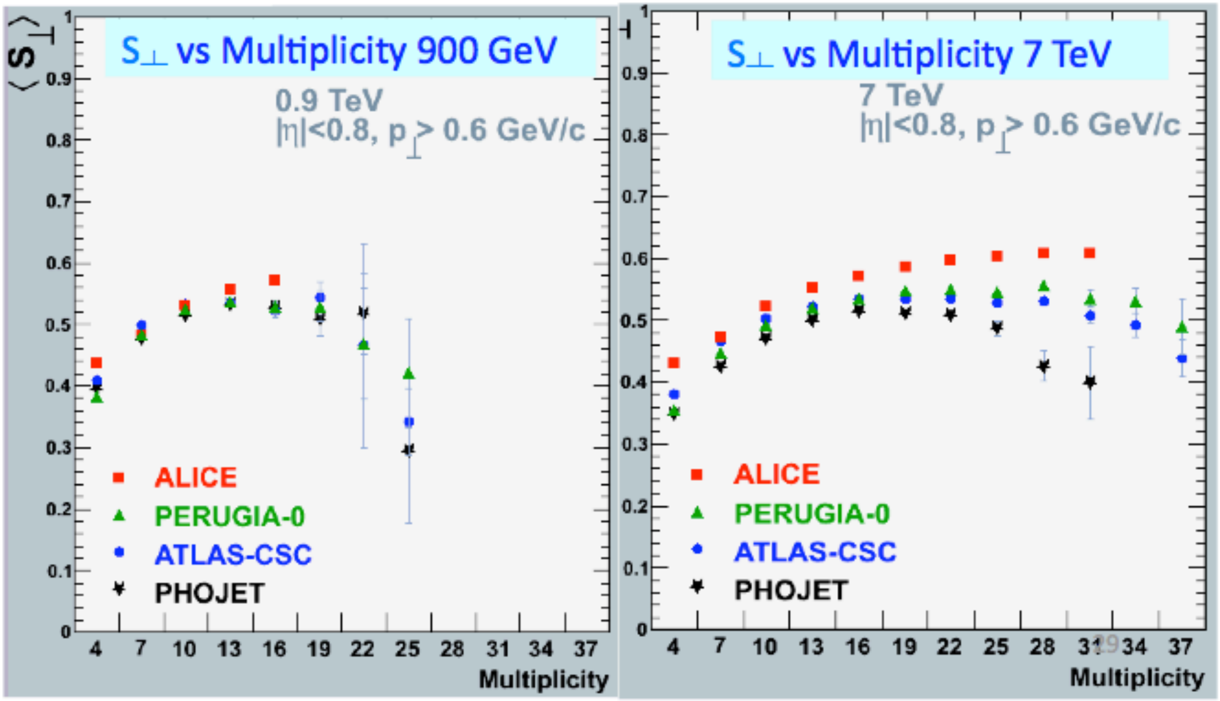
$$\mathbf{S_{xy}} = \sum_i \begin{pmatrix} p_x^{(i)\,2} & p_x^{(i)} p_y^{(i)} \\ p_x^{(i)} p_y^{(i)} & p_y^{(i)\,2} \end{pmatrix}$$

Transverse sphericity $S_\perp$:
eigenvalues of the momentum tensor S_{xy}

$$S_\perp \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

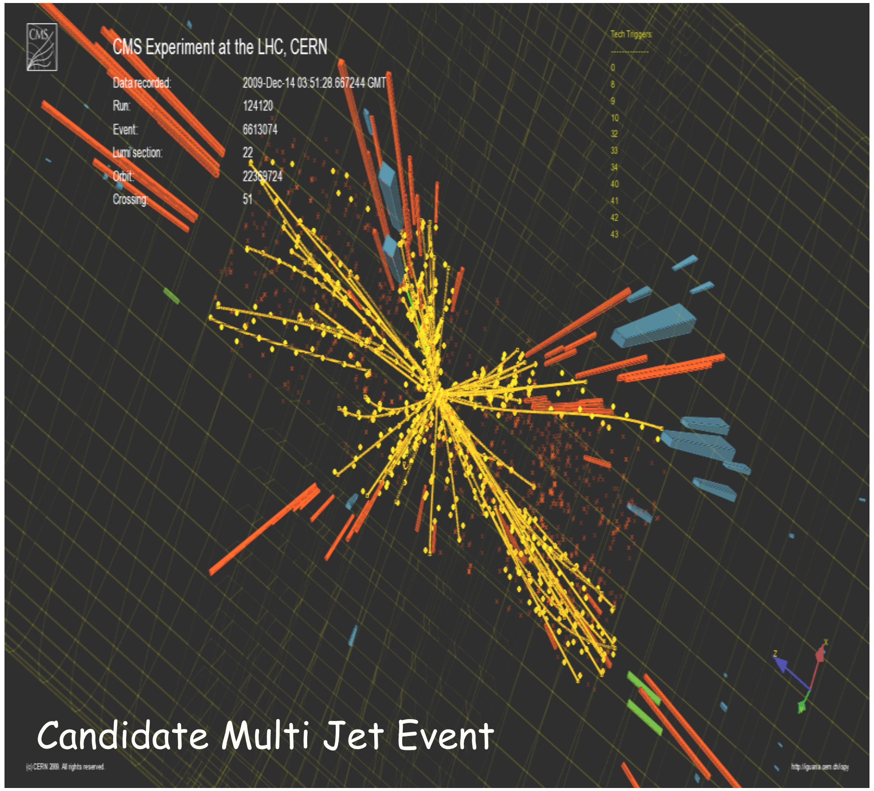
Work in progress

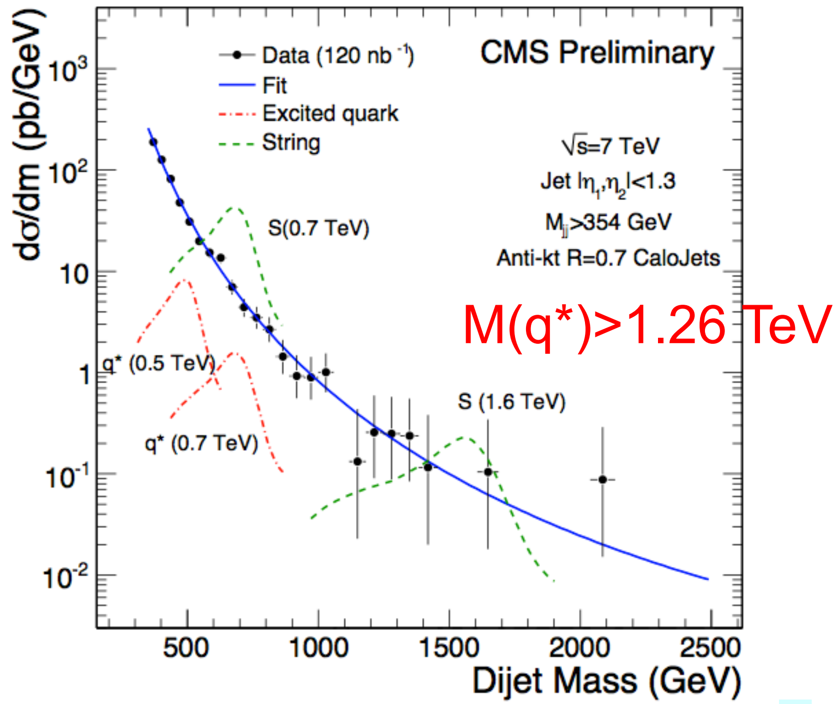
HM events more spherical than models



Jets!

LHC starts already to probe a new regime eg with jets



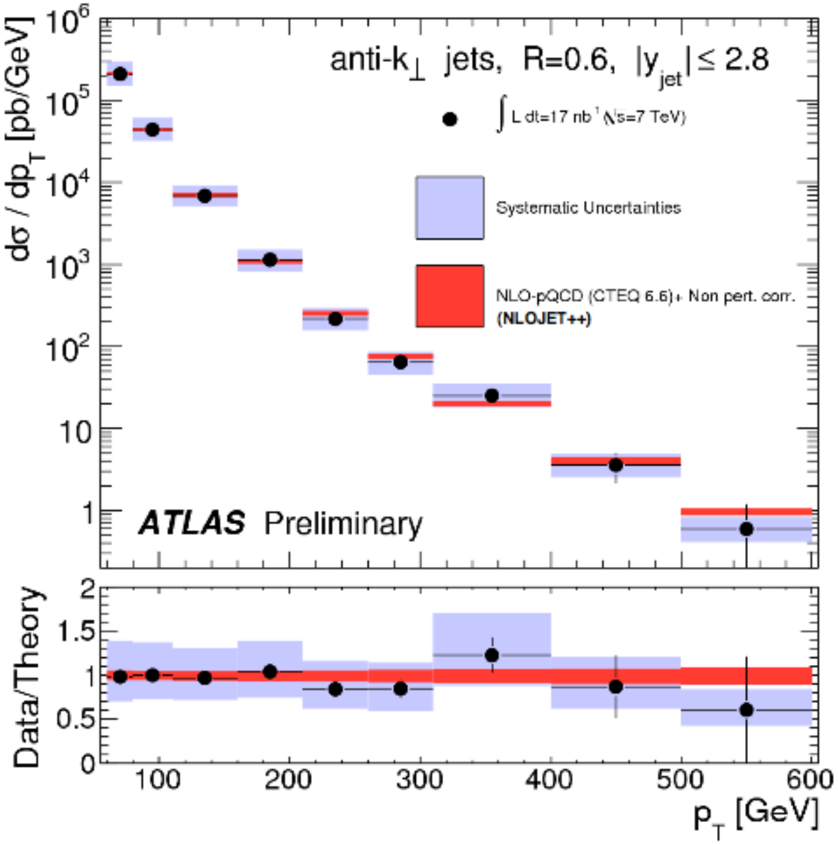


Can be used to test models for New Physics: eg excited quarks.
LHC has already best world limits

Inclusive Jet Cross Sections

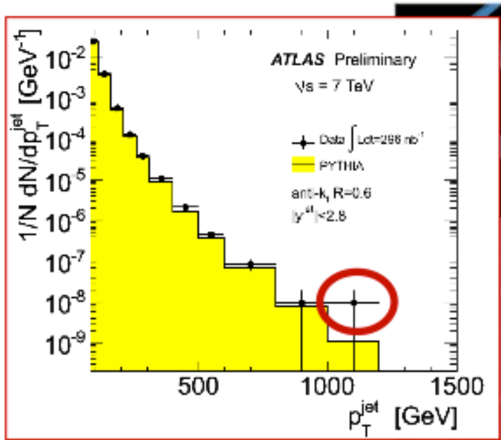
❑ Inclusive jet cross-section (~Tevatron x 100)

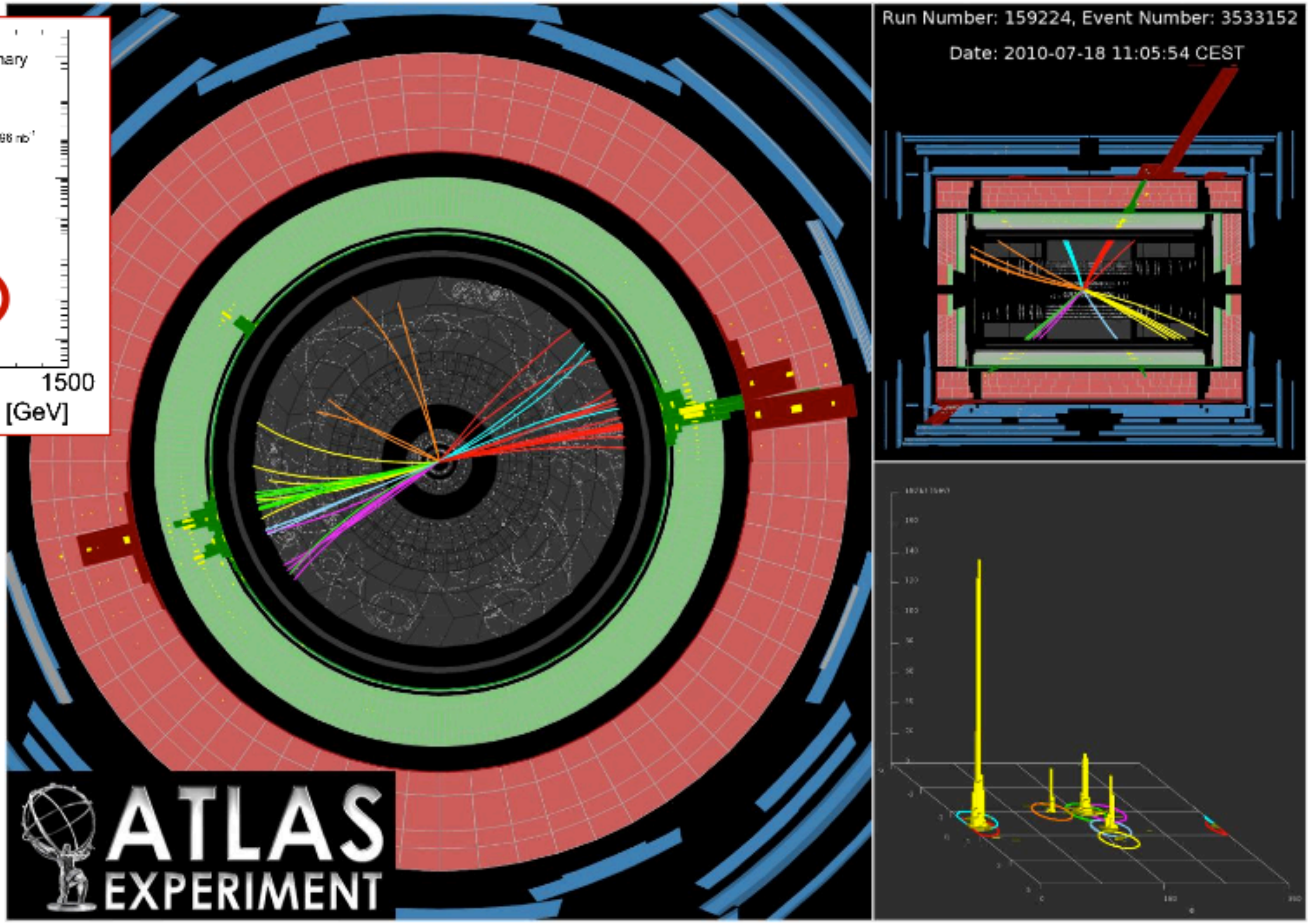
- Restricted to 17 nb^{-1} (no pile-up contamination) and p_T^{jet}>60 GeV and $|y^{jet}|$<2.8
- Correct measured jets to particle level using parton-shower MC (Pythia, Herwig):
  ➔ Compare to NLO pQCD prediction corrected from hadronization and underlying event
- Theoritical uncertainties on σ (PDF, α_S, scale): ■
  ✓ **10%** over measurable p_T range y~0
  ✓ Increase to **30-40%** at |y|~2.8
- Experimental uncertainties on σ: □
  ✓ **30-40%** dominated by Jet Energy Scale
  ✓ 11% from Luminosity not included



Good agreement data-MC over 5 orders of magnitude

Di-jet events





p_T (j_1)= 1.12 TeV

p_T (j_2)= 480 GeV

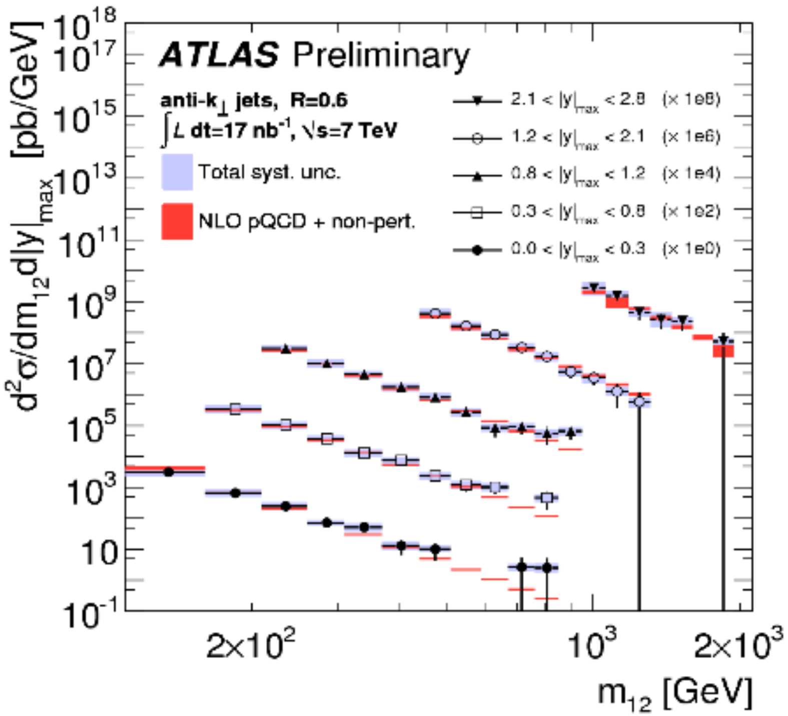
p_T (j_3)= 155 GeV

p_T (j_4)= 95 GeV

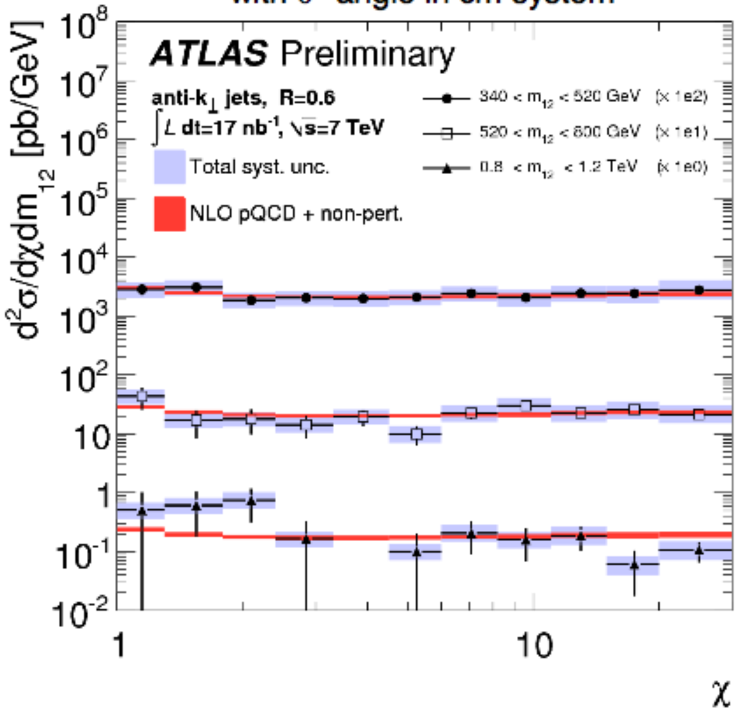
Di-jet Cross Sections

❑ Dijet cross-section

- Main jet : p_T>60 GeV. Sub-leading jet: p_T>30 GeV



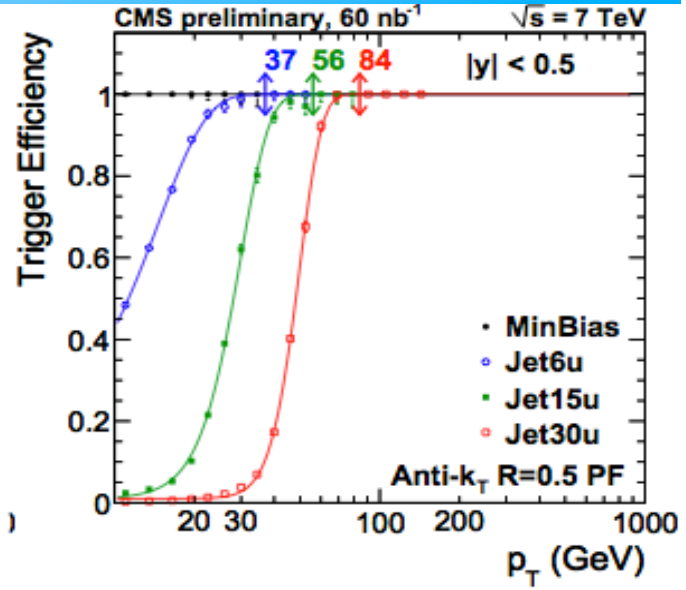
χ= exp(|y1-y2|) ~ (1+cos θ*)/(1-cos θ*)
with θ* angle in cm system

