Diffraction at CMS

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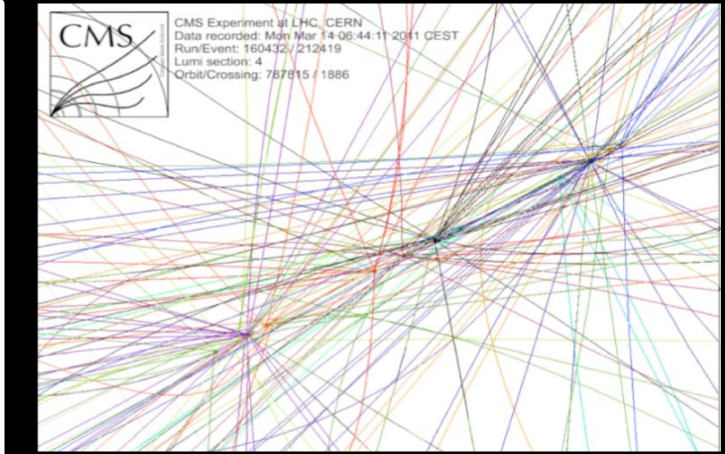
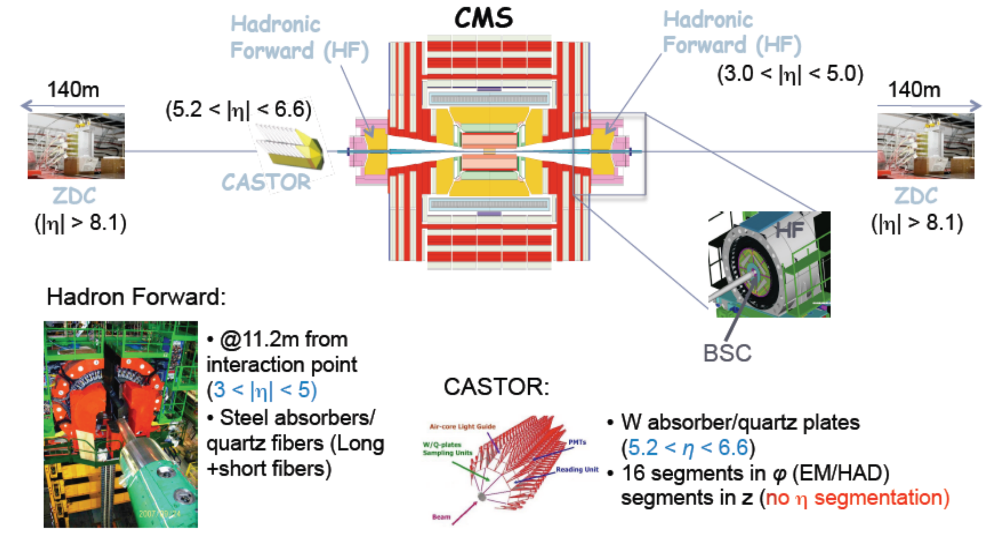
for the CMS collaboration

The setting:CMS@LHC

- High energy and high luminosity
  - Allows high statistics precision measurements, and sensitivity to “rare” processes (hard diffraction, exclusive production)
  - But high luminosity comes with high “pileup” – average 2-4 extra interactions/crossing in 2010, 5-8 in 2011





Hadron Forward:

- @11.2m from interaction point ($3 < |\eta| < 5$)
- Steel absorbers/ quartz fibers (Long +short fibers)

CASTOR:

- W absorber/quartz plates ($5.2 < \eta < 6.6$)
- 16 segments in φ (EM/HAD) segments in z (no η segmentation)

- Good detector coverage
  - Tracking to $|\eta| < 2.4$
  - Hadronic calorimeter (HF) to $|\eta| < 5$
  - Forward calorimeters (cover $-6.6 < \eta < -5.2$ (CASTOR) and $|\eta| > 8.1$ (ZDC)

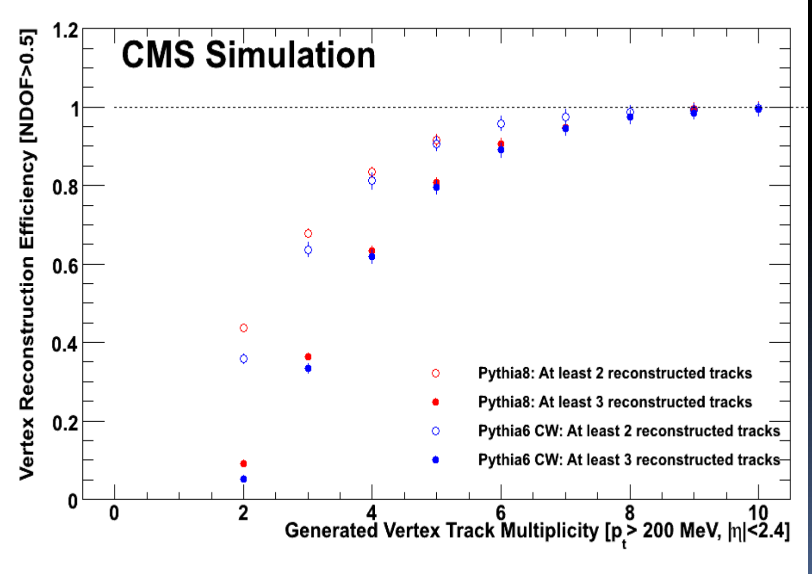
Measurement of the inelastic cross-section using pileup events

CMS PAS FWD 11-001

Motivation & method

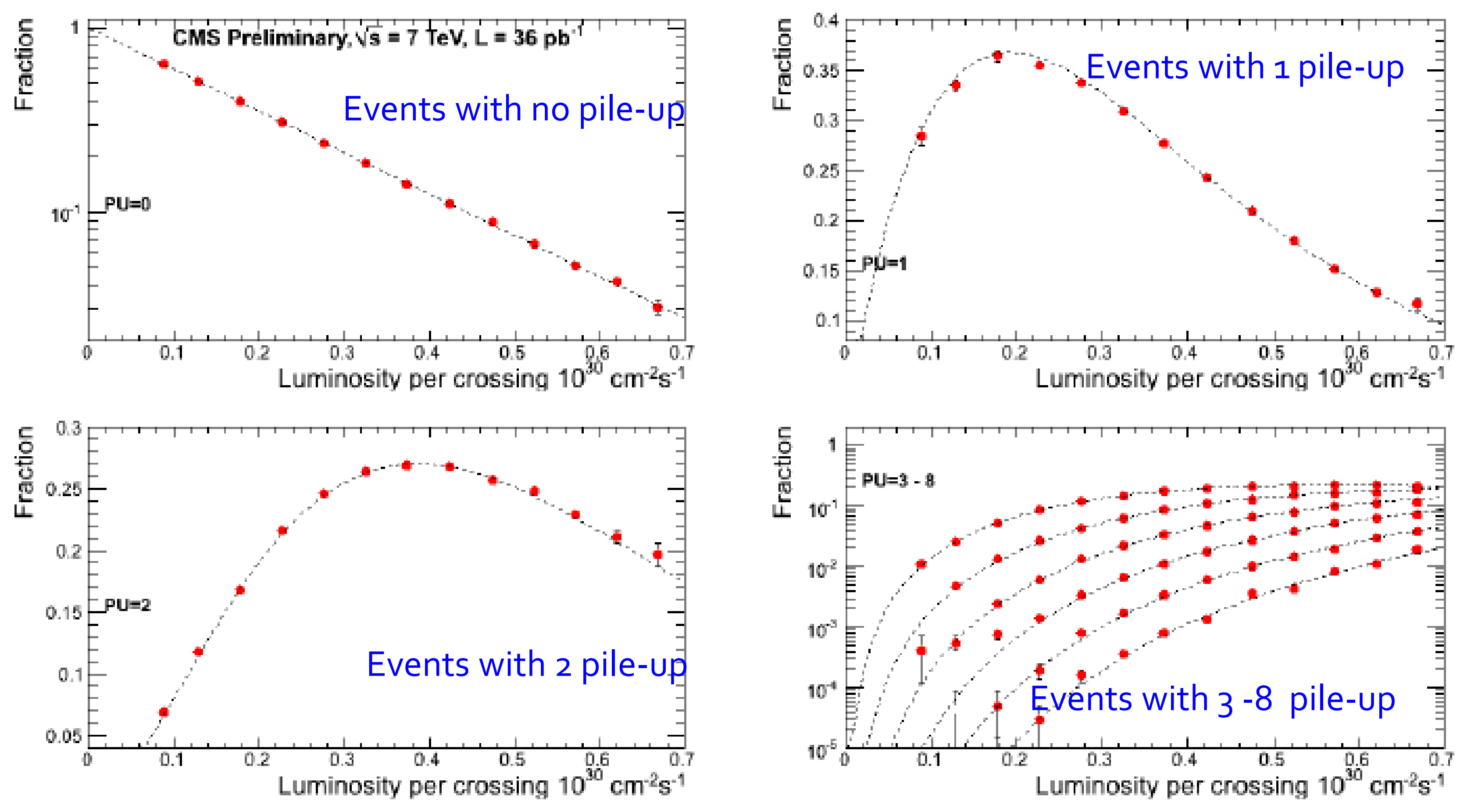
- Probability of a number interactions occurring in a crossing depends on the total *pp* cross-section
  - => Turn pileup into an advantage for measuring σ(*pp*)

$$P(n_{pileup}) = \frac{(L\cdot\sigma)^{n_{pileup}}}{n_{pileup}!}\cdot e^{-(L\cdot\sigma)}$$



- Method based on counting # of vertices as a function of luminosity
  - Samples collected with high-efficiency triggers (e.g. di-electrons)
  - Data is corrected for vertex merging, and inefficiencies in reconstructing vertices with low track multiplicity

Fitting



- Unfolded distributions are fit to a Poisson distribution for each value of pileup (=$N_{vertices}$-1) from 0-8