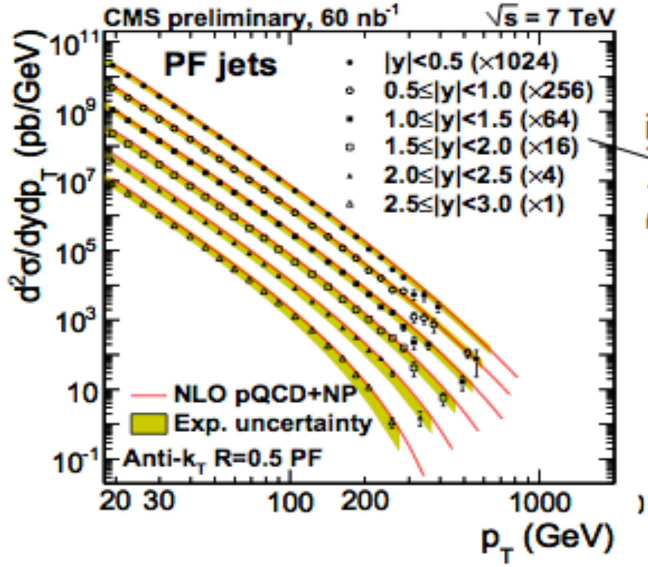


Good agreement data-MC in all rapidity and mass regions

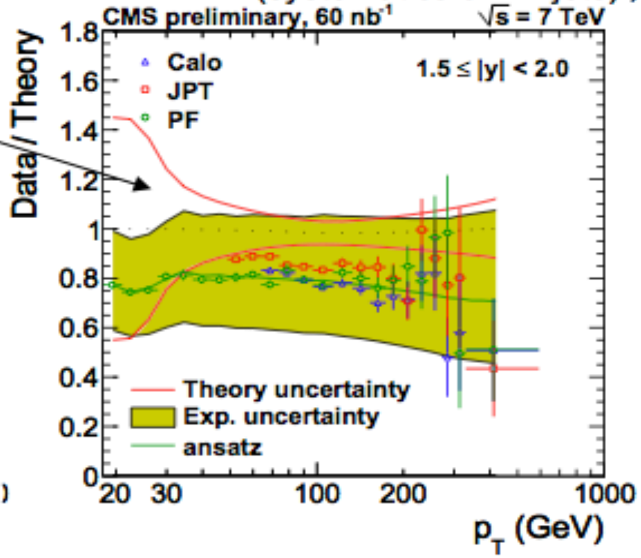
Jet Cross Sections

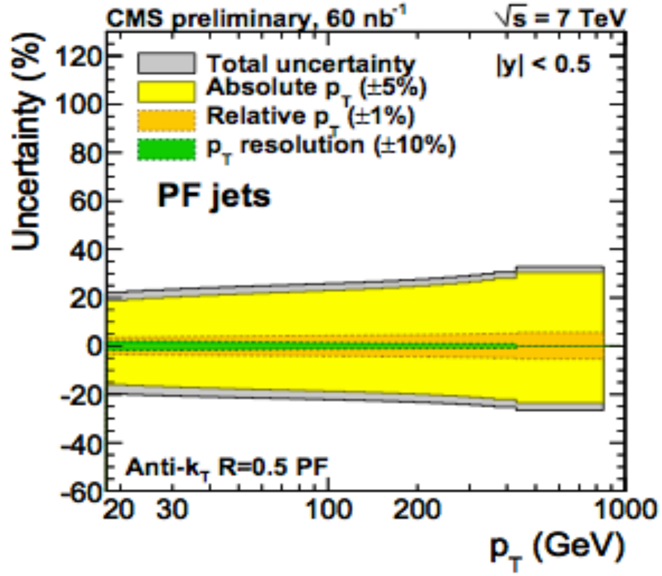
- Triggers: min.bias + single jet > 6,15,30 GeV
  combined exclusively at ~99% turn-on
- Resolution unfolding → hadron level
- Agreement with NLO using CTEQ6.6
  non-perturb. correction from Pythia-Herwig average
  PDF uncertainty comparing different PDF sets
  μ_f, μ_r uncertainty: pT/2 → 2 pT





(systematics of PF jets)



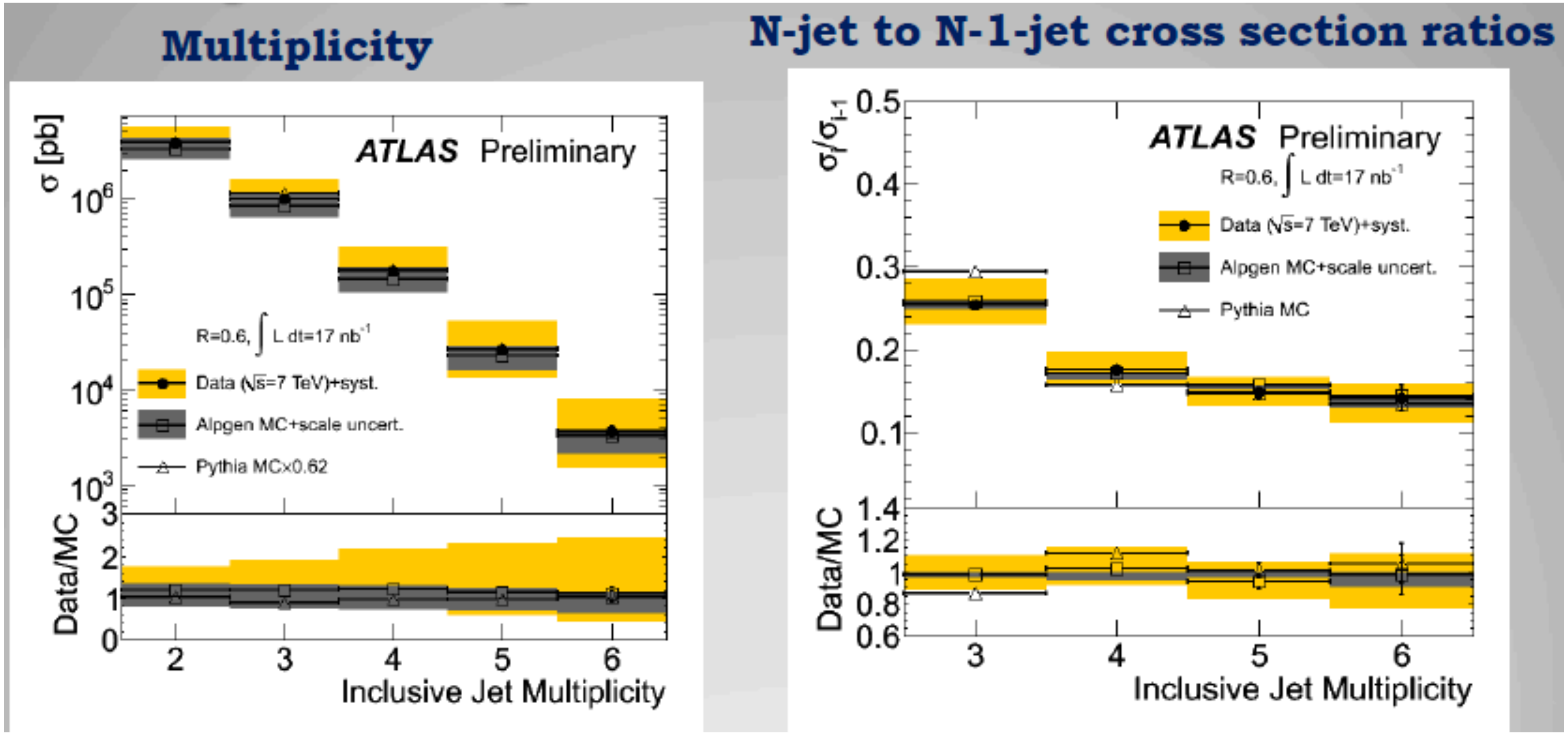


- Few % difference in JES between algos → 10% on the xsec

Anti-K_T jet algorithm with R=0.5

Jet Multiplicity

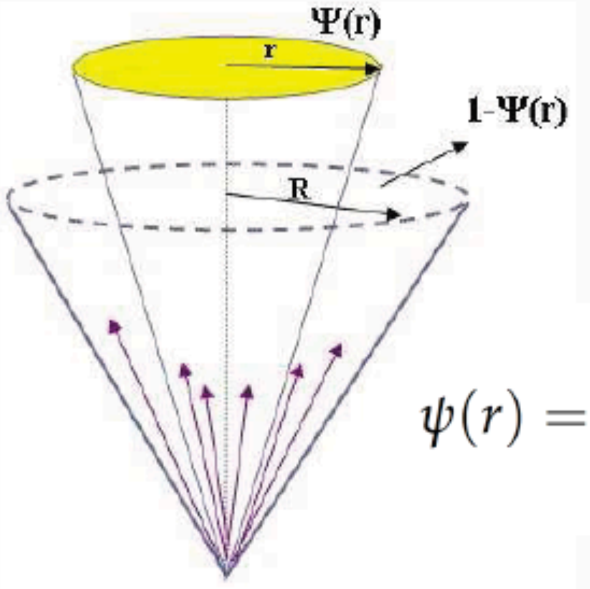
How many jets do we have per event?



Data are more or less as expected, but still large experimental errors…

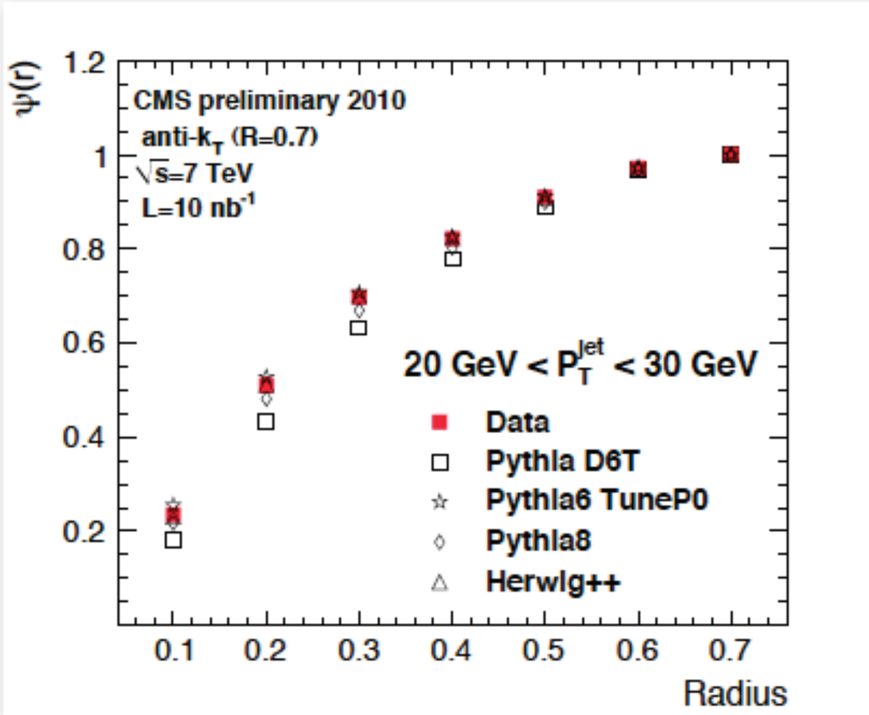
Jet Shapes/Structure

- Jet transverse shapes probe transition between hard pQCD and soft gluon radiation
- Phenomenological models motivated by QCD and tuned at e^+e^- colliders
- At hadron colliders underlying event is an important ingredient; models tuned at 2 TeV, but extrapolation to LHC uncertain
- Jet data dominated by gluon jets

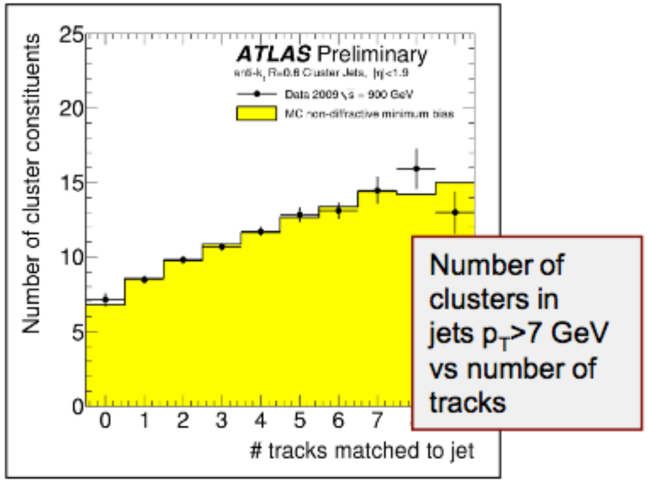


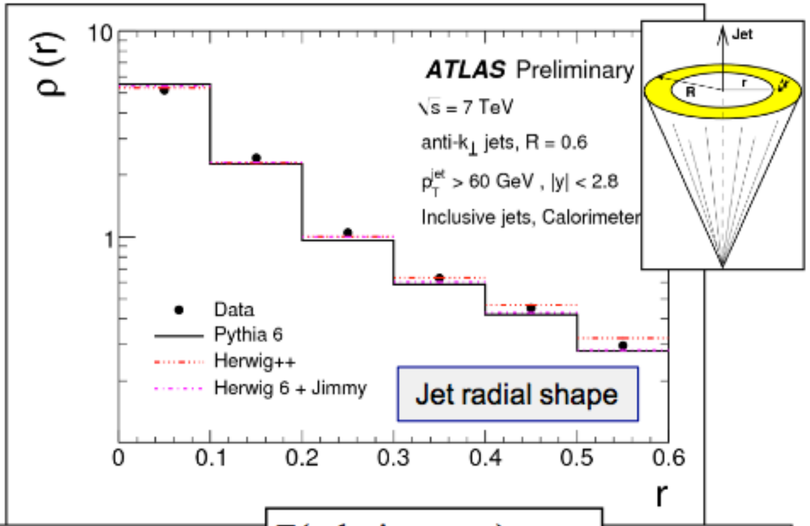
$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$

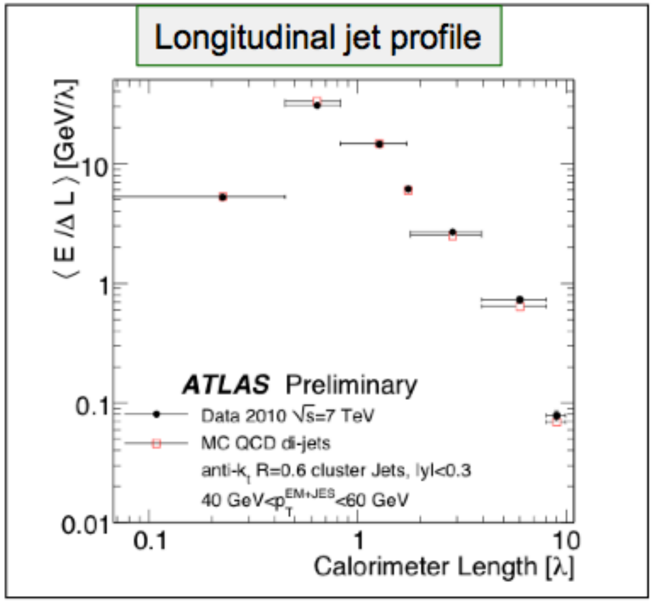
$$\langle \delta\phi^2 \rangle = \frac{\sum_{i\in \text{jet}} (\phi_i - \phi_C)^2 \cdot p_{T,i}}{\sum_{i\in \text{jet}} p_{T,i}}$$

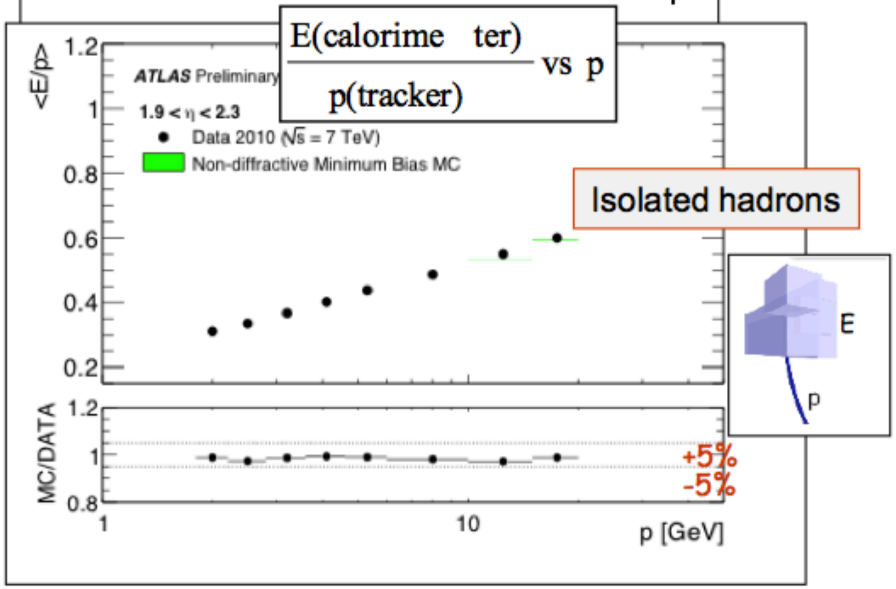


Jet Shapes/Structure





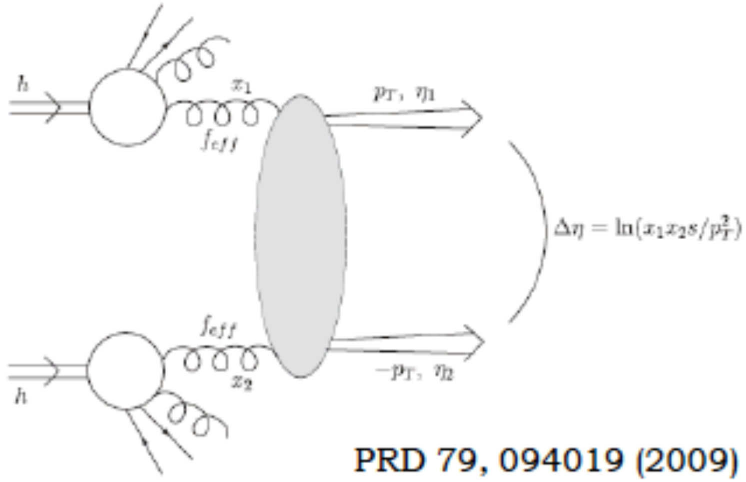




More Di-jet Studies

Dijet Production with a Jet Veto

- Measures the fraction of dijet events in that do not contain an additional jet in the rapidity region bounded by the dijet system.
- Requirement: Two good anti-kt jets (R=0.6) with average $p_T > 60$ GeV, Each with $p_T > 30$ GeV, within rapidity $|y| < 4.5$ and rapidity separation $\Delta y > 2$. Forward calorimeter is used in this measurement.

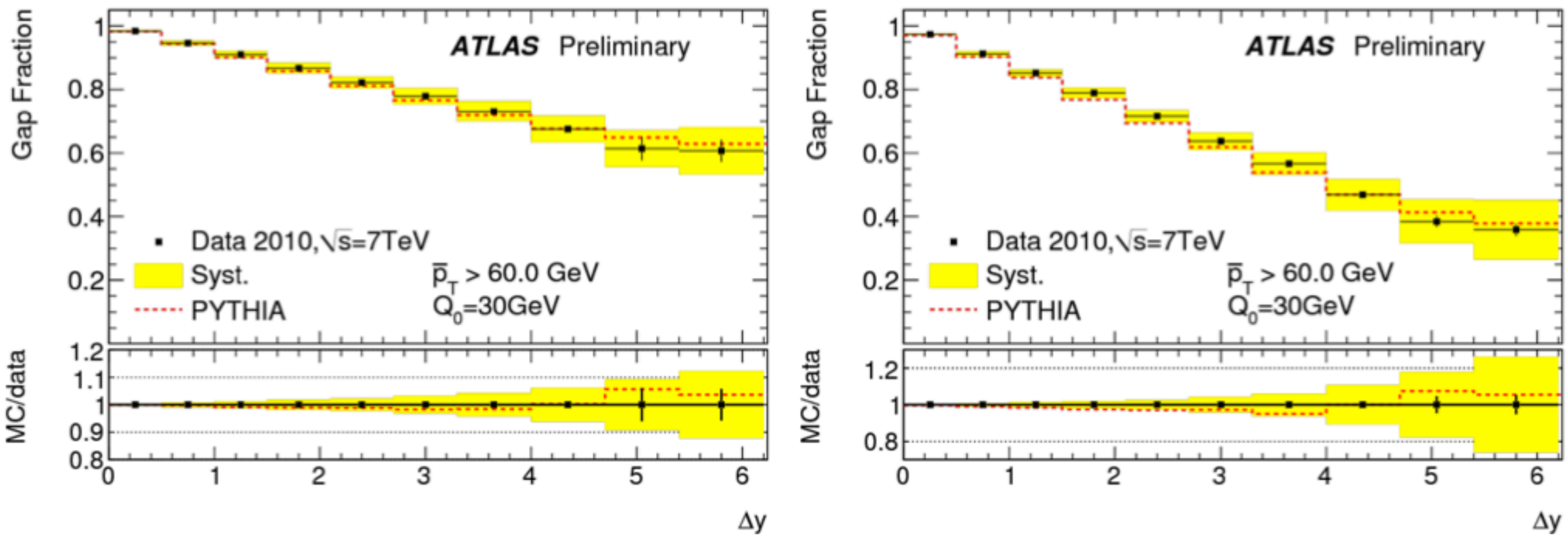


PRD 79, 094019 (2009)

Minijets with a jet veto

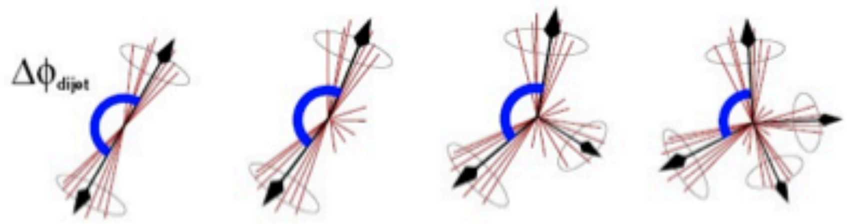
Minijet Veto

- Select dijet events; jet p_T > 30 GeV, average jet pT > 60 GeV. Two selections:
  - A:boundary jets are the highest pT jets
  - B:boundary jets are the most forward/backward satisfying the above
- Veto on any extra jets between the boundary jets with p_T>30 GeV

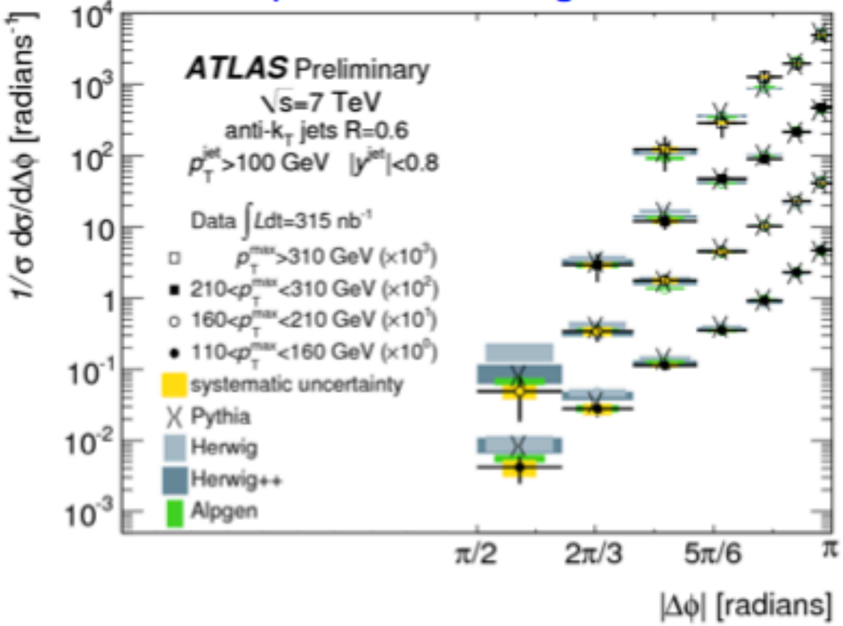


Azimuthal Decorrelations

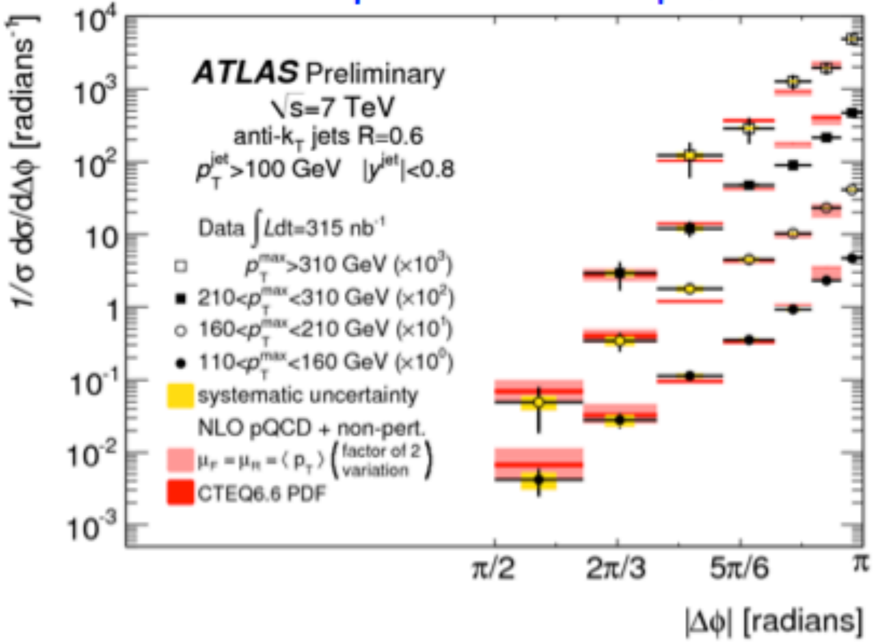
Angle between leading jets sensitive to higher-order QCD radiation without explicit 3rd jet reconstruction



Comparison to MC generators



Comparison to NLO pQCD



Good agreement for both Alpgen and NLO pQCD

Azimuthal Decorrelations

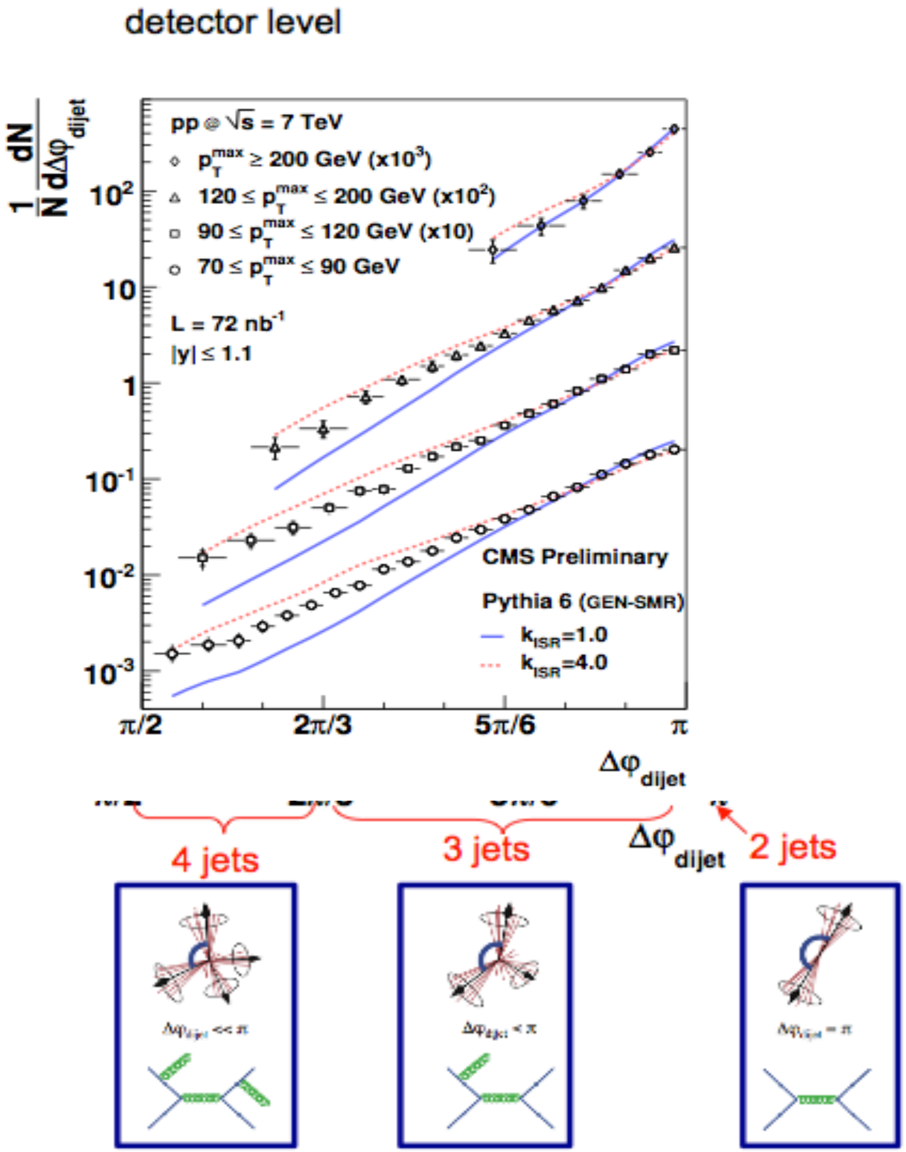
Dijet Azimuthal Decorrelations

- $\Delta\varphi_{dijet} = |\varphi_{jet1} - \varphi_{jet2}|$

  sensitive to higher order QCD radiation effects

- Madgraph underestimates low $\Delta\phi$ (multi-jet) region

- High sensitivity to ISR, much less to FSR

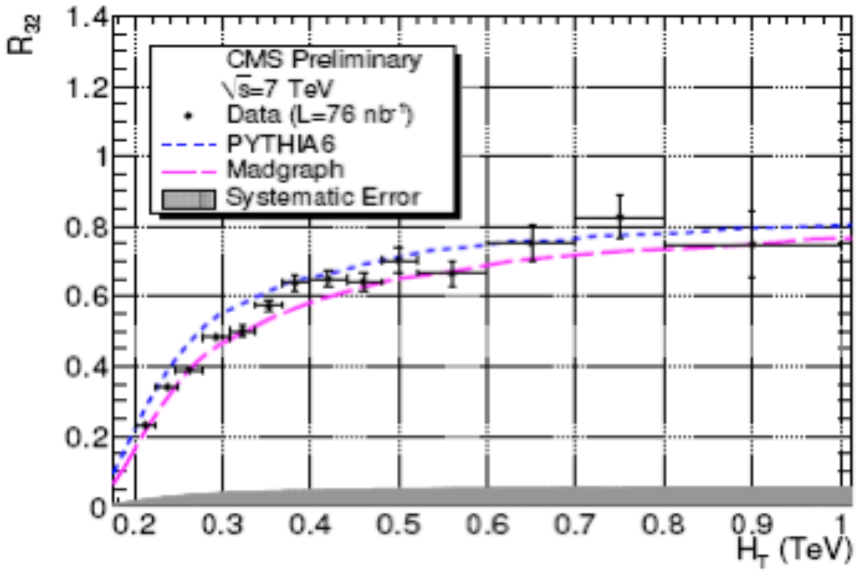


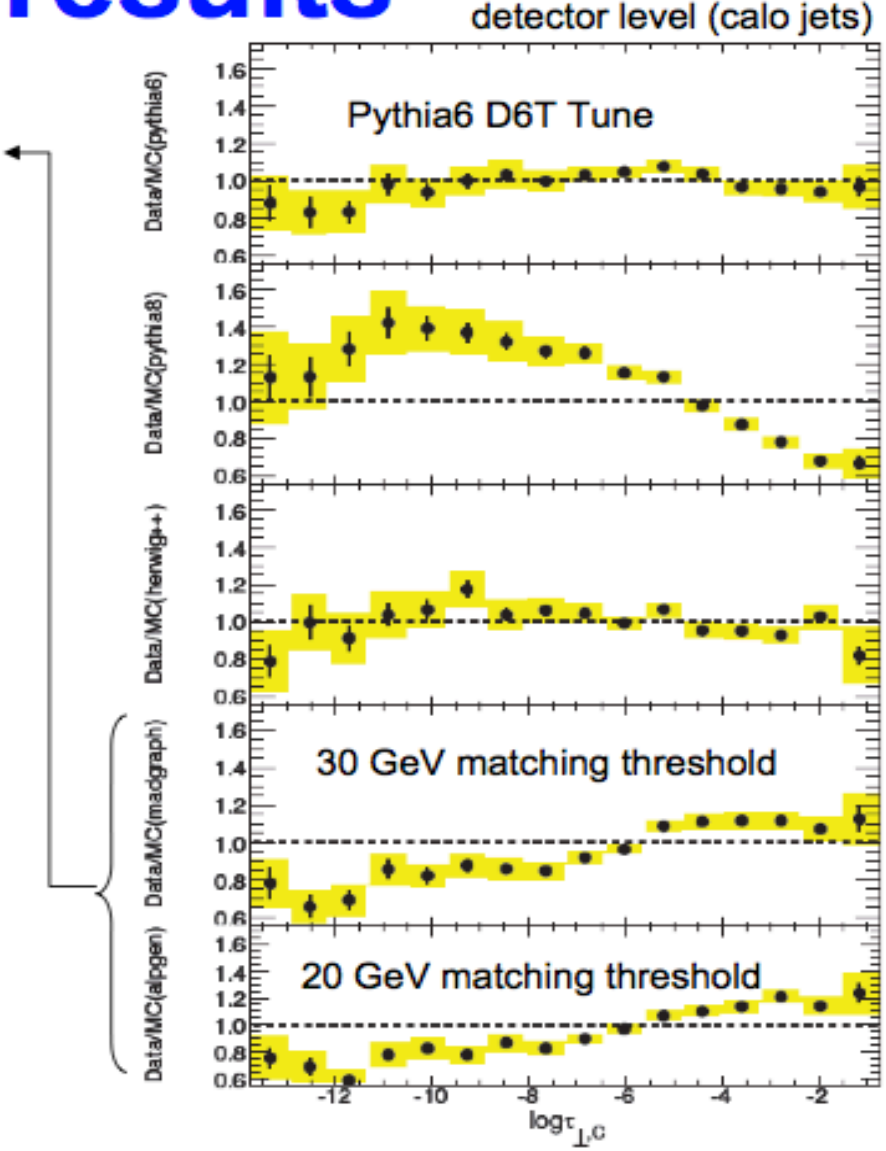
3 to 2 jet ratios

2j → 3j results

- **Hadronic event shape:**
  ME MC underestimate 3jets region
  - same bahviour for higher $p_T^{leading}$
  - improves for higher jet multiplicity