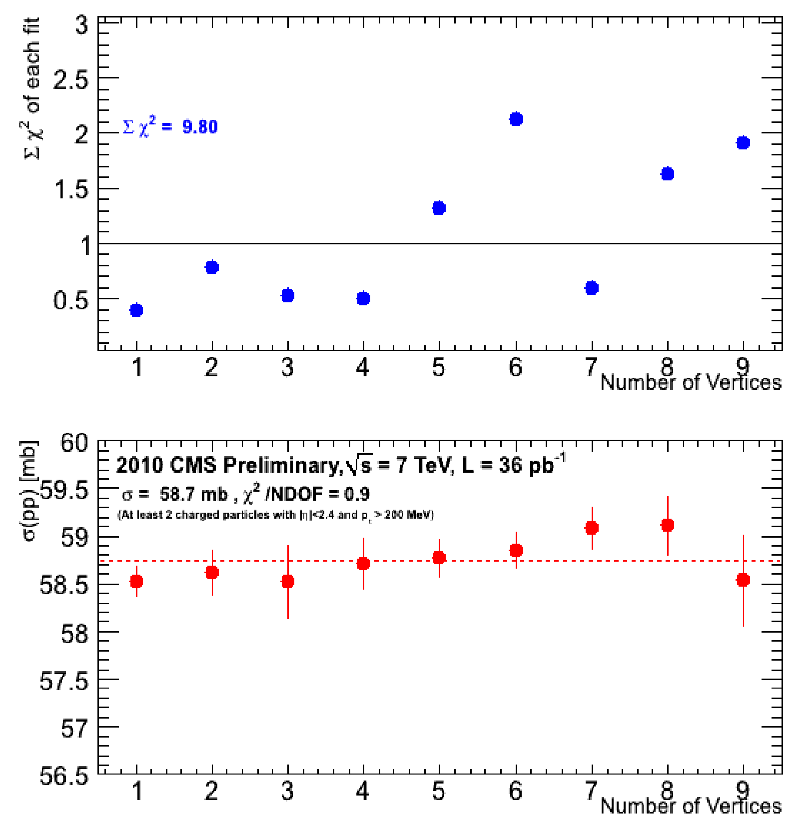
Results (I)

- Nine statistically independent measurements, for each value of the pileup

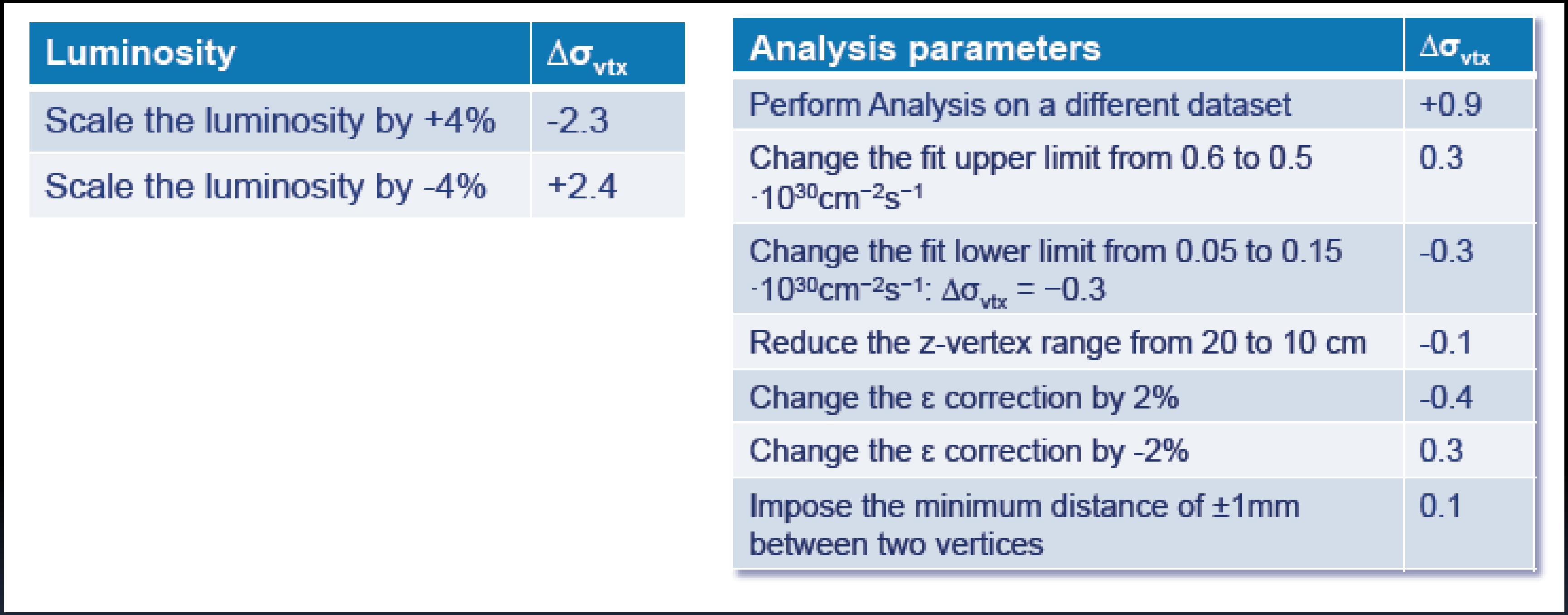
- Final result from a fit to all nine points

- For 3 tracks with p_T>200MeV, $|\eta| < 2.4$, the resulting cross-section is:

$$\boxed{\sigma\ = 58.7 \pm 2.0\ (\mathrm{Sys}) \pm 2.4\ (\mathrm{Lumi})\ \mathrm{mb}}$$



cross-section systematics



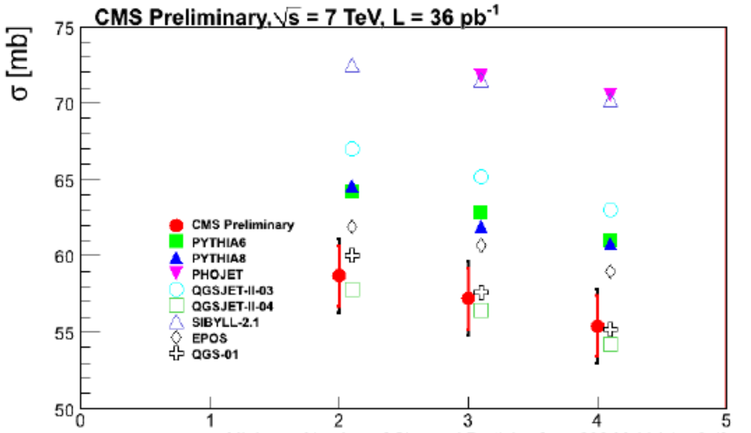
Luminosity	$\Delta\sigma_{vtx}$
Scale the luminosity by +4%	-2.3
Scale the luminosity by -4%	+2.4

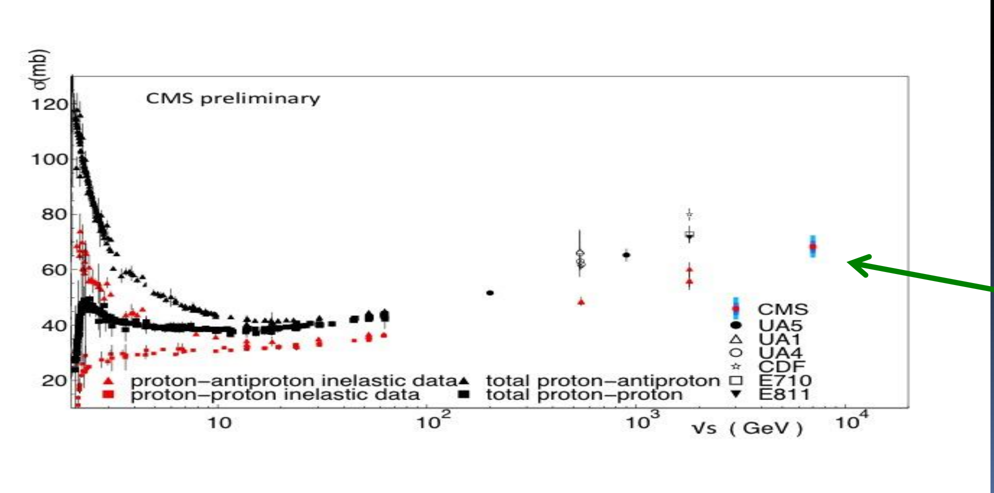
Analysis parameters	$\Delta\sigma_{vtx}$
Perform Analysis on a different dataset	+0.9
Change the fit upper limit from 0.6 to 0.5 $\cdot 10^{30} cm^{-2}s^{-1}$	0.3
Change the fit lower limit from 0.05 to 0.15 $\cdot 10^{30} cm^{-2}s^{-1}$: $\Delta\sigma_{vtx} = -0.3$	-0.3
Reduce the z-vertex range from 20 to 10 cm	-0.1
Change the ε correction by 2%	-0.4
Change the ε correction by -2%	0.3
Impose the minimum distance of ±1mm between two vertices	0.1

Results (II)

- Measurement is compared to predictions of several models
  - Gives a range of extrapolation factors that can be used to bound the total inelastic cross-section:

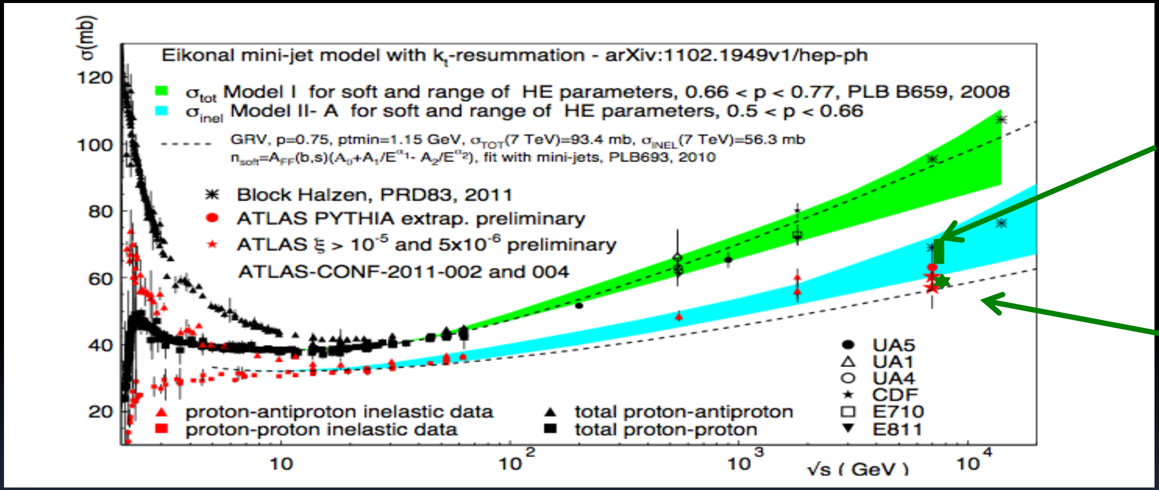
$$\sigma(pp) = 68.0 \pm 2.0\ (\mathrm{Sys}) \pm 2.4\ (\mathrm{Lumi}) \pm 4.0\ (\mathrm{Extr.})\ \mathrm{mb}$$





CMS model-dependent extrapolation

Total cross-section



CMS Model dependent extrapolation

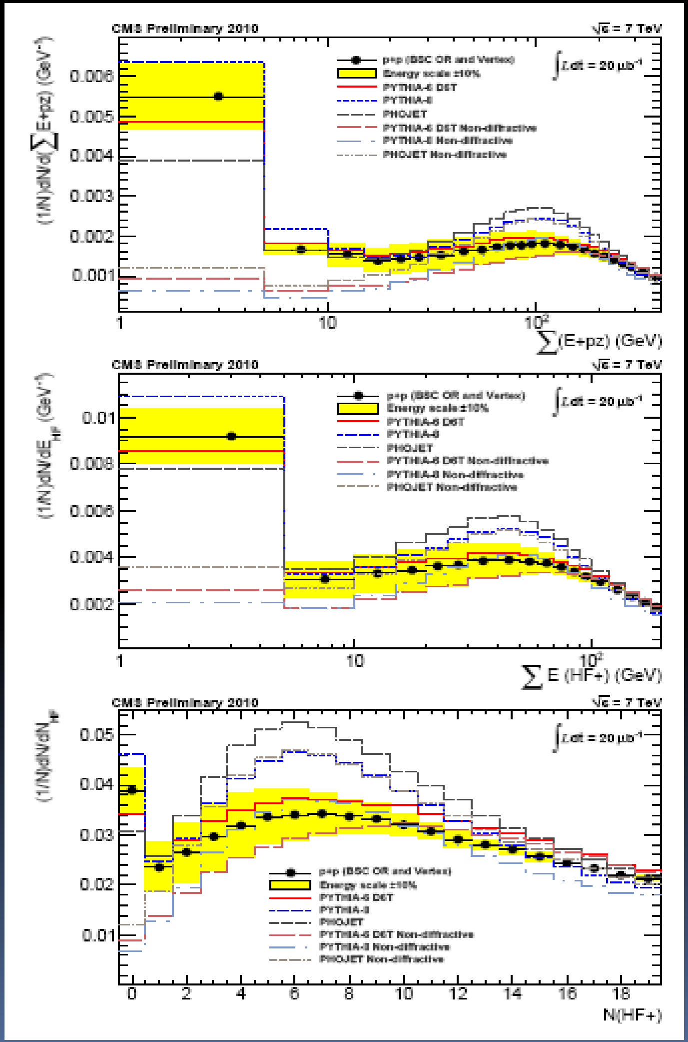
CMS

Diffraction @ 7TeV

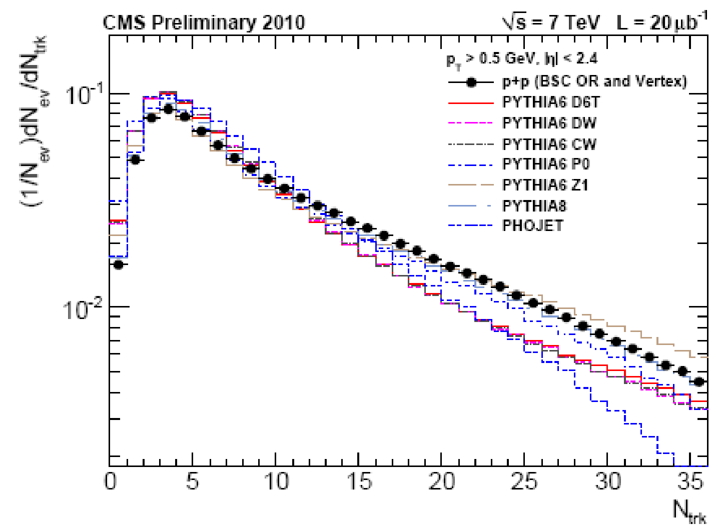
CMS PAS FWD 10-007

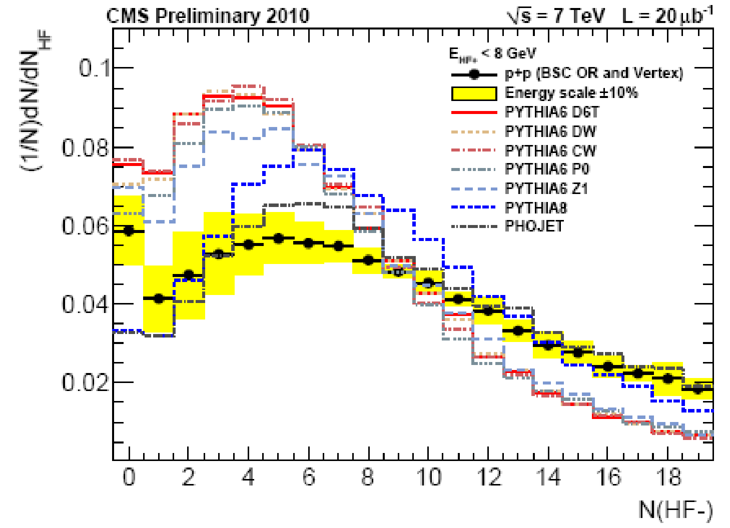
Inclusive Diffration

- Analysis based on 20μb^{-1} of low-pileup 7TeV data
  - Extends previous CMS results on diffraction at 900GeV and 2.36TeV
  - Trigger with scintillator counters (BSC) and require a vertex consistent with collisions
- Diffractive signal appears as an enhancement near zero in several sensitive variables
  - N(HF towers over threshold)
  - ΣE(HF)
  - ΣE-p$_Z$ (~ξ), summed over all calorimeter towers



Event distributions





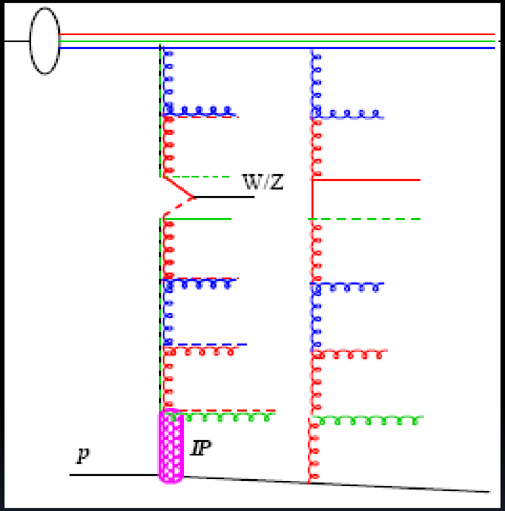
- Select a diffractively enhanced sample by requiring <8GeV in HF+
- Track multiplicities, track p_T distributions, and energy deposits opposite the gap side compared a range of models
  - Pythia 8 and Phojet better describe the diffractive component, while Pythia 8 and several Pythia 6 tunes perform better for inclusive distributions
- None of the models describe all features of the data

Diffractive W/Z

CMS PAS FWD 10-008

Introduction and selection

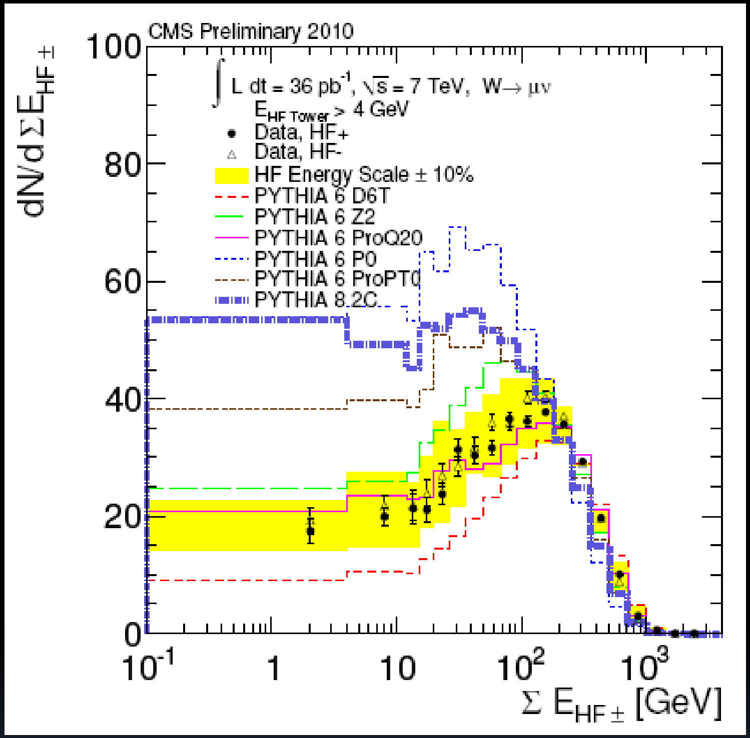
- Part of a larger systematic study of track multiplicity and forward energy flow in W/Z events
- Search for a diffractive component in *W/Z* events
- Sensitive to multi-parton interactions (MPI), gap-survival probabilities
  - Additional interactions may "fill the gap" in diffractive interactions →



- Select *W/Z* events with a single-vertex to suppress pileup
  - Residual contamination from soft pileup events studied in MC, and in data as a function of average instantaneous luminosity