- **3j / 2j VS H_T:**
  not conclusive yet



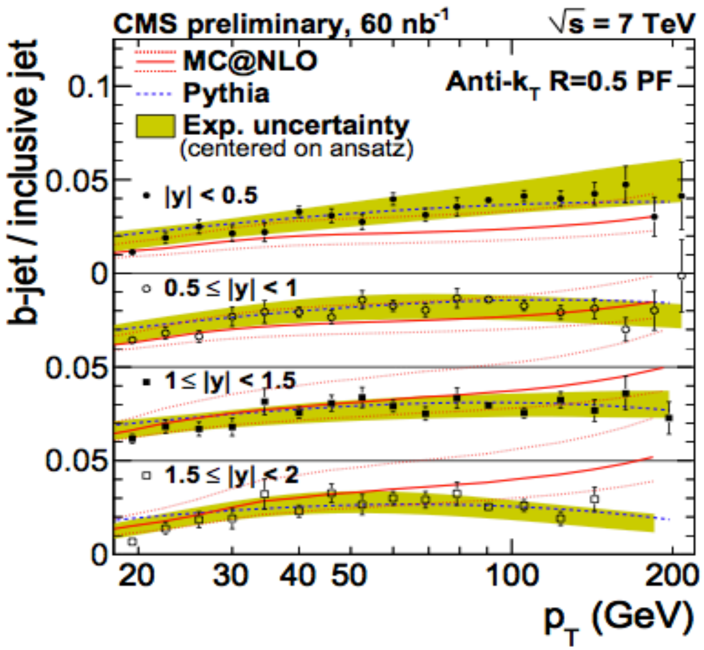


b-jet Cross Sections

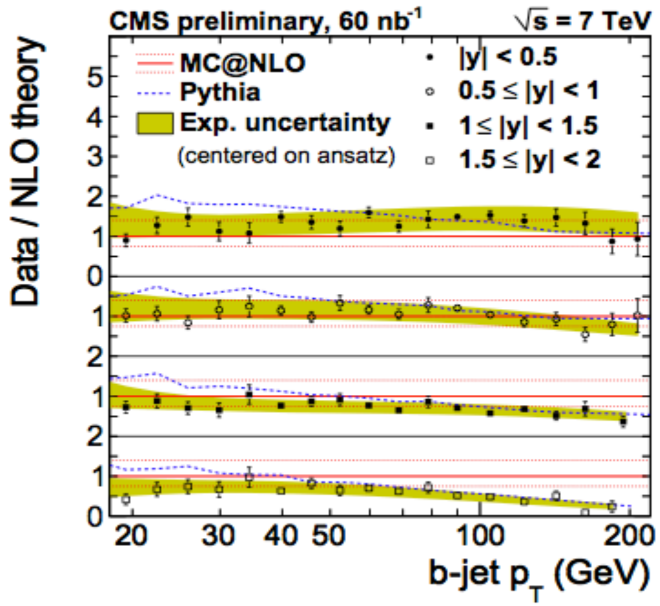
Special jets: Jets containing a b quark

b-jet dσ/dp$_T$

- ❑ Ratio to inclusive → partial syst cancellation
  - b-tag efficiency ~ 20%
  - JES b-jets VS LF jets ~1%



❑ b-jet xsec



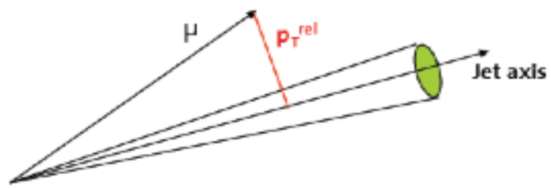
❑ Comparison to theory:

- b-jets from MC@NLO (CTEQ5M)
- inclusive jets from NLO (CTEQ6.6M)

→ reasonable agreement with NLO
but different p$_T$, η shapes

b-Production Cross Sections

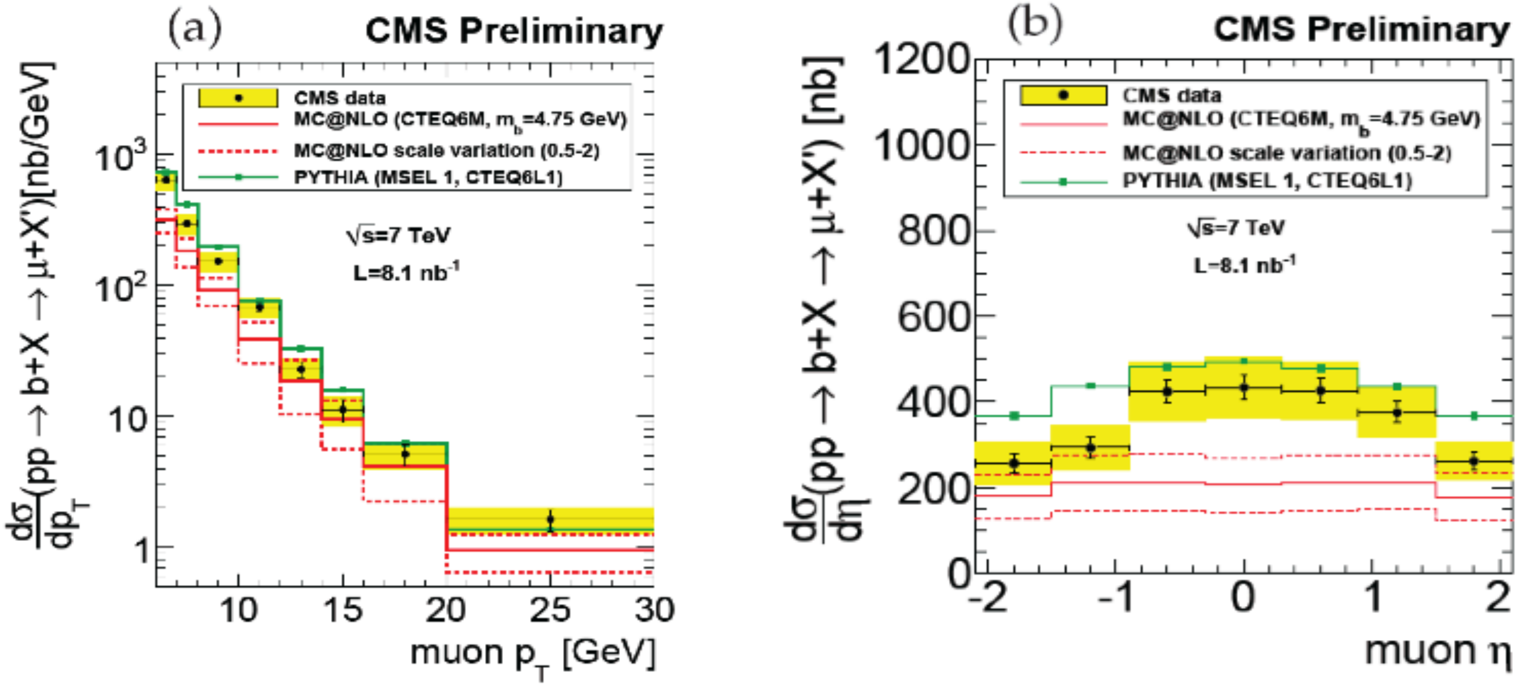
$b \rightarrow \mu + X$



- Measurement from p^T_{rel} distribution fit with b and cudsg templates ($p_T^\mu > 6$ GeV, $|\eta^\mu| < 2.1$)

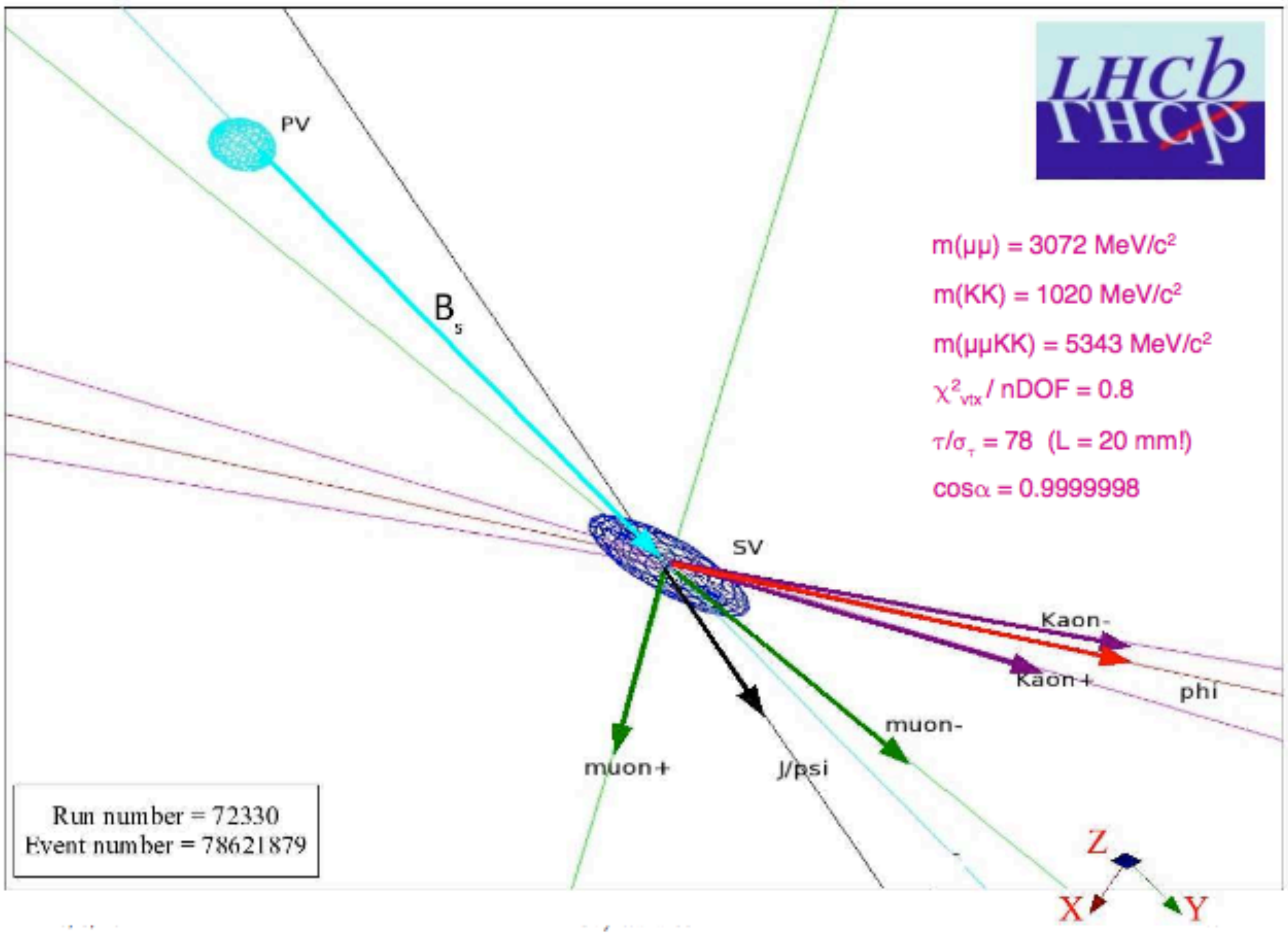
$$\sigma = (1.48 \pm 0.04_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.16_{\text{lumi}})\ \mu\text{b}.$$

$$\sigma_{\text{MC@NLO}} = [0.84^{+0.36}_{-0.19}(\text{scale}) \pm 0.08(m_b) \pm 0.04(\text{pdf})]\ \mu\text{b}.$$



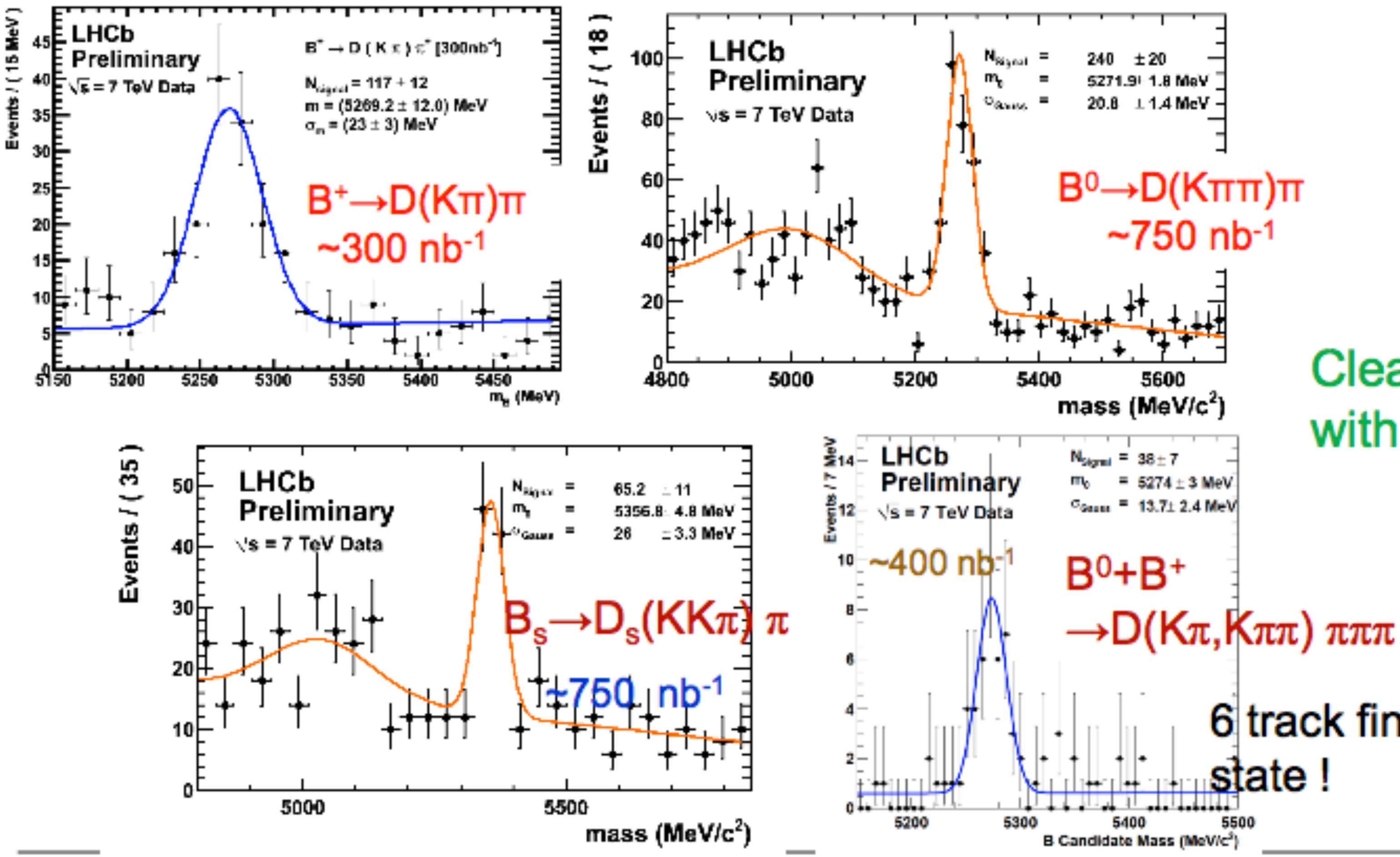
- Same results as inclusive b-jets: **NLO underestimates xsec at low η and low p_T**

b-tagging in LHCb



B Meson Measurements

On the road for tree level [redacted] measurement: many channels and strategies will give a complete picture. Trigger and tracking performing well.