W/Z with gaps

- Search for a diffractive component in W/Z events
- Define Large Rapidity Gap selection using sum of calorimeter towers in HF ($3 < |\eta| < 5$) above 4 GeV
- Excess of events with zero energy compared to Pythia 6 D6T tune
    - But – deficit compared to Pythia 6 Z2, Pythia 8



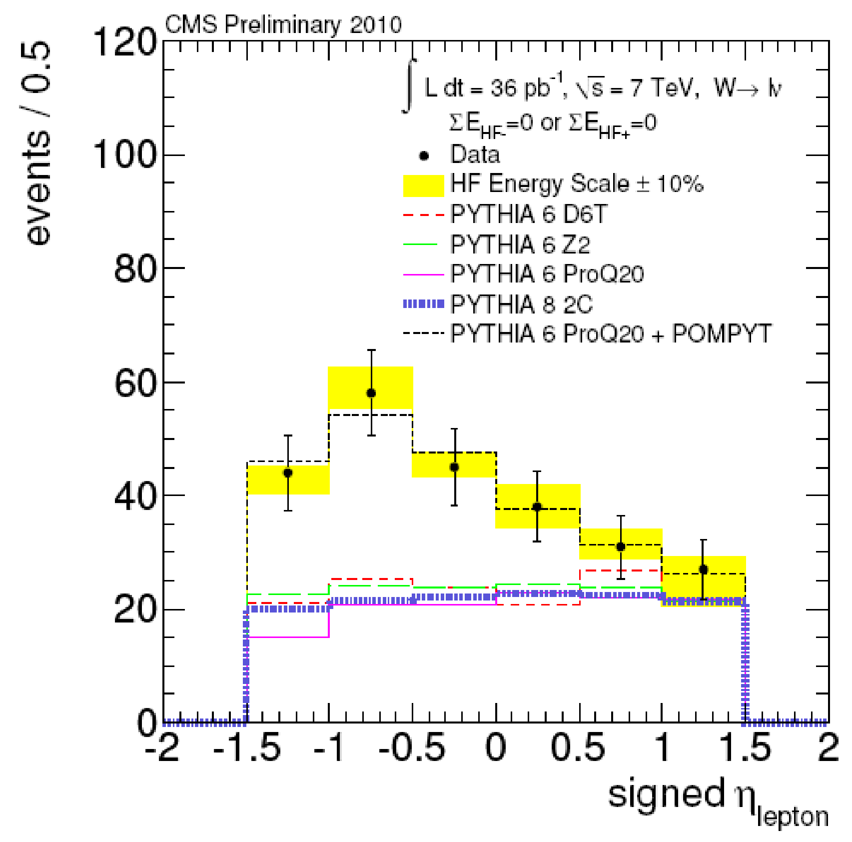
$W \to \mu\nu X$

Fraction of LRG events

$W \to l\nu = 1.46 \pm 0.09\ (\text{stat.}) \pm 0.38\ (\text{syst.})\ \%$

$Z \to ll = 1.60 \pm 0.25\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \%$

Lepton asymmetry



$W \rightarrow l \nu X$

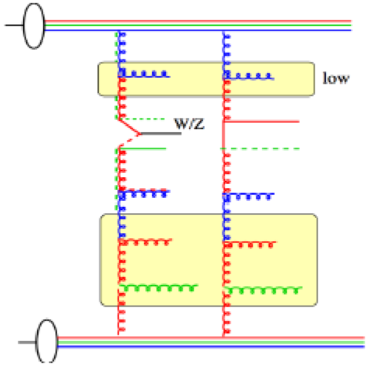
- Additional sensitivity to diffraction from the charged lepton asymmetry η_{Lepton}
  - POMPYT MC predicts leptons from diffractive *W/Z* are preferentially produced opposite the LRG (small-x diffractive PDF's)
  - All Pythia tunes predict a flat distribution
- Large asymmetry observed in the LRG sample in data, with best-fit fraction for the diffractive component:

$$50.0 \pm 9.3\ (\text{stat.}) \pm 4.2\ (\text{syst.})\ \%$$

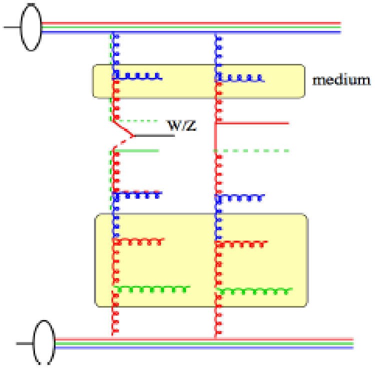
Energy Flow

CMS-PAS-FWD-10-008

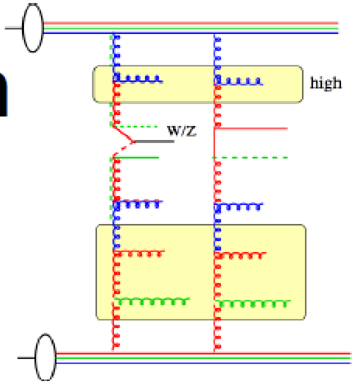
Correlation between forward and backward energy distribution



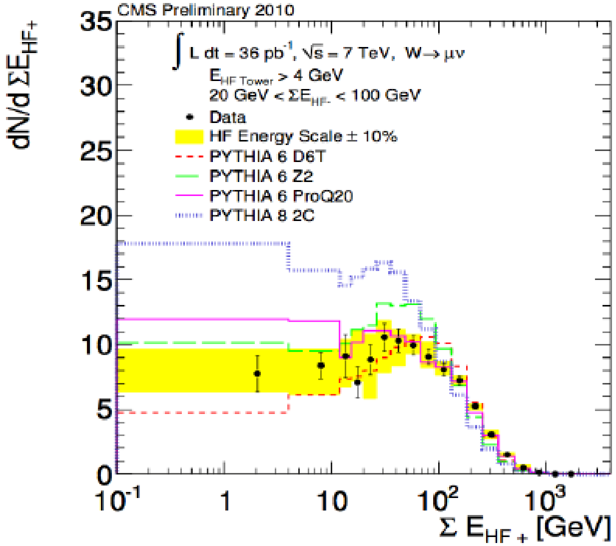
low

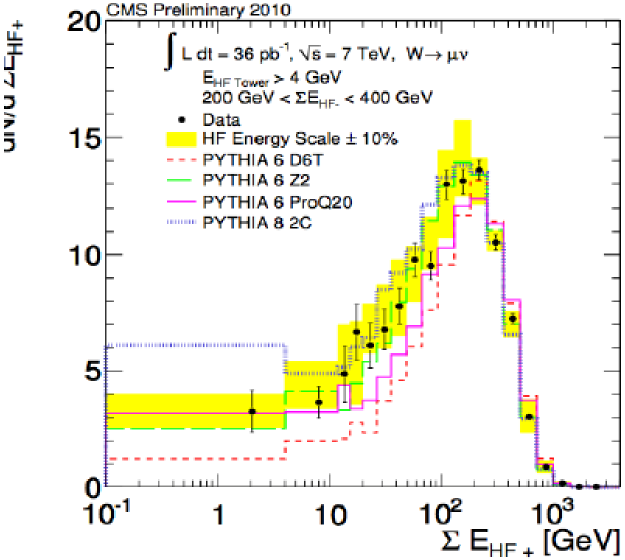


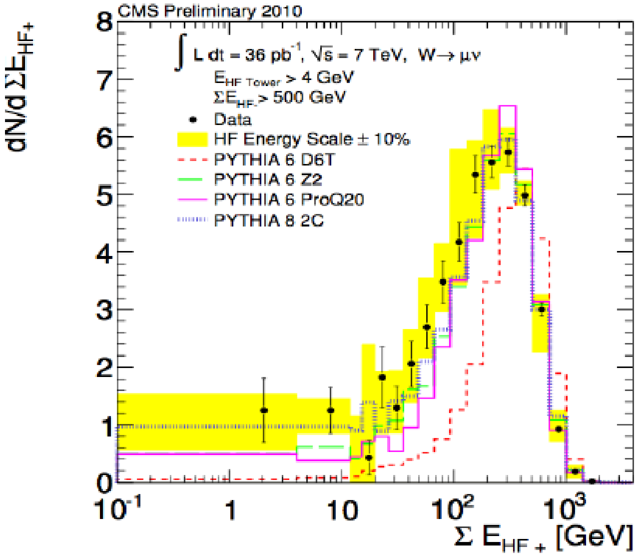
medium



high





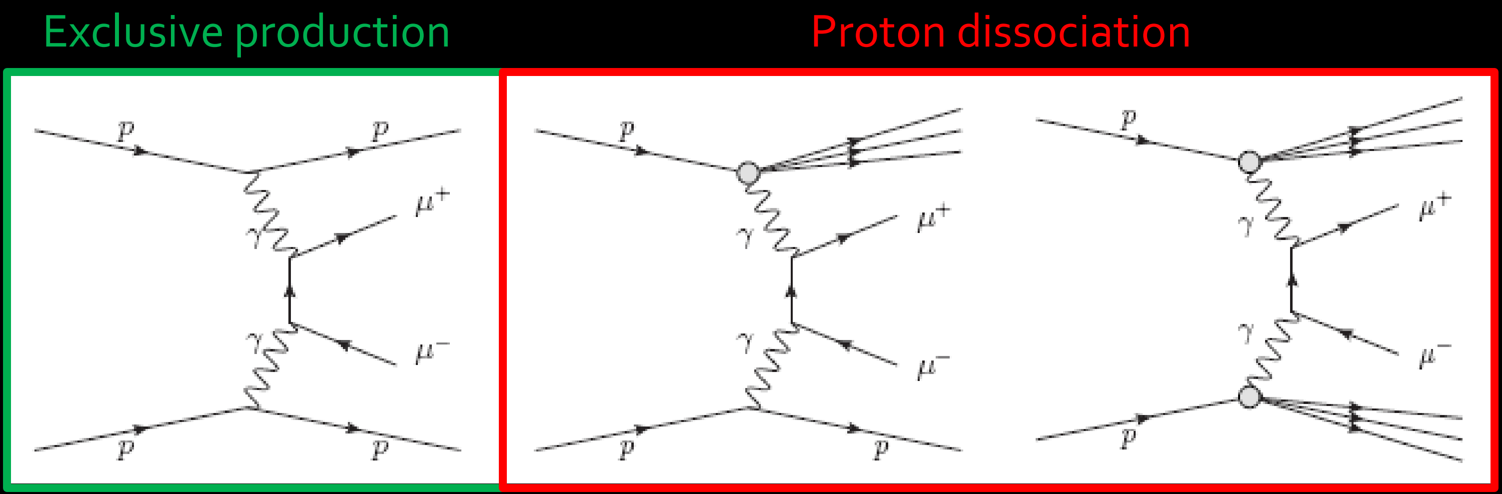


- Energy distribution in forward/backward region strongly correlated
- Energy spectra and correlations are not well modeled

Exclusive $\gamma\gamma\rightarrow\mu\mu$

CMS PAS FWD 10-005

$\gamma\gamma \to \mu\mu$

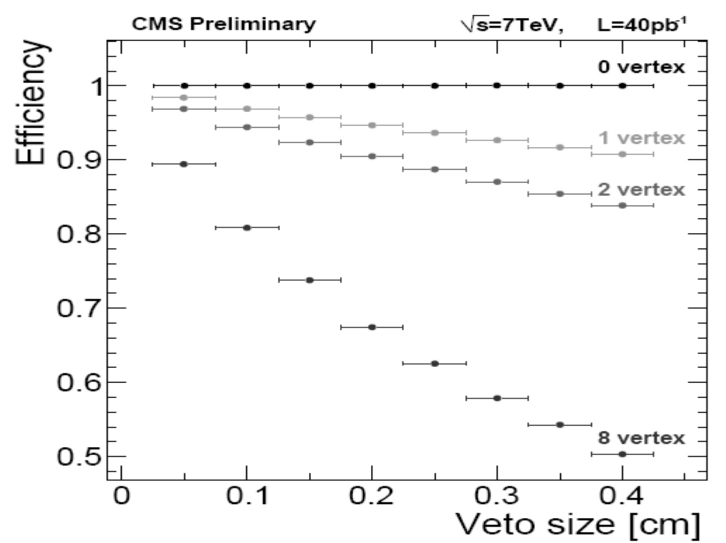

Exclusive production

Proton dissociation

- Exclusive production $pp \to p\mu\mu p$
  - QED like "Standard Candle", proposed as a possible future luminosity measurement
- Largest "background" from $\gamma\gamma \to \mu\mu$ with proton dissociation
  - $pp \to p\mu\mu Y$, or $pp \to X\mu\mu Y$ with proton remnants undetected

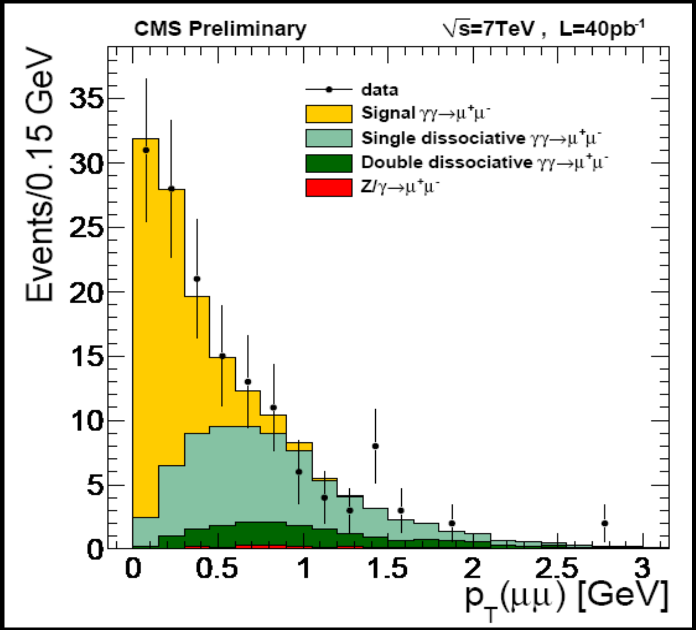
Exclusive dimuons

- Selection based on tracking only, to keep high efficiency with pileup
- Require a $\mu\mu$ vertex, with no other tracks associated
  - Measurement in a restricted phase space $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$, $m(\mu\mu) > 11.5$ GeV , to minimize systematic errors and remove Υ photoproduction



- Efficiency of the track veto is measured in beam-crossing triggered data
  - 92% for full 2010 sample
  - ~70% for events with 8 vertices and 2mm veto size

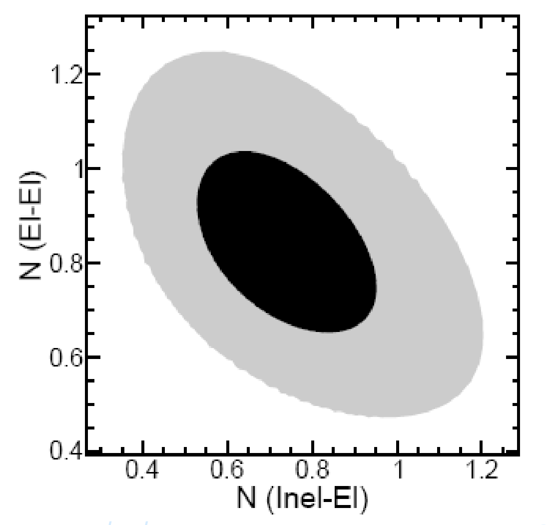
Exclusive dimuons



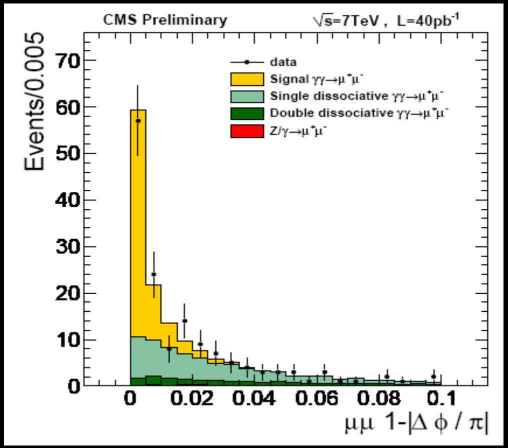
- Signal yield and ratio to the prediction obtained from a fit to the $p_T(\mu\mu)$ distribution
  - Signal yield, single *p*-dissociation yield, and a correction to the slope of the *p*-dissociation are free parameters
  - Signal and p-dissociation yields are highly anti-correlated

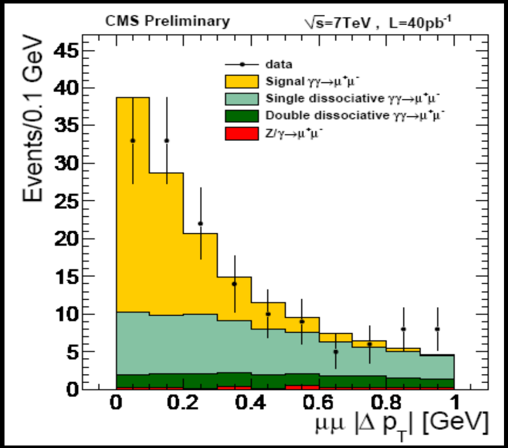
For $p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$ GeV:

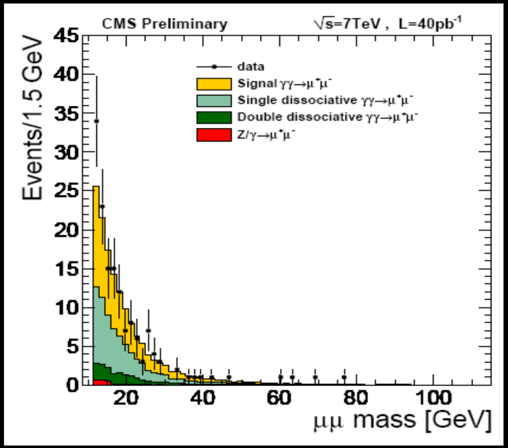
$\sigma = 3.38^{+0.58}_{-0.55}$ (stat.) ± 0.16 (syst.) ± 0.14 (lum.) pb
Ratio = $0.83^{+0.14}_{-0.13}$ (stat.) ± 0.04 (syst.)