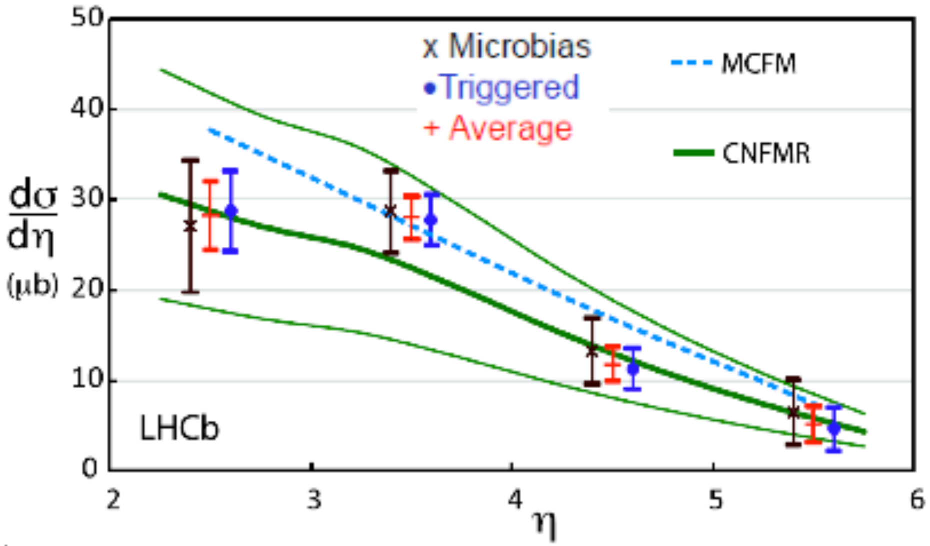


Clean samples with high S/B

6 track final state !

b quark production Cross Sections

Cross section in four η bins, open trigger (~3 nb^{-1}) and muon trigger sample (~12 nb^{-1}) submitted to PLB (arXiv:1009.2731)



Shapes and scales agree well with expectation. Validates QCD predictions at LHC energies

(pp→H_bX) = 75.3 5.4 13.0 μb for 2<η<6, any p_T, √s=7 TeV

Extrapolating to 4   with PYTHIA 6.4: **(pp→b$\bar{b}$X) = 284   20   49 μb**

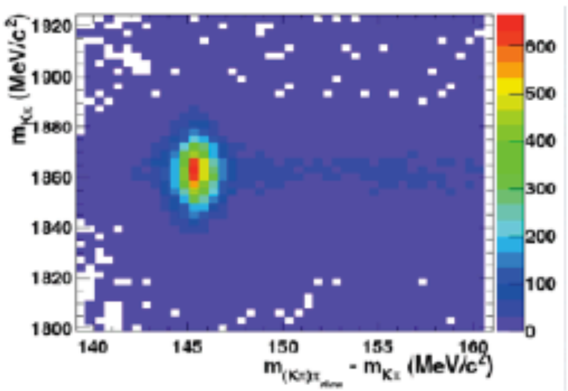
Averaging with prel. result from b→J/ **(pp→b$\bar{b}$X) = 292 ± 15 ± 43 b**

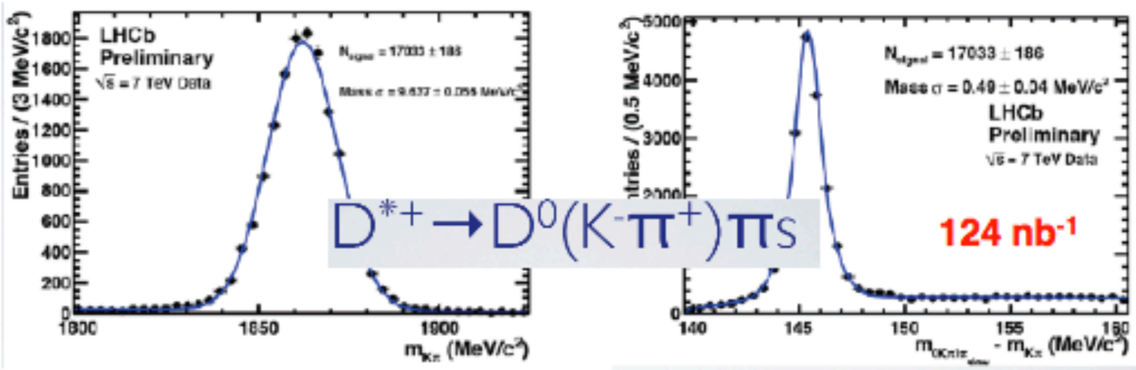
Theory: MCFM 332 μb, NFMR 254 μb

→ b rate (at least) as high as assumed in LHCb sensitivity studies.

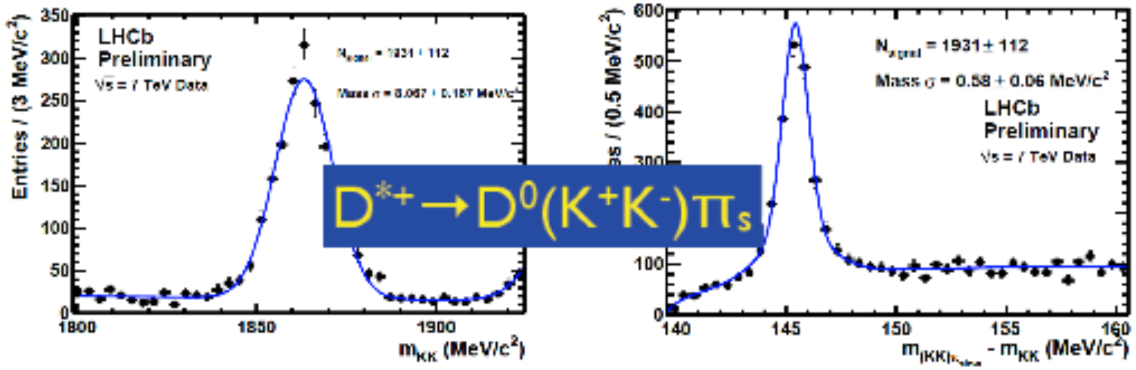
Charm Measurements

- Collecting large samples of $D^* \rightarrow D^0$ tagged events in $D^0 \rightarrow K$, KK,





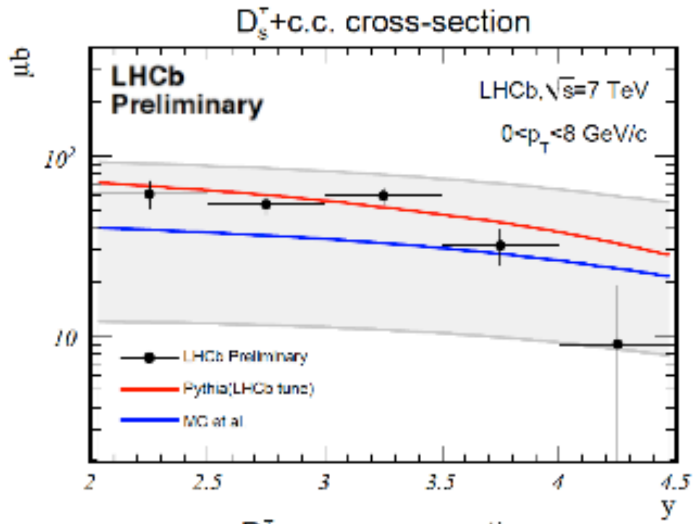
- Should surpass
B-factory yield in 2010.

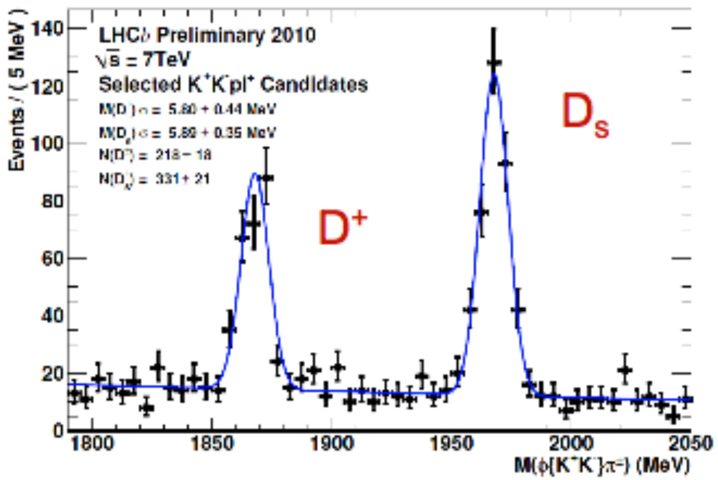


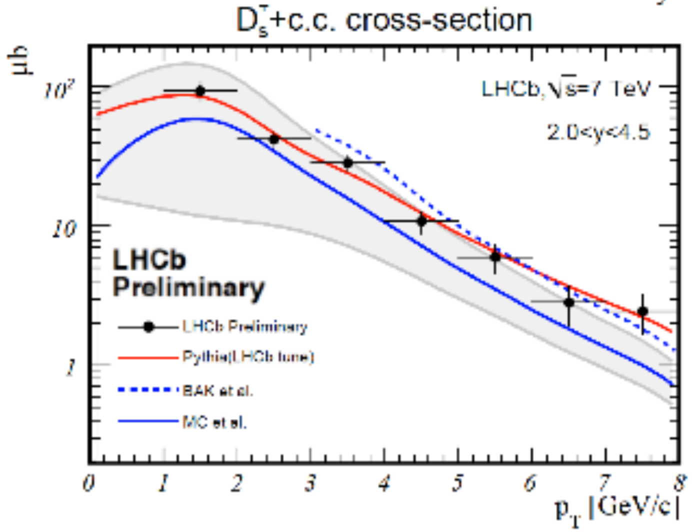
- Immediate opportunity to probe for finite CPV in D^0 mixing at new sensitivities. A crucial test of the SM vs New Physics.

Charm Measurements

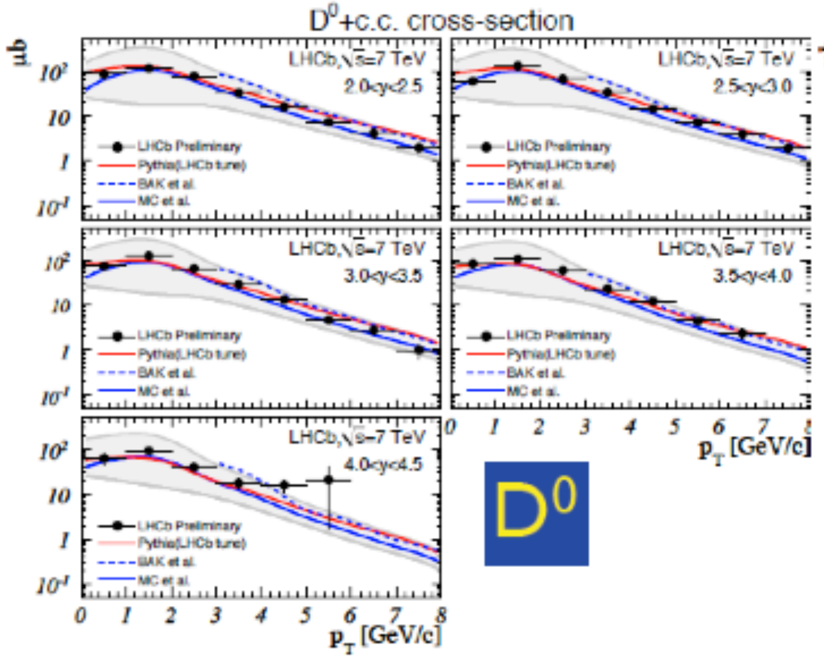
- First measurement at $\sqrt{s}$=7 TeV.
- Measure cross section vs y, p_T in ~2 nb^{-1}, with open trigger.
- Impact parameter distribution used to separate prompt $D^{0,+}$,D^+, D_s from secondary.
- Good agreement with expectations!

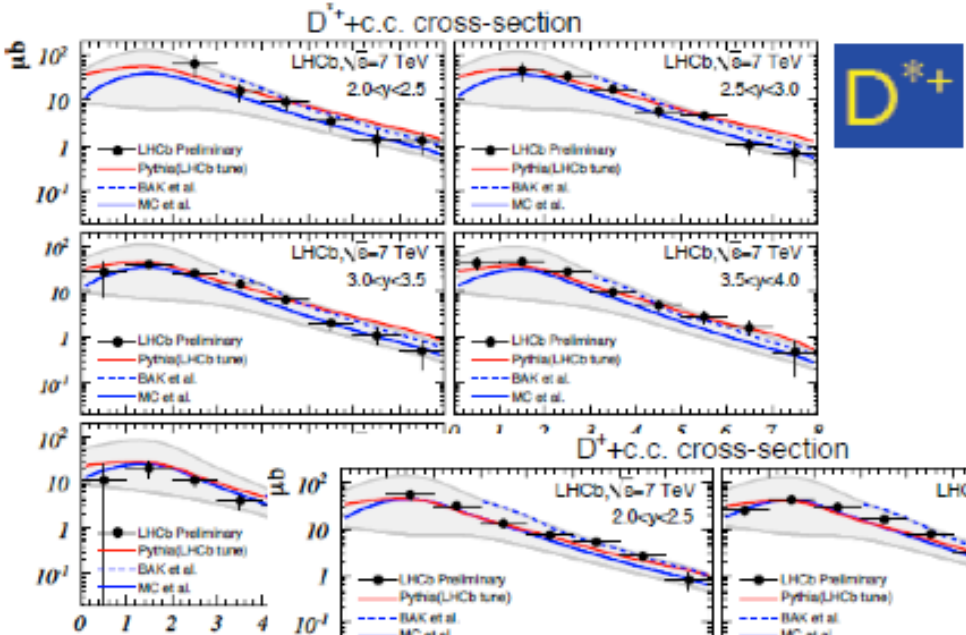


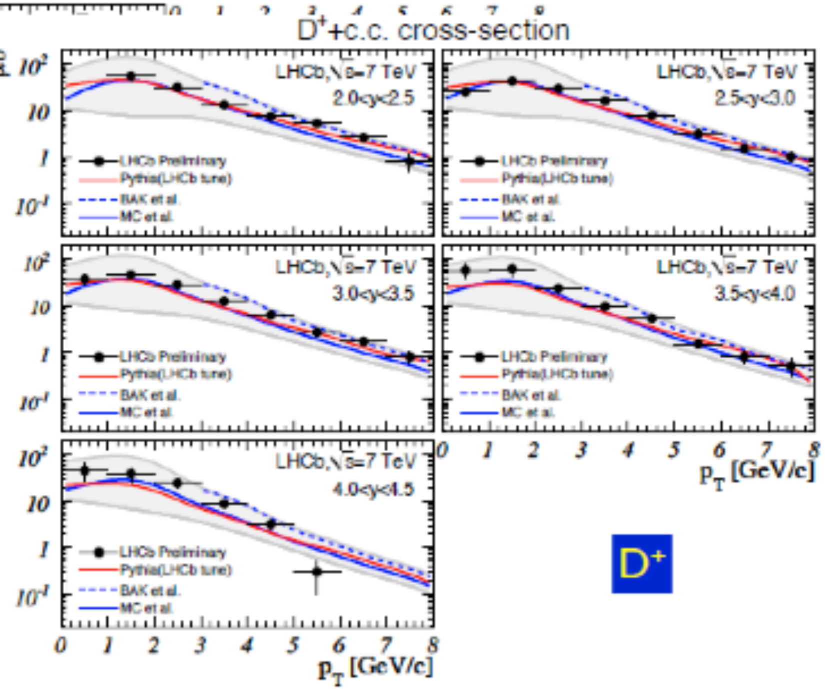




Charm Measurements







Extrapolating to all p_T and 4 can also confirm the expectation on ratio at $\sqrt{s}$=7TeV

$(pp \rightarrow c\bar{c}X) \approx 20 \times (pp \rightarrow b\bar{b}X)$

→ Good news for LHCb charm program

Experiments at the LHC (part III)

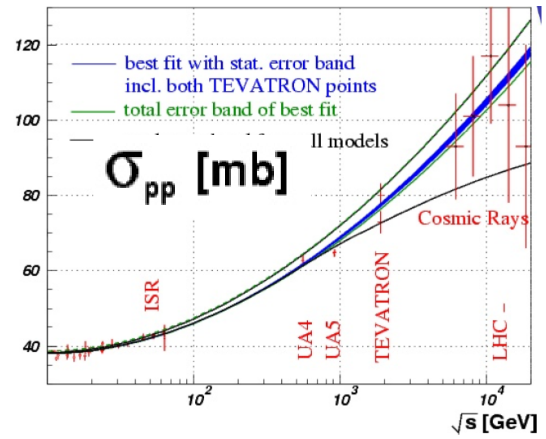
TOTEM and LHCf

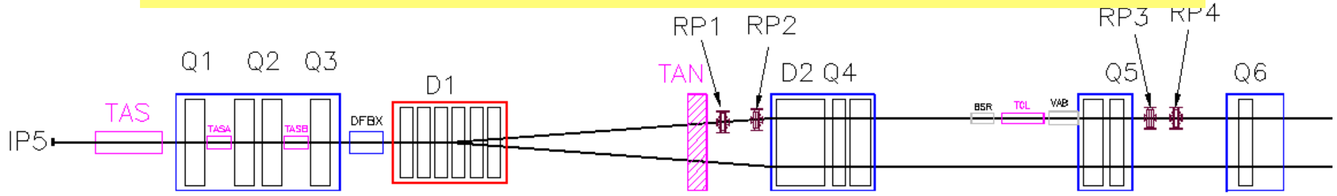
Experiments at the LHC for special QCD measurements

A Few Smaller Experiments: TOTEM & LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions (200 m from IP)
Common runs with CMS planned

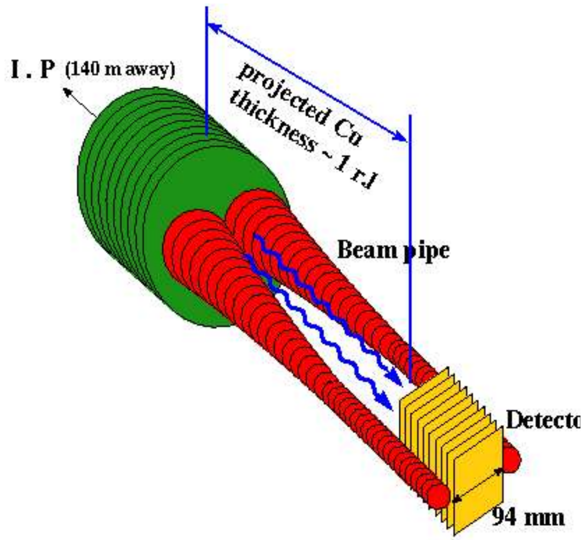
TOTal and Elastic cross section Measurement