Kinematic distributions

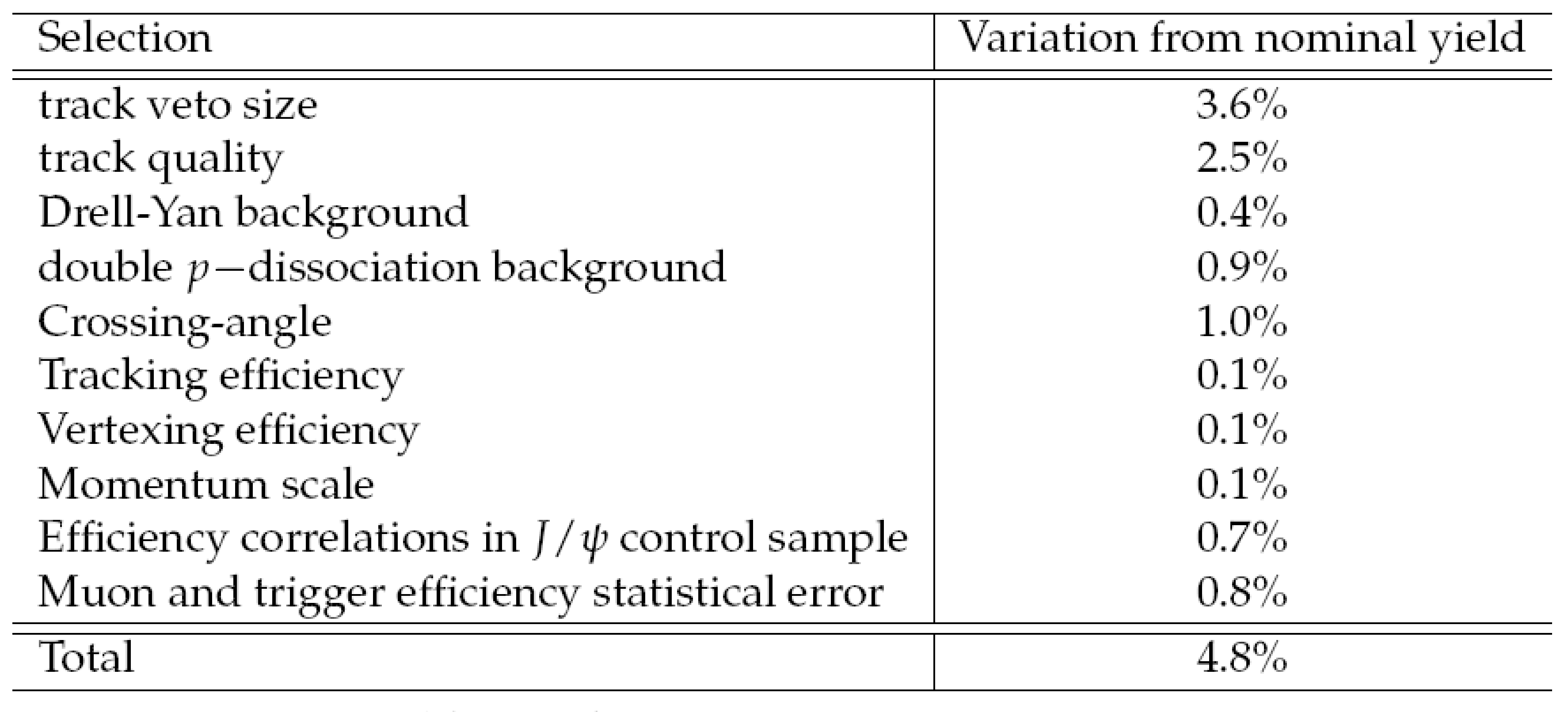






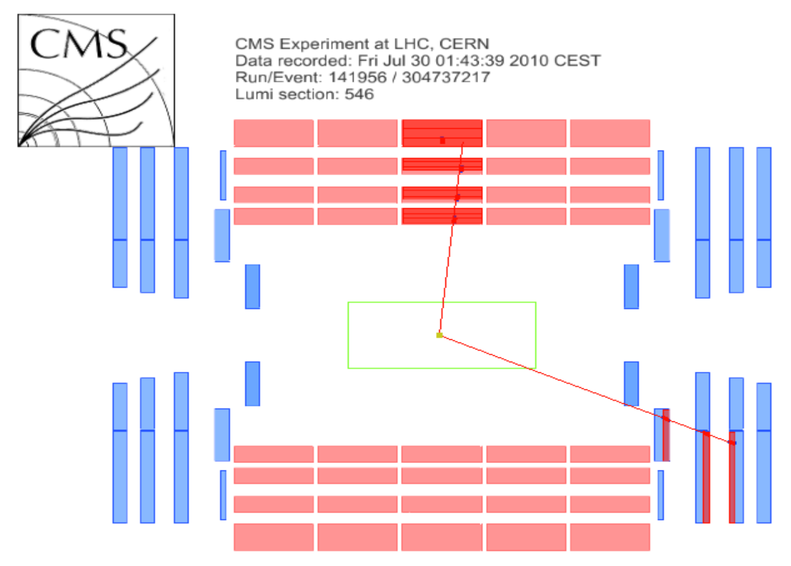
- Kinematic distributions compared to LPAIR MC with best fit normalization
- Good agreement with expectations for exclusive $\gamma\gamma\rightarrow\mu\mu$ plus proton dissociation
  - |1-Δφ($\mu\mu$)/π|, Δp$_T$($\mu\mu$) peak at ~0, consistent with exclusive production
  - m($\mu\mu$) spectrum extends to 76 GeV, no events consistent with $Z\rightarrow\mu\mu$ (consistent with suppression of spin-1 resonance production $\gamma\gamma$ interactions)

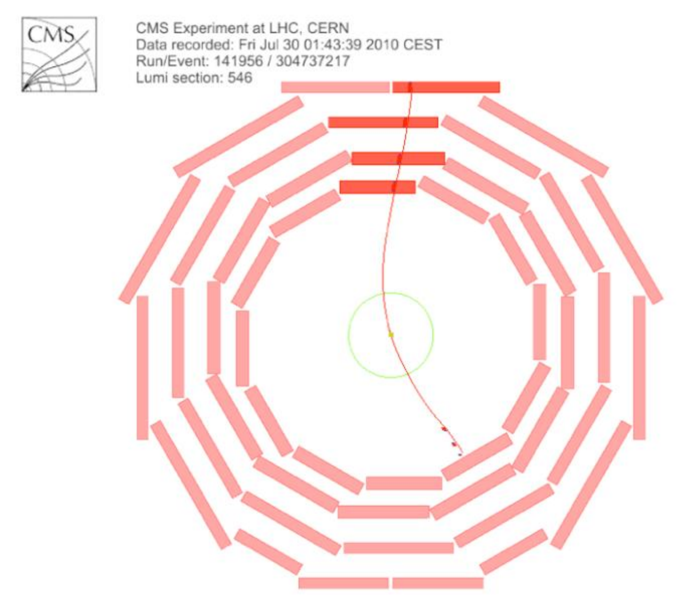
$\gamma\gamma\rightarrow\mu\mu$ systematics



Selection	Variation from nominal yield
track veto size	3.6%
track quality	2.5%
Drell-Yan background	0.4%
double $p-$dissociation background	0.9%
Crossing-angle	1.0%
Tracking efficiency	0.1%
Vertexing efficiency	0.1%
Momentum scale	0.1%
Efficiency correlations in J/ψ control sample	0.7%
Muon and trigger efficiency statistical error	0.8%
Total	4.8%

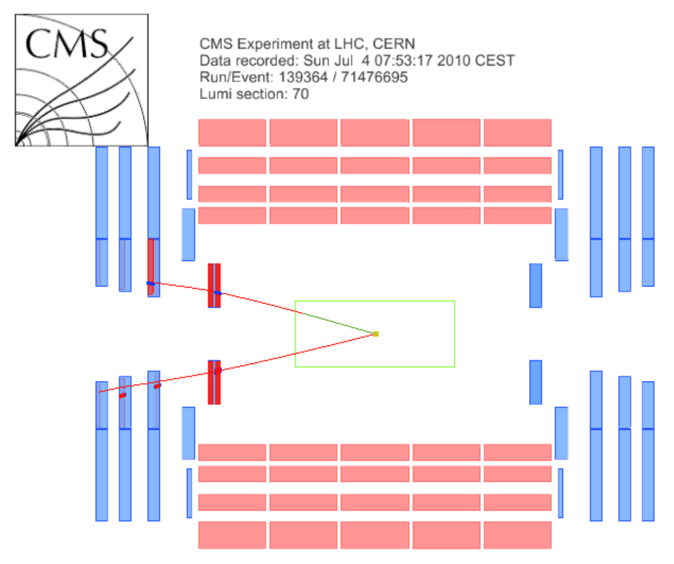
Exclusive $\gamma\gamma\rightarrow\mu\mu$ candidates



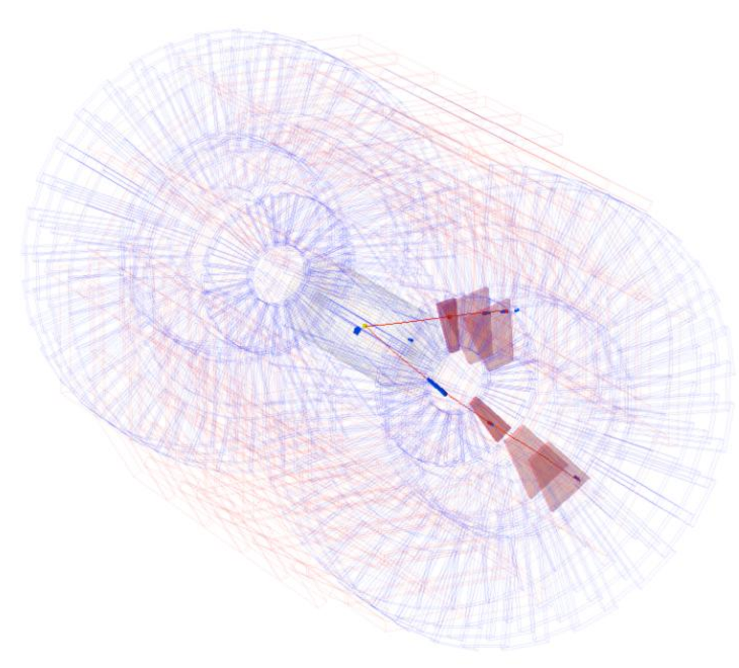


$$
\begin{aligned}
m &= 20.51 \pm 0.2\ \mathrm{GeV} \\
\frac{\Delta\phi}{\pi} &= 0.98 \\
\Delta p_T &= 0.48
\end{aligned}
$$

Exclusive quarkonia candidates



$$\begin{aligned} m &= 3.05 \pm 0.03 \text{ GeV} \\ \frac{\Delta\phi}{\pi} &= 0.98 \\ \Delta p_T &= 0.05\text{GeV} \end{aligned}$$



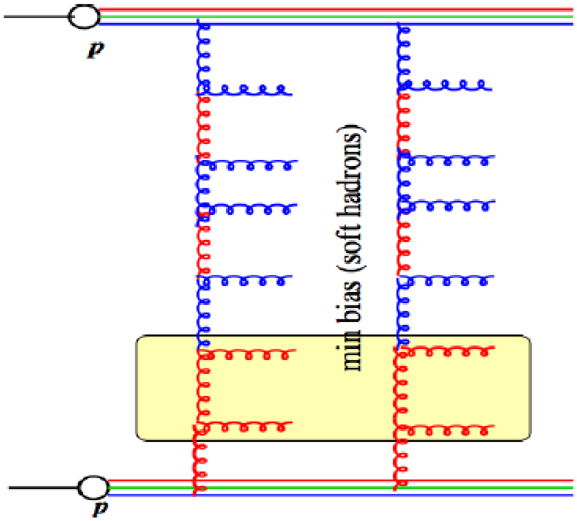
$$\begin{aligned} m &= 9.44 \pm 0.08 \text{ GeV} \\ \frac{\Delta\phi}{\pi} &= 0.99 \\ \Delta p_T &= 0.20\text{GeV} \end{aligned}$$