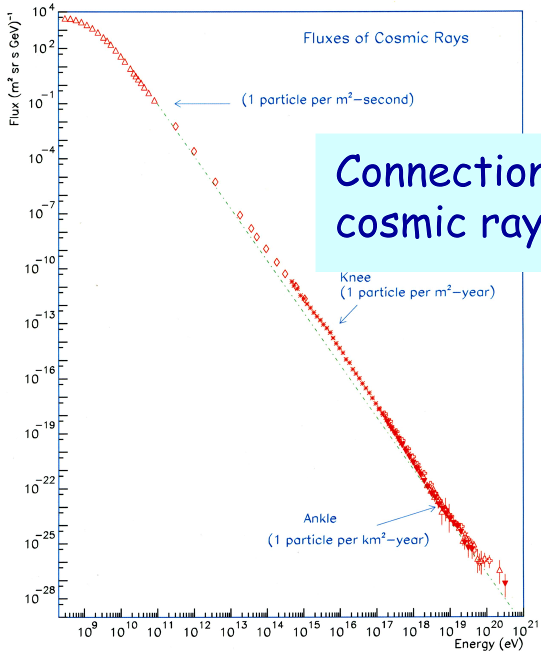




LHCf: measurement of photons and neutral pions in the very forward region of LHC

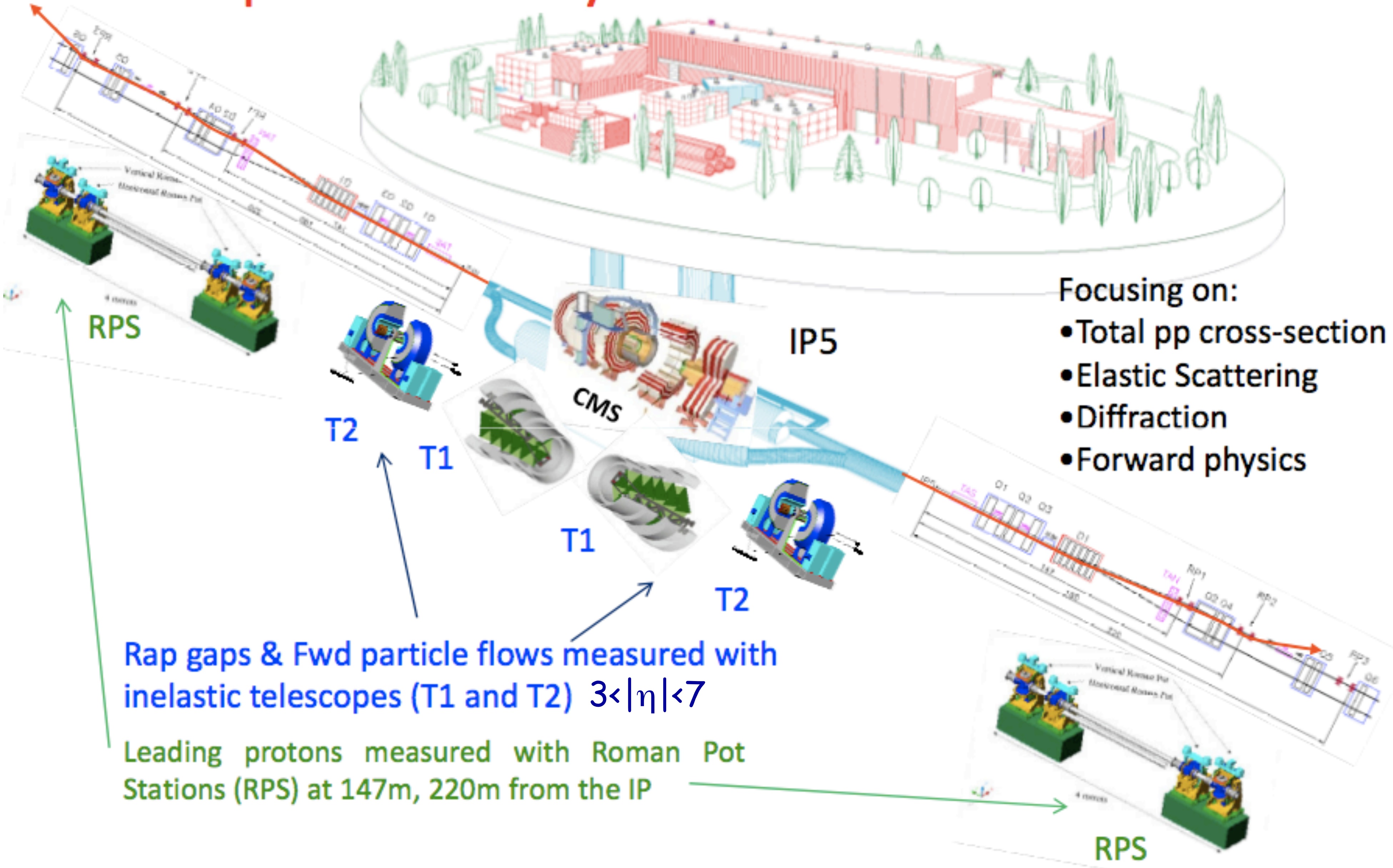
Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)





Connection with cosmic rays

Experimental layout of the TOTEM Detector



Focusing on:

- Total pp cross-section
- Elastic Scattering
- Diffraction
- Forward physics

Rap gaps & Fwd particle flows measured with inelastic telescopes (T1 and T2) $3<|\eta|<7$

Leading protons measured with Roman Pot Stations (RPS) at 147m, 220m from the IP

Experimental Aspects of Elastic Scattering

pp→pp: Scattered proton detected in Roman Pot telescope

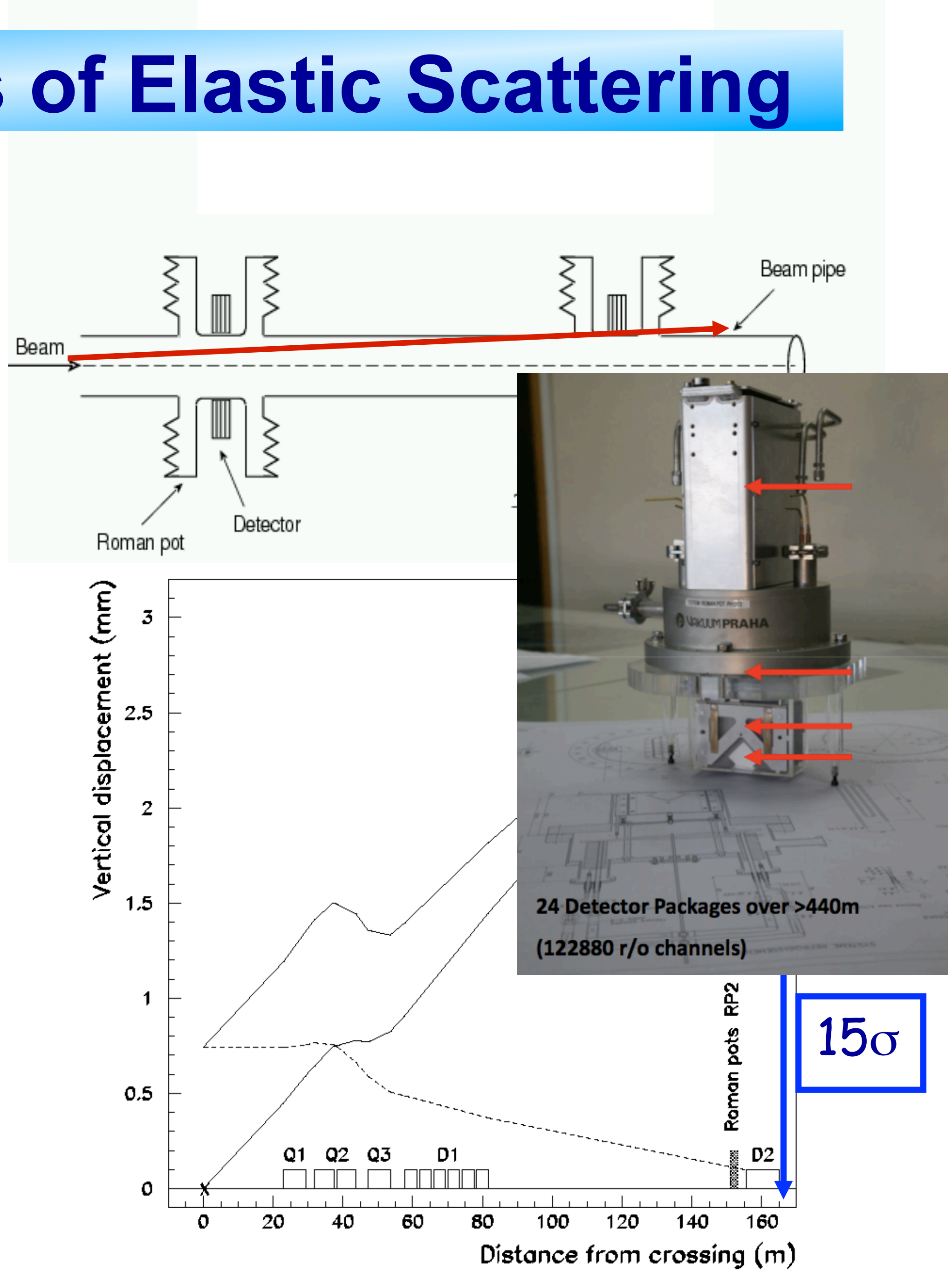
Measure x,y position in the roman pot detectors

Position the Pots at locations of "parallel to point" focussing

Use special optics with a large value of the accelerator β function (weak focusing, here β^* = 1100 m and beam angular spread ~ 0.67μrad)

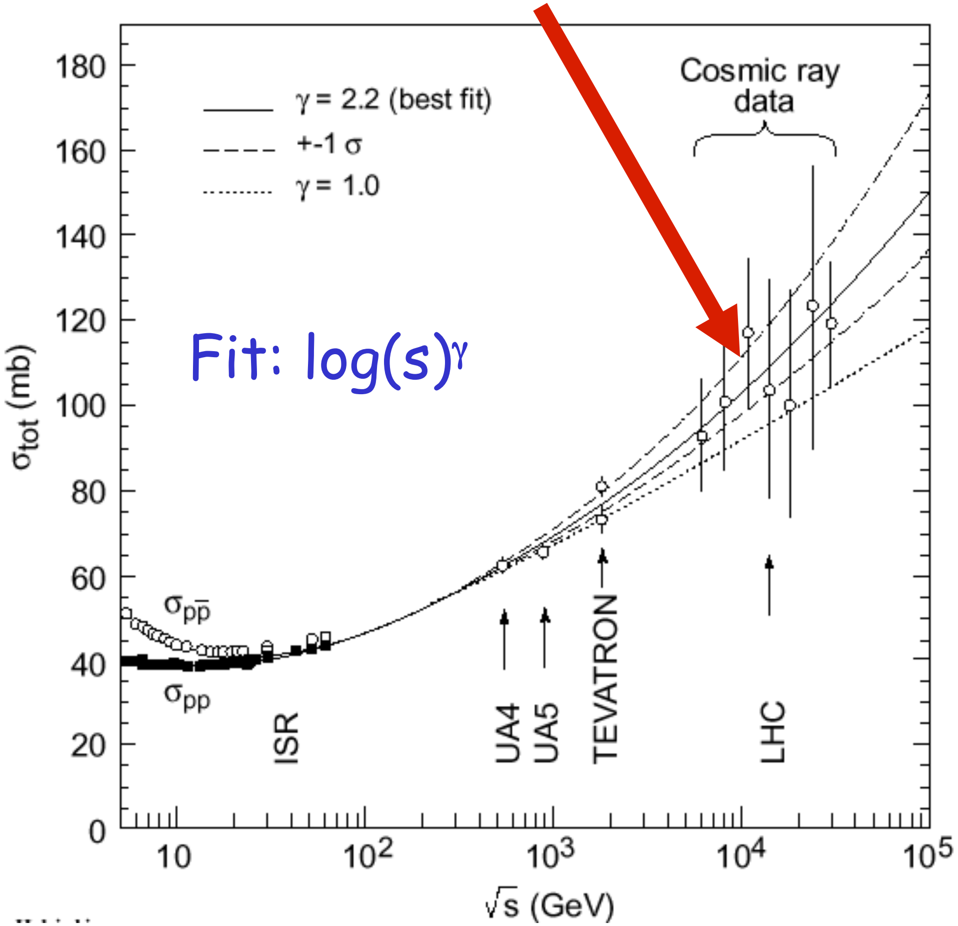
Roman Pot can be lowered to "15 sigma" from beam (ie 15 times the beam size)

Resolution: $\Delta t \approx 0.7 \times 10^{-2} \sqrt{|\, t\,|}.$

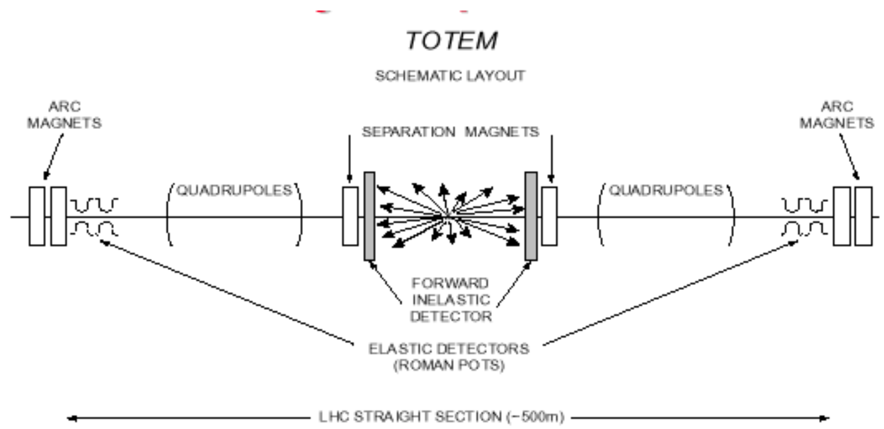


TOTEM: Total cross sections

Aim: ~1-2 mb precision



$\gamma = 2 \rightarrow \sigma_{tot}$ @LHC = 110 mb
$\gamma = 1 \rightarrow \sigma_{tot}$ @LHC = 95 mb



The measurement of σ_{tot}
Historical: CERN tradition (PS-ISR-SPS)
Current model predictions 95-130 mb at the LHC
Some extreme models give higher values
(like 200 mb!!)

How to measure σ_{tot} ?
(naively..) Well, just count the events…

TOTEM: Total and Elastic Cross Sections

Here is a catch! σ_{tot} = # events/ luminosity
How to measure luminosity? Precision? (5-10% estimated)

Get σ_{tot} from Luminosity independent method

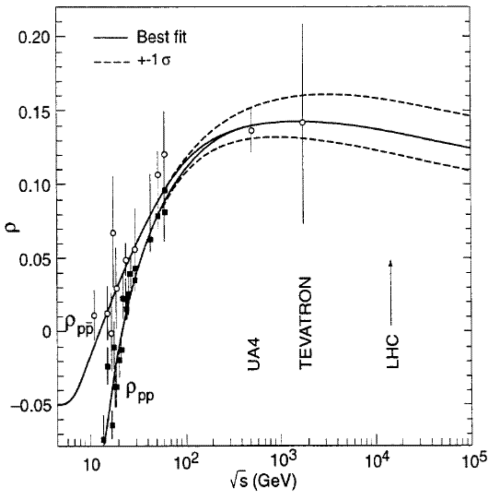
(i) $$L\sigma_{tot}^2 = \frac{16}{1+\rho^2} \times \left.\frac{dN}{dt}\right|_{t=0}$$ "OPTICAL THEOREM"

(ii) $$L\sigma_{tot} = N_{elastic} + N_{inelastic}$$

Use elastic scattering ($t \rightarrow 0$) and total inelastic rate

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el} + N_{inel}}$$

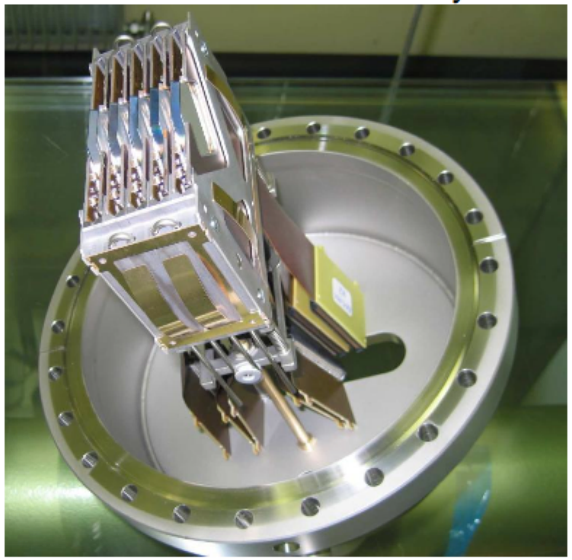
Here ρ = ratio of the real to imaginary part of the forward scattering amplitude
Measurement difficult at LHC
But impact on precision small



Aim of TOTEM try to measure σ_{tot} with ~1-2% accuracy
(~5% at startup with preliminary optics)
σ_{tot} can then be used for an absolute calibration of the luminosity