Energy Flow measurements

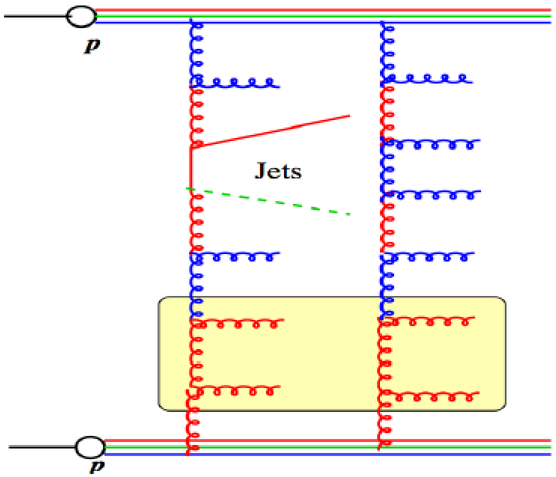
CMS PAS FWD 10-011

Measure $\frac{dE}{N d\eta}$ in min bias and dijet events

- minimum bias events at $\sqrt{s}$ = 0.9 (7) TeV

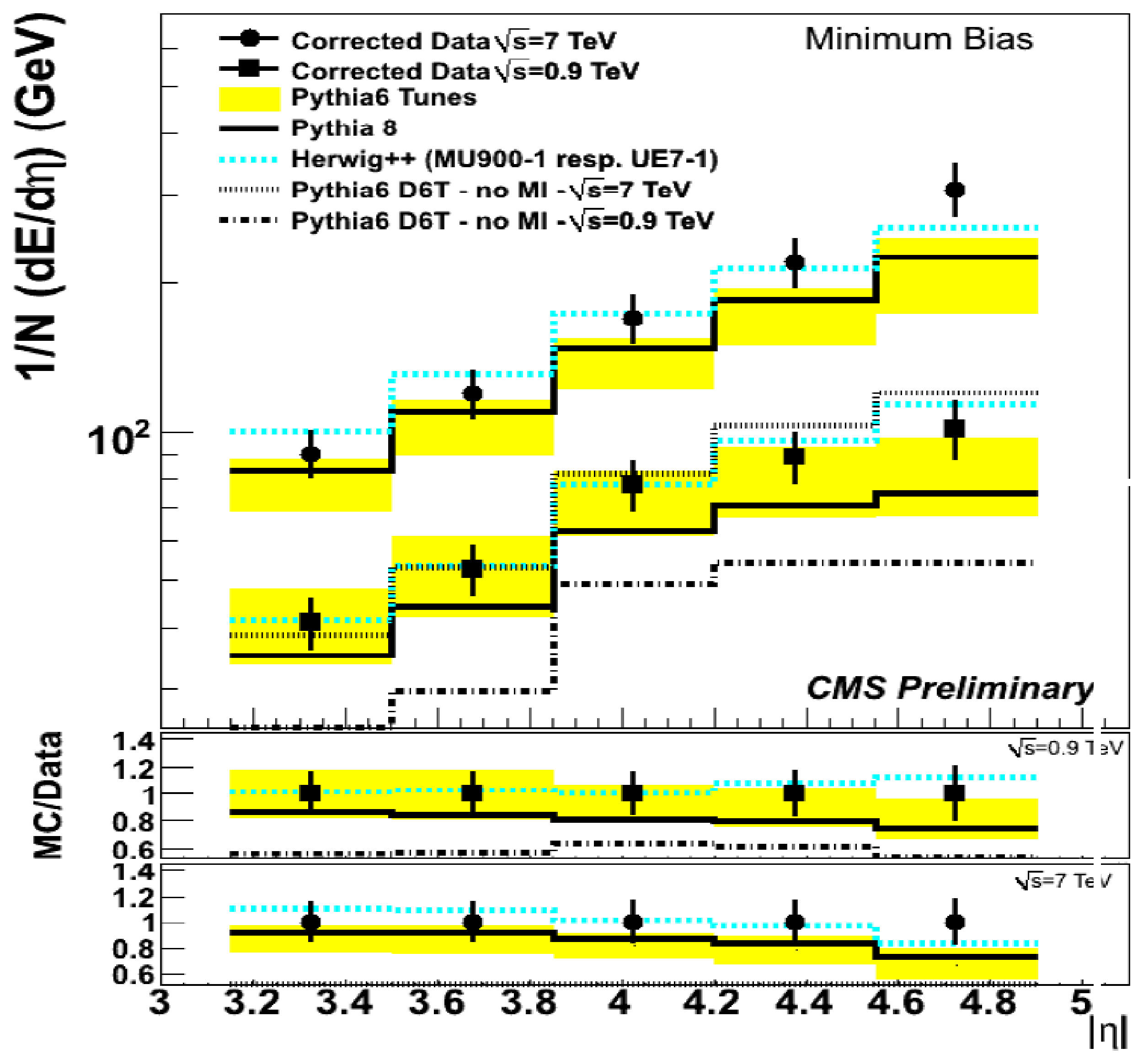


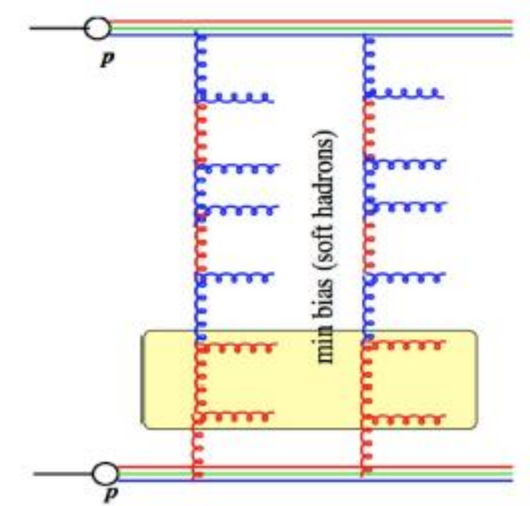
- central dijet events $|\eta|<2.5$, $E_T > 8(20)$ GeV at $\sqrt{s}$ = 0.9 (7) TeV



- Trigger: charged particles in fwd/back region ($3.9 < |\eta| < 4.4$)
- Systematics: energy scale uncertainty → 10%
  - Model uncertainty: 3 – 8% (min bias) ; 4 – 18% (dijets)
  - Total 11 – 14% (min bias) ; 13 – 22% (dijets)