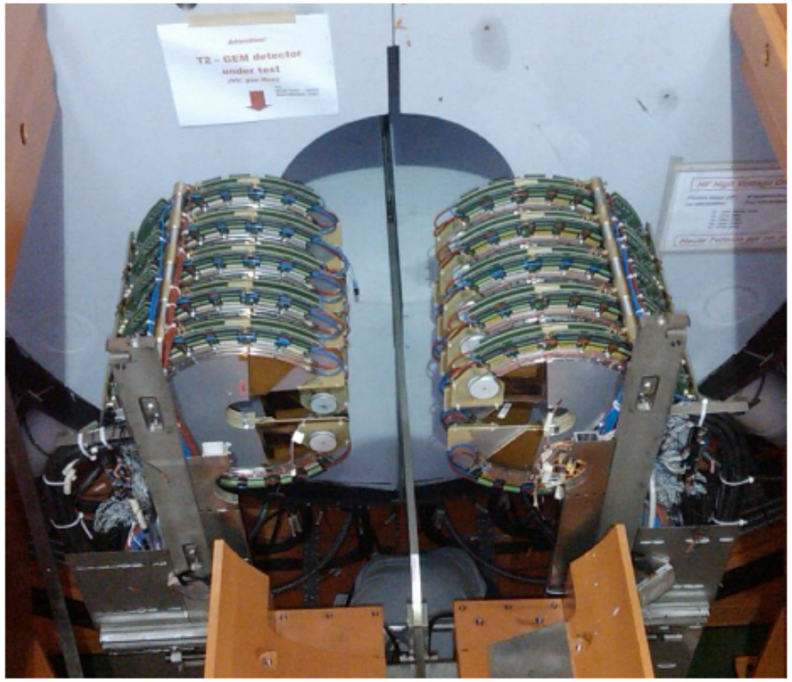
TOTEM in Operation

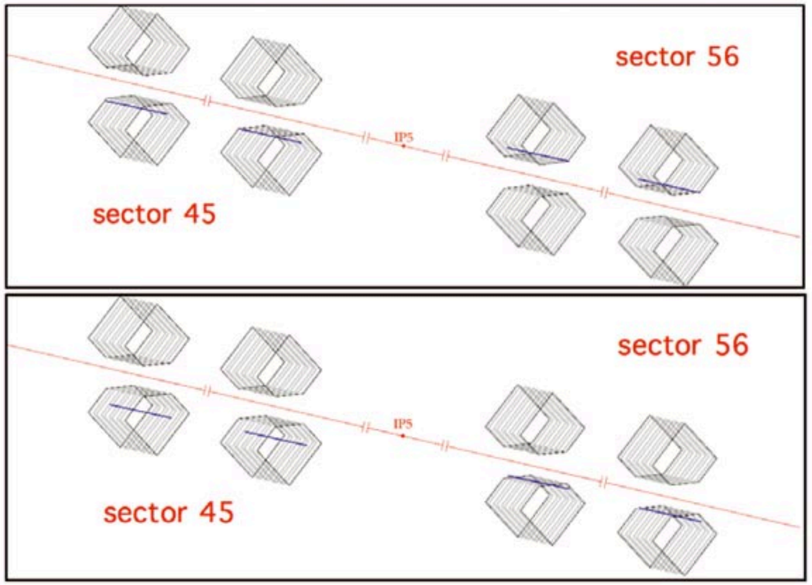
Roman Pot detector assembly



Detectors approach the beam by ~ 20σ

T2 Detectors





First elastic and DPM collisions

TOTEM Operation

RP alignment was performed at 450 GeV

→ needs to be corrected to beam width at 3.5 TeV

Careful approach staged over 3 normal fills in STABLE_BEAMS:

30 σ → 25 σ → 20 σ

For closer approach (15 σ) a new alignment exercise at 3.5 TeV will be needed.

Objectives with standard runs:

- RP triggers at 30 σ – 15 σ
  - → large |t| elastic scattering
  - → diffraction
- Optimization of T2 (noise, efficiency), study of beam-gas background

Request special TOTEM runs with ~10^{10} p / bunch

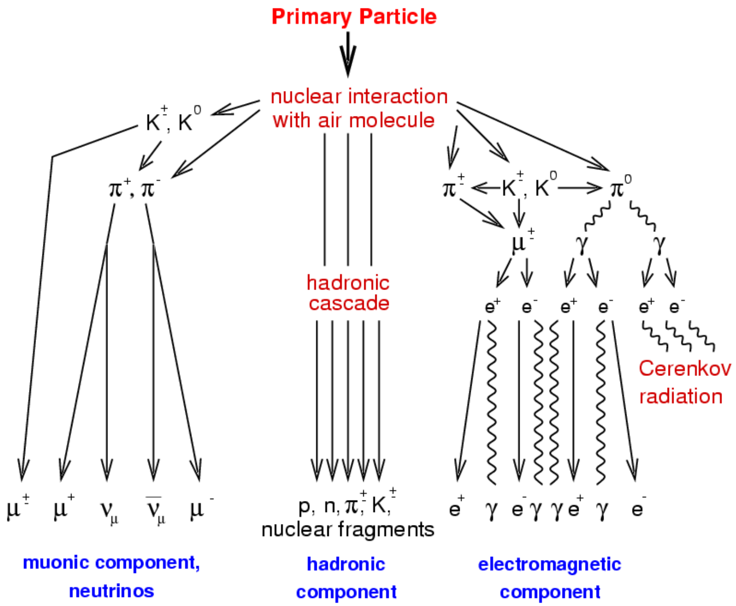
→ multiplicity distributions with small pileup (difficult to resolve in the very forward region)

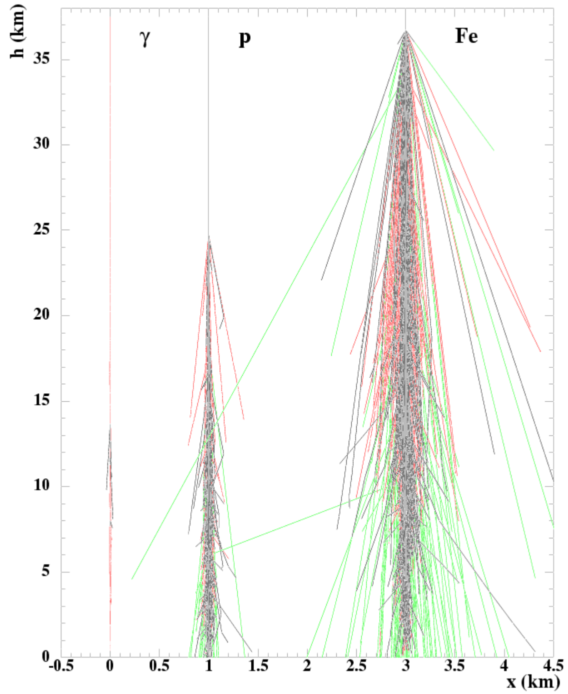
10^{11} p/b: 1.7 events in T2 / bx

10^{10} p/b: 0.017 events in T2 / bx

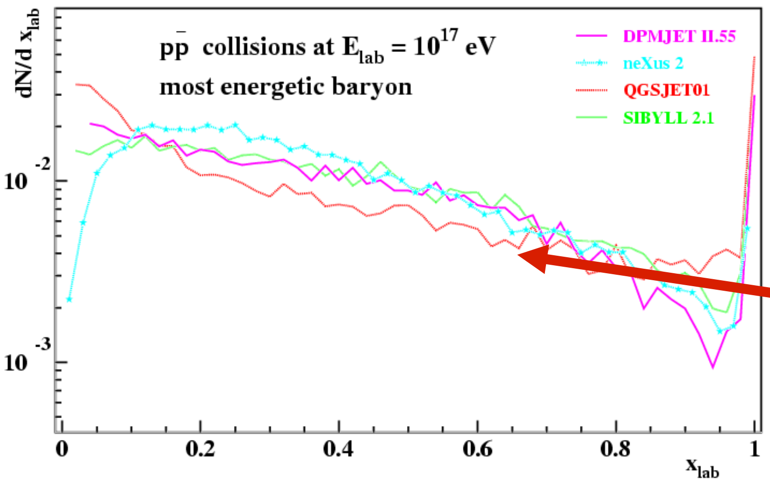
First runs with β* = 90 m

High Energy Cosmic Rays



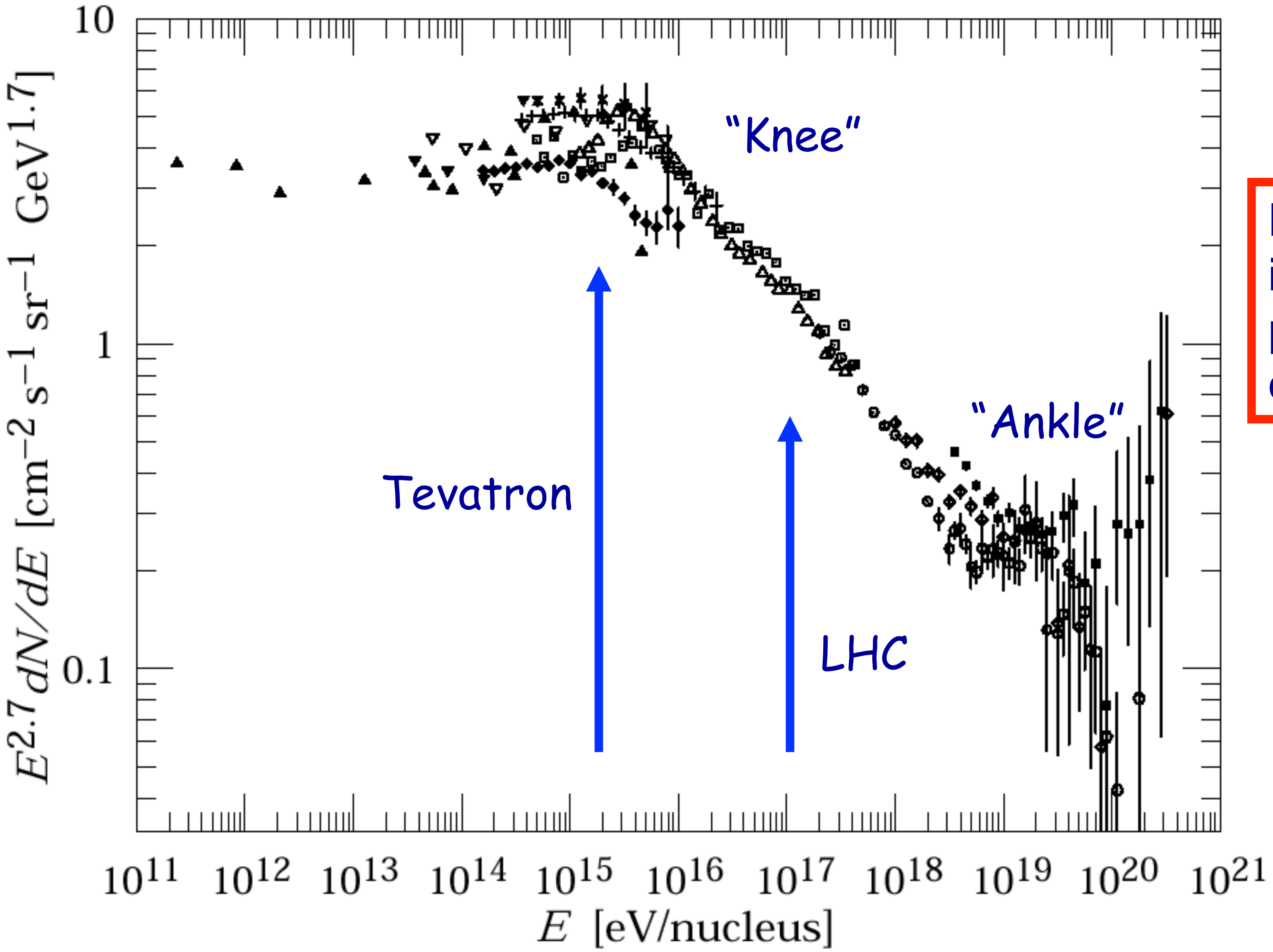


Cosmic ray showers: Dynamics of the high energy particle spectrum is crucial



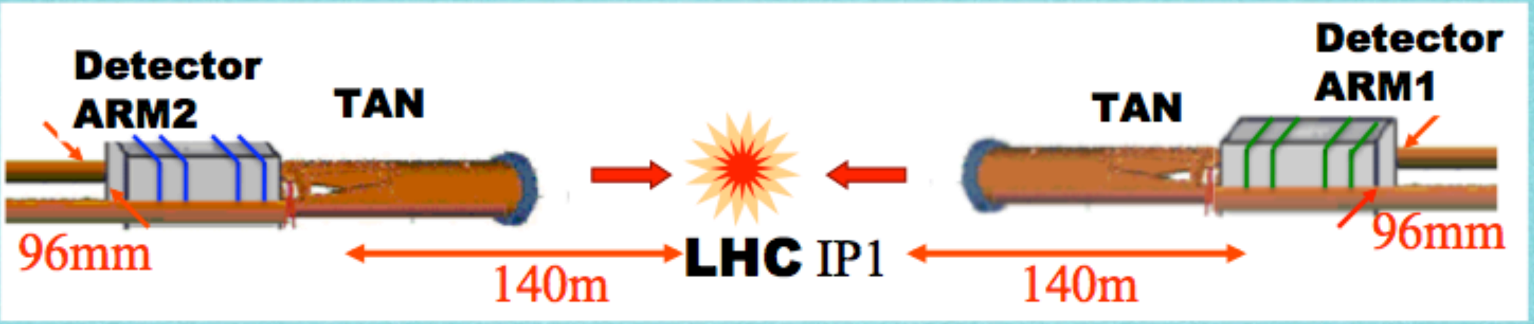
Interpreting cosmic ray data depends on hadronic simulation programs
Forward region poorly know/constrained
Models differ by factor 2 or more
Need forward particle/energy measurements
e.g. $dE/d\eta$…

Connection to Cosmic Rays



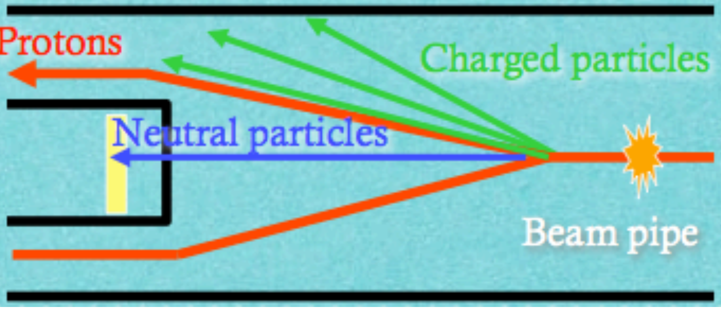
Energy of incident particles in cosmic rays

LHCf: an LHC exp. for Astroparticle Physics

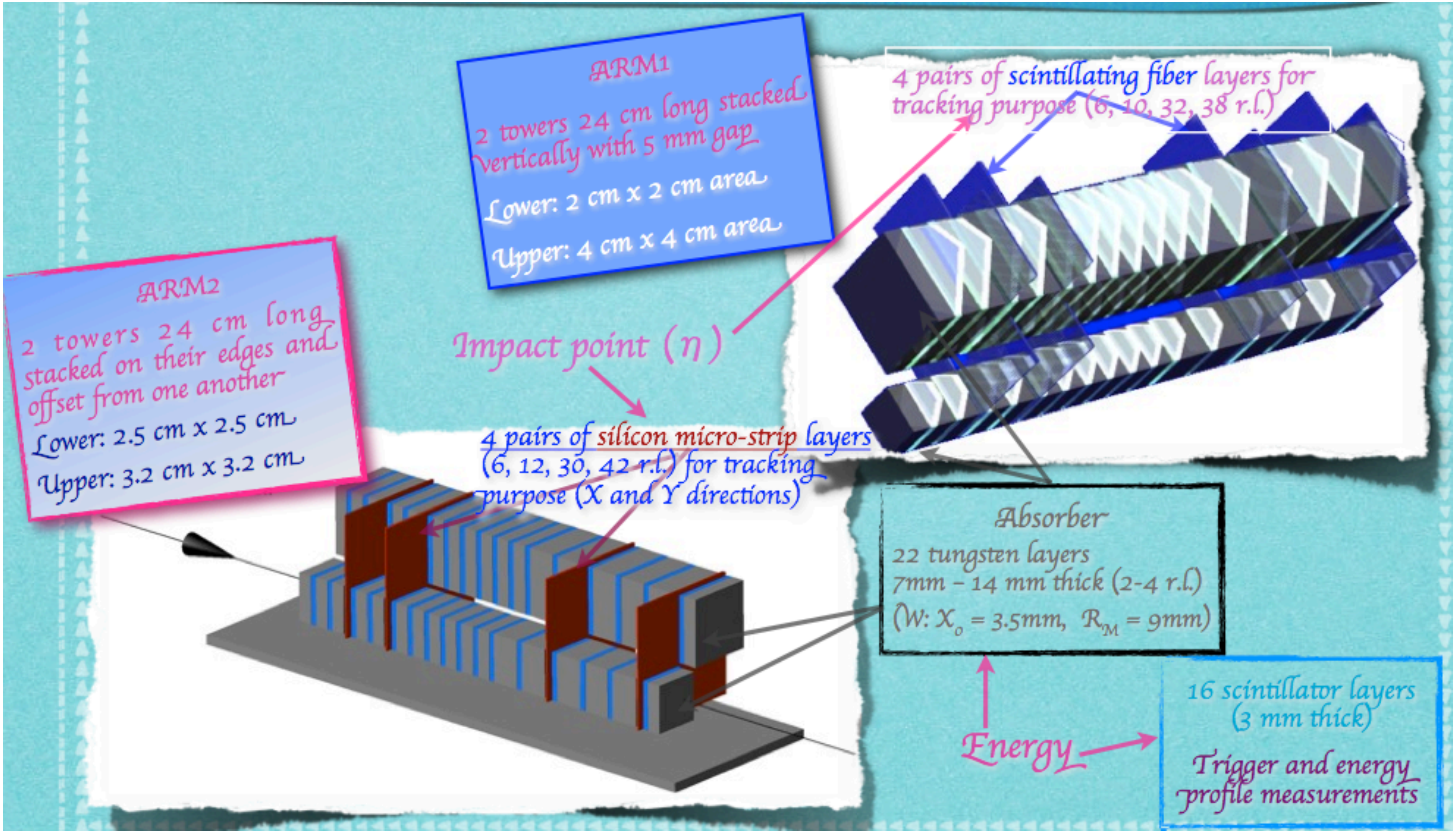


Detectors installed in the TAN region, 140 m away from ATLAS Interaction Point (IP1)

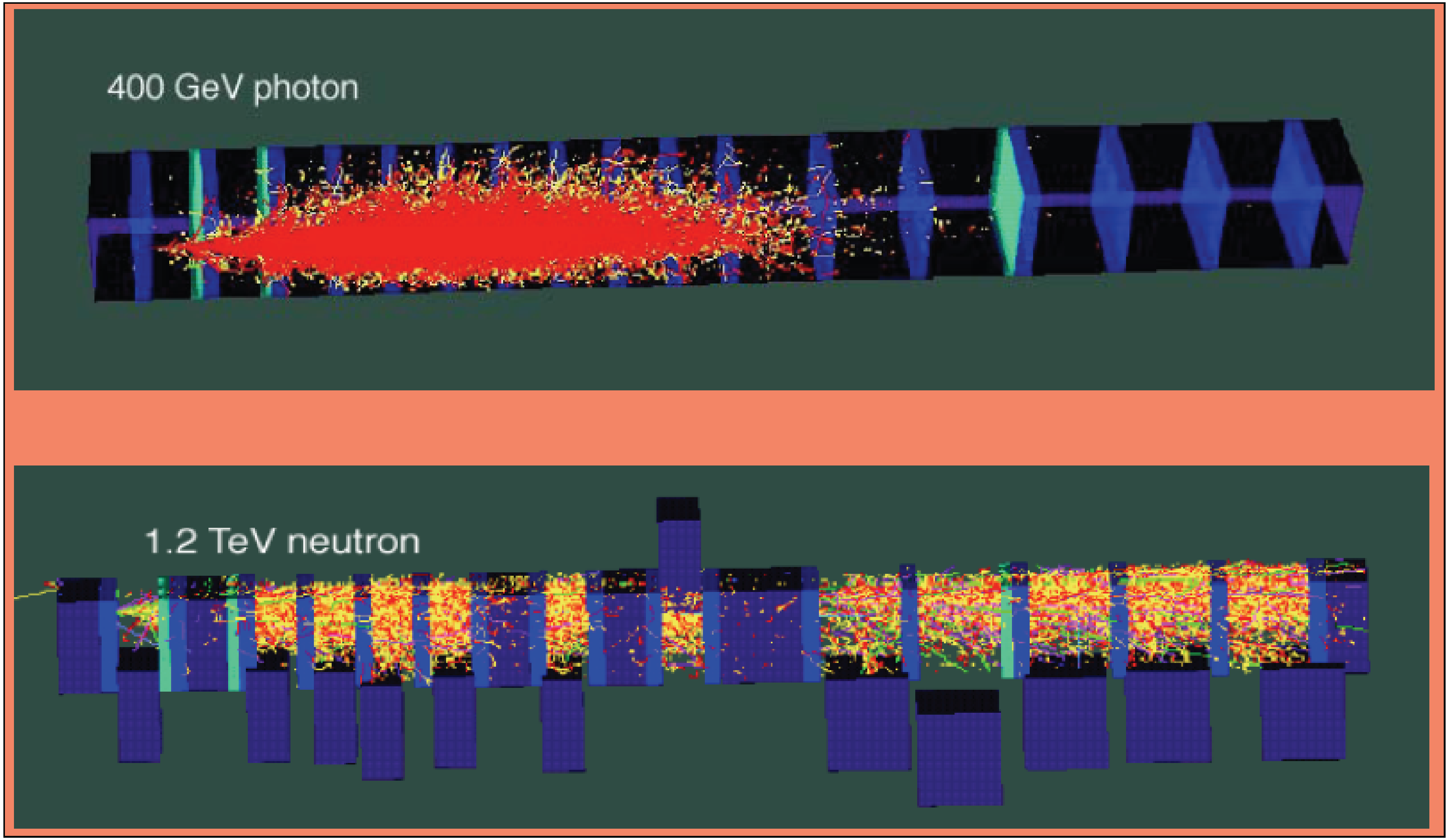
- Here the beam pipe splits in 2 separate tubes.
- Charged particle are swept away by magnets
- We will cover up to y→∞



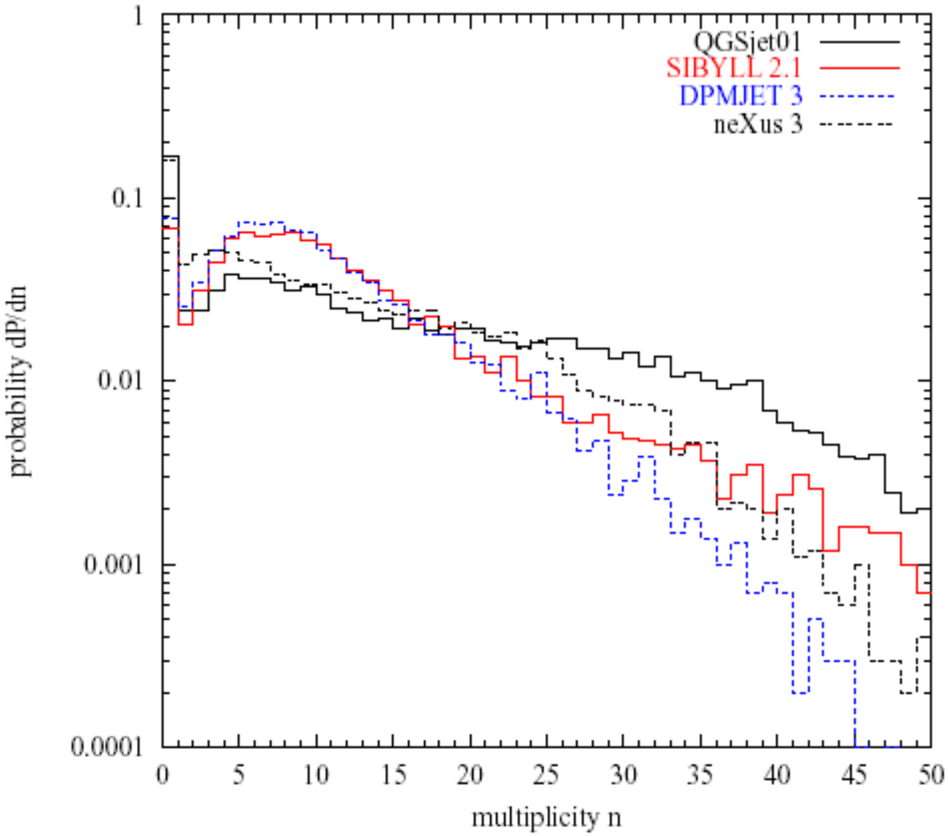
LHCf: an LHC exp. for Astroparticle Physics



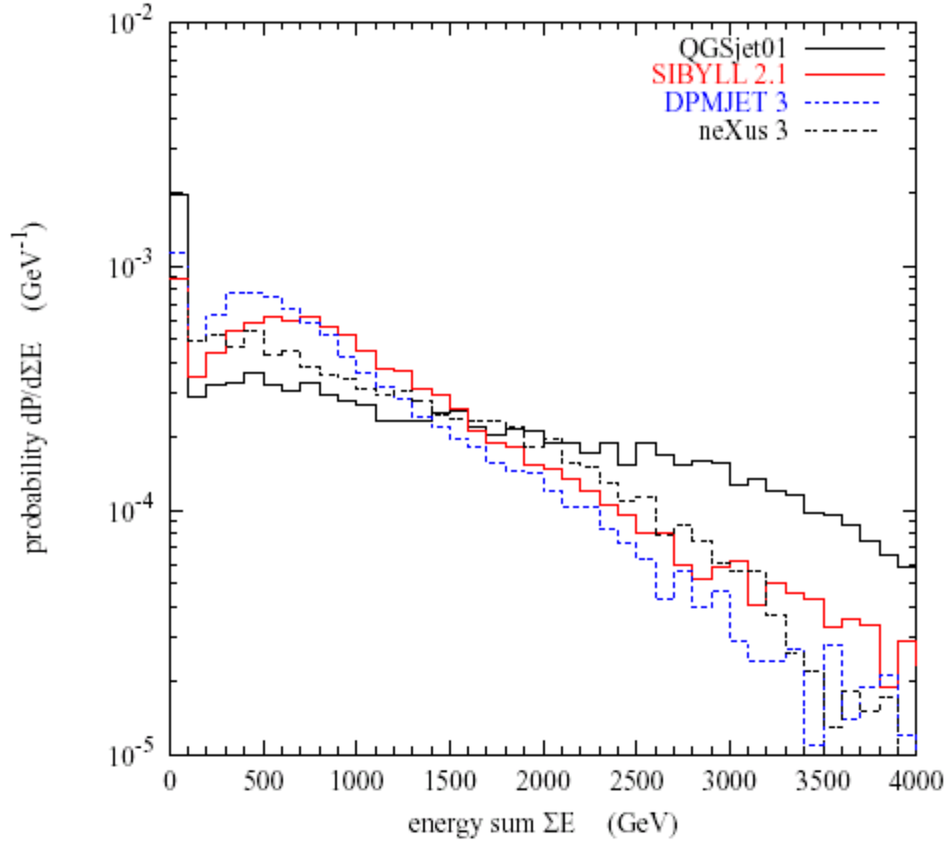
Particle response



Model Predictions: proton-proton at the LHC



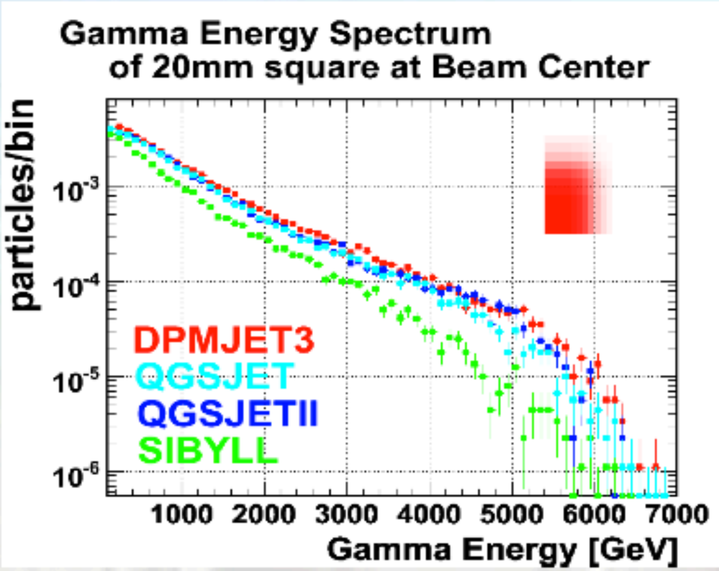
total multiplicity in forward detector
$(5 \leq \eta \leq 7)$



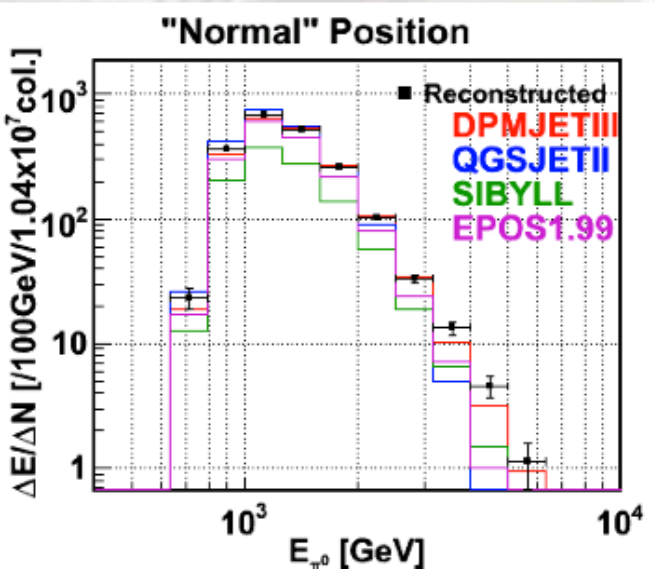
total energy in forward detector
$(5 \leq \eta \leq 7)$

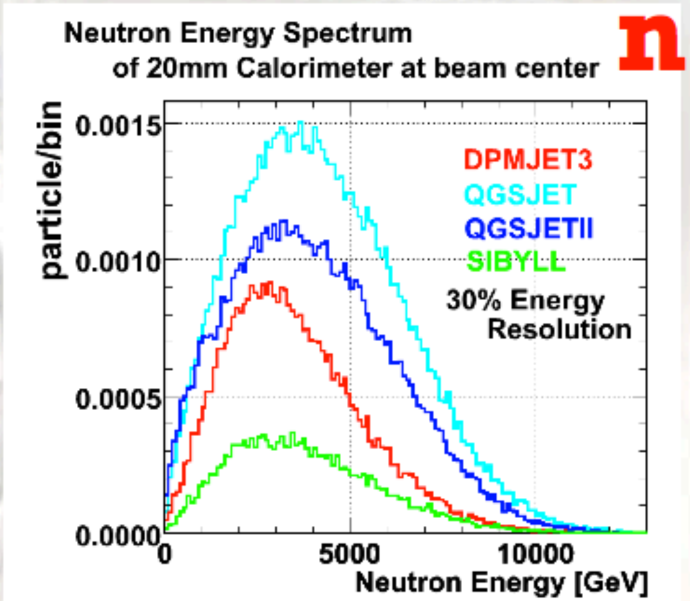
Predictions in the forward region within the CMS/TOTEM acceptance
Large differences between models

Expectations from MC studies

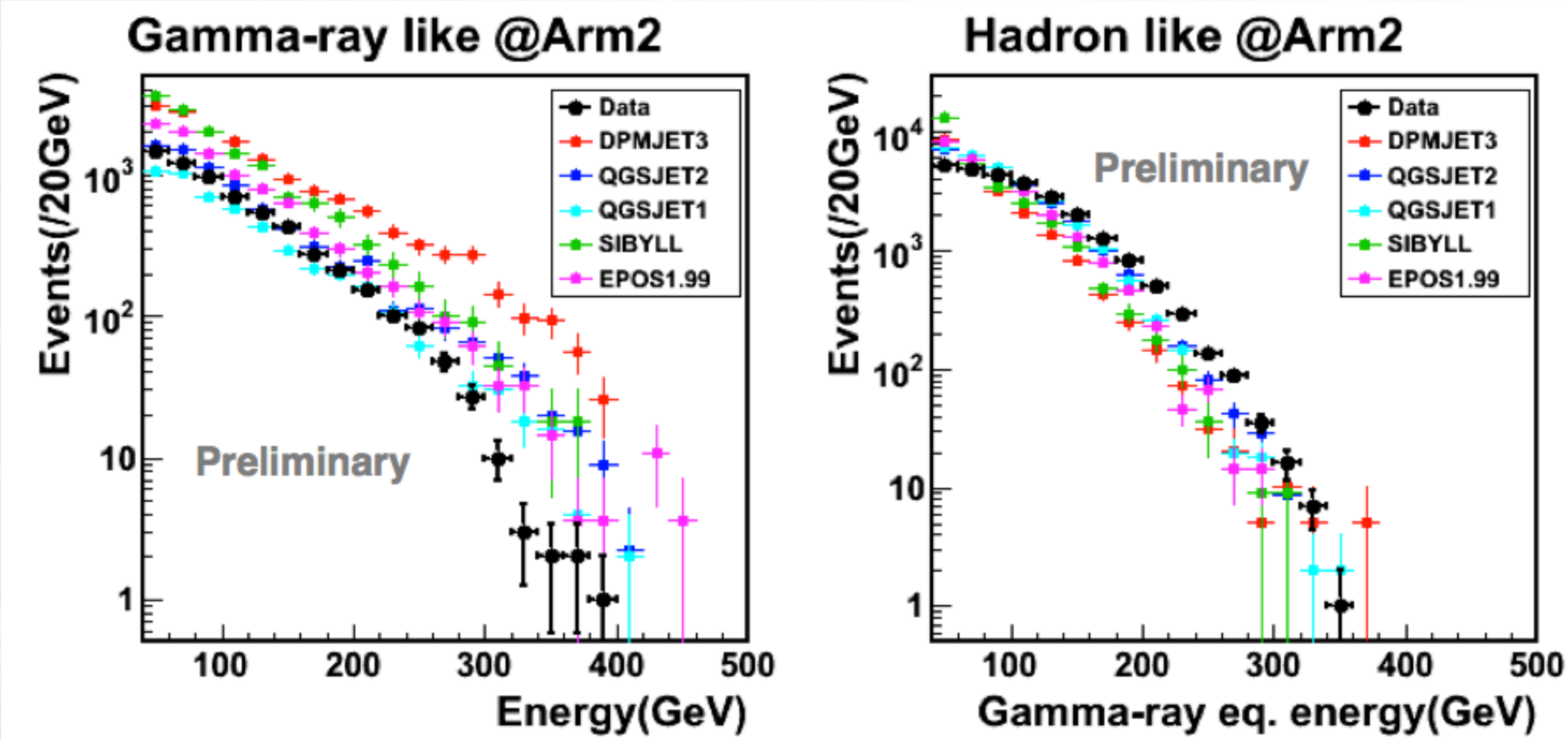


$10^6/10^7$ generated LHC interactions
at 7+7 TeV→
1 minute exposure@10^{29} $cm^{-2}s^{-1}$ luminosity





900 GeV Data Analysis



Only statistical errors are quoted

MC normalized to the total number of events in the 2 towers,without PID.
Only one normalization factor common to all models

Summary of Lecture I: QCD

- QCD results are the first measurements from the LHC. All experiments are contributing
- For ATLAS and CMS these are also crucial measurements to prepare for the searches
- So far the measurements agree with the QCD predictions based on lower energy data and theory within ~20%
- More precision with the next luminosity phase
- Some items to be understood, eg the ridge in particle correlations; a new effect

END