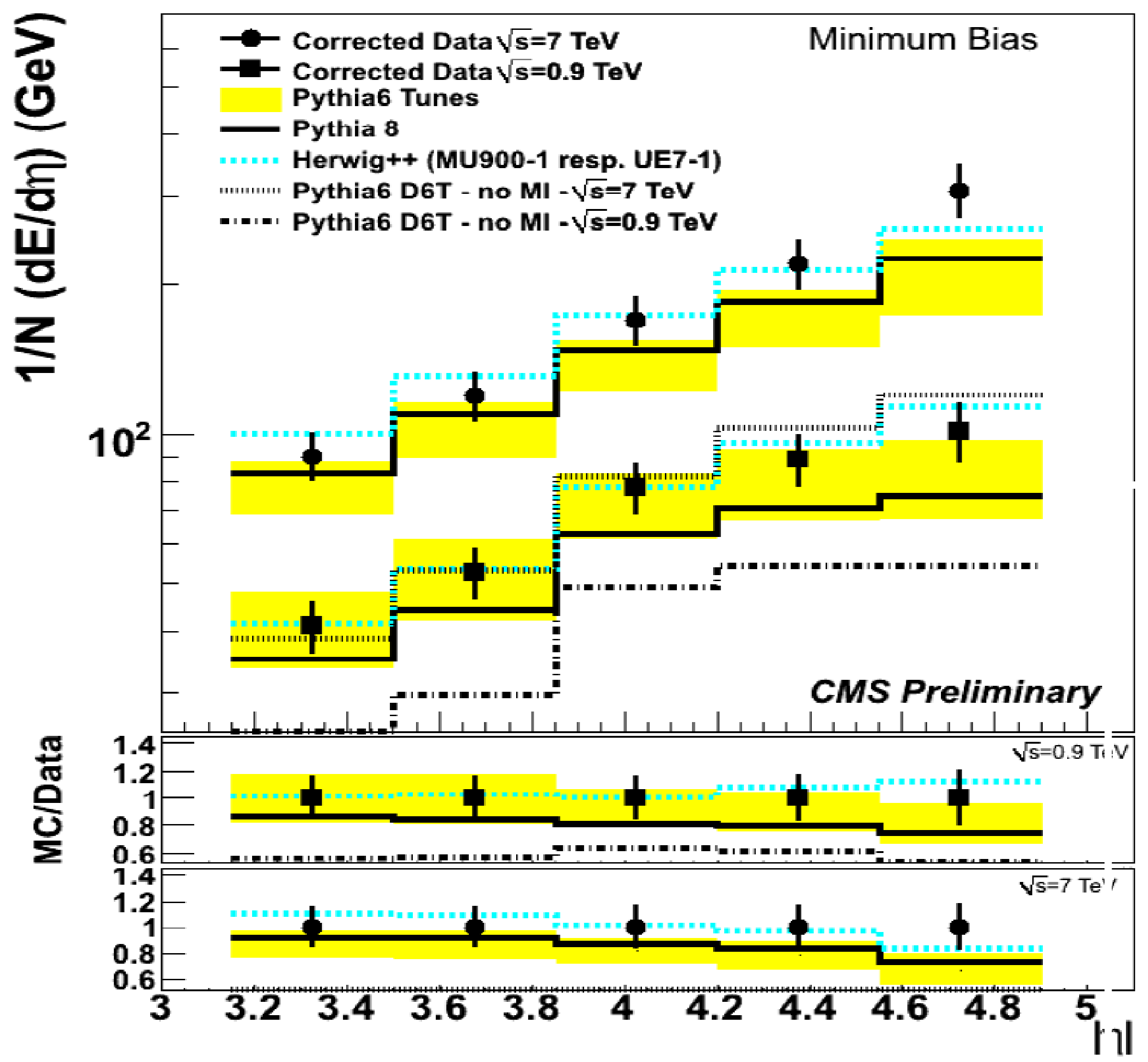
MinBias Energy Flow measurements

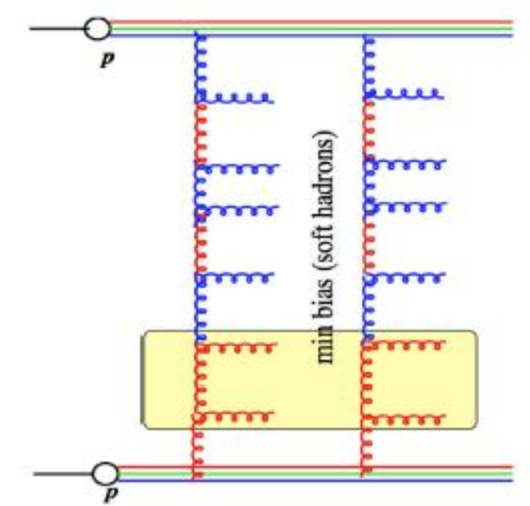




- Measurements at $\sqrt{s}$ = 0.9 and 7 TeV
- Rise with η corresponds to flat E_t-flow at 2.5 (6) GeV
- Change in E_t-flow from 0.9 to 7 TeV similar to change in N_{ch}
- At $\sqrt{s}$ = 0.9 T Ev similar to UA1 measurement

MinBias Energy Flow measurements

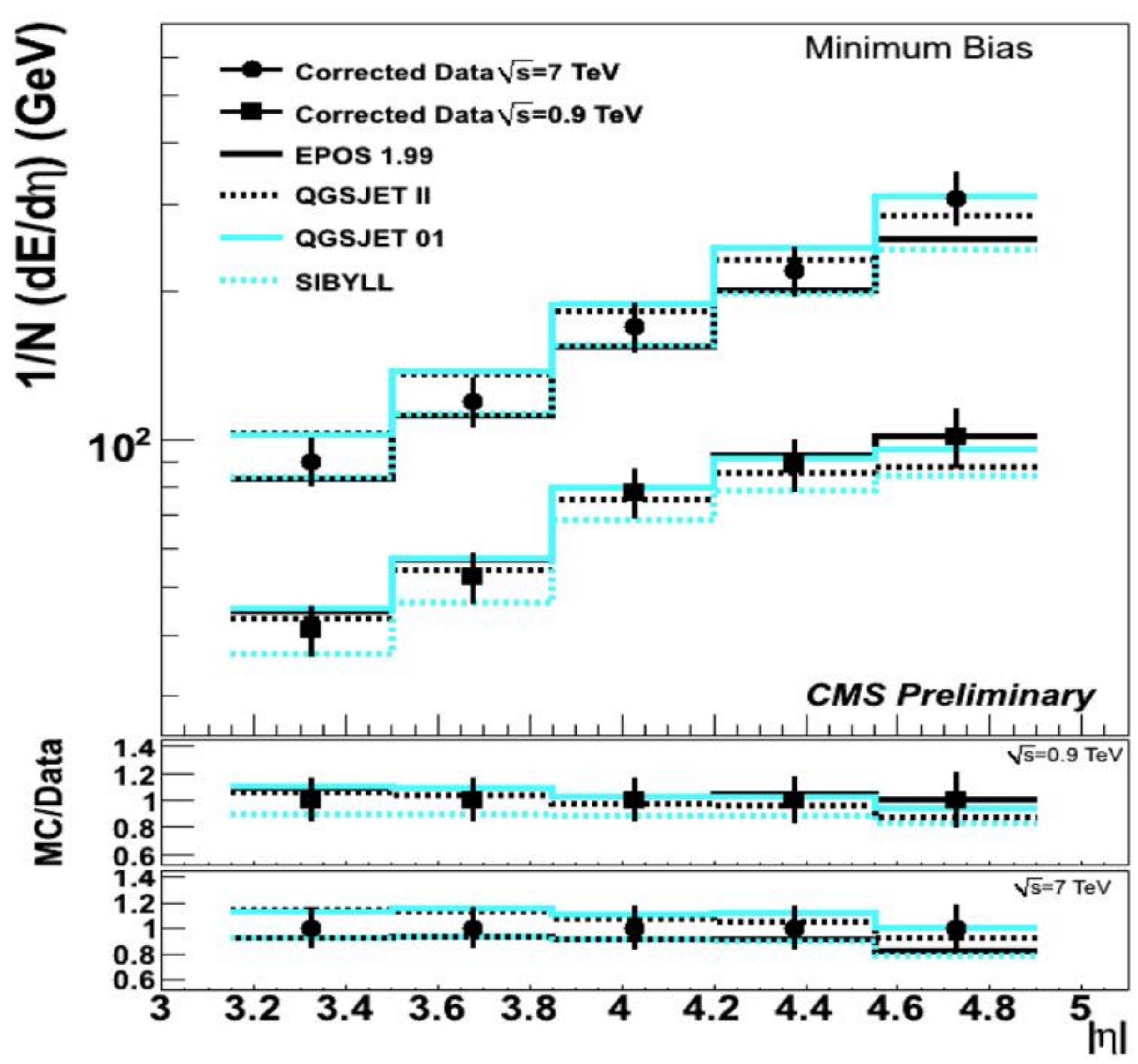


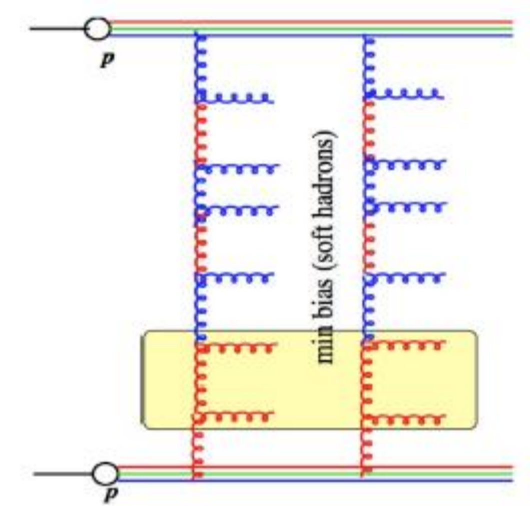


Comparison to MC

- Predictions w/o MI too low
- Herwig
  - √s dependent tunes work
- Pythia
  - Large spread between tunes
  - Even LHC tunes do not work well

MinBias Energy Flow measurements

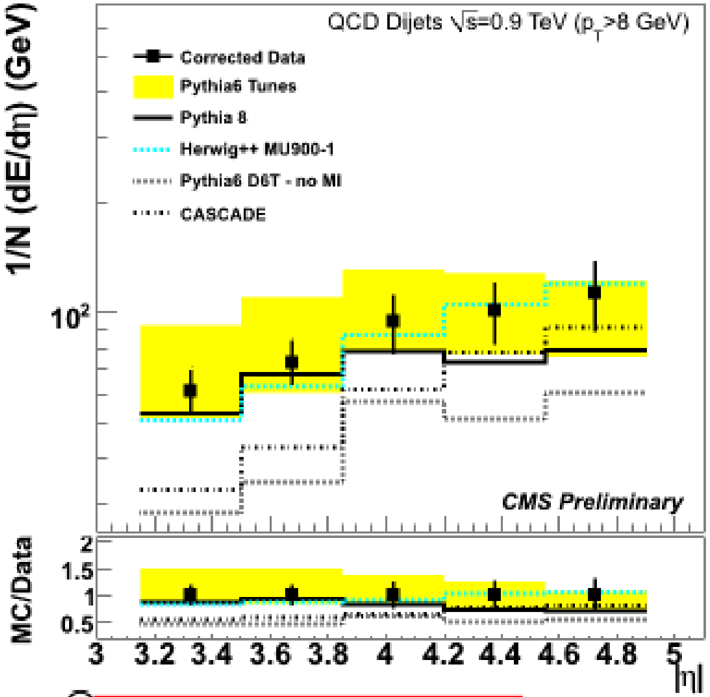


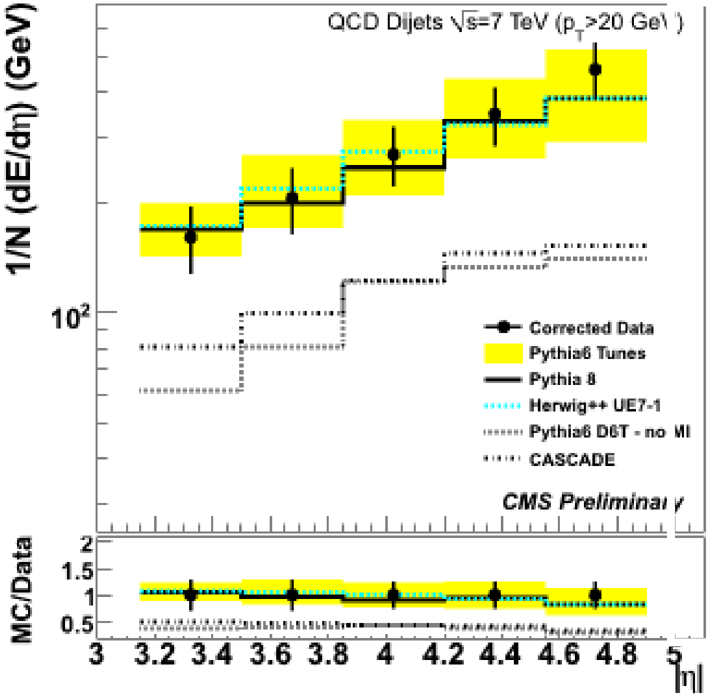


Comparison to MC

- Cosmic Ray generators
  - Work fairly well without extra tuning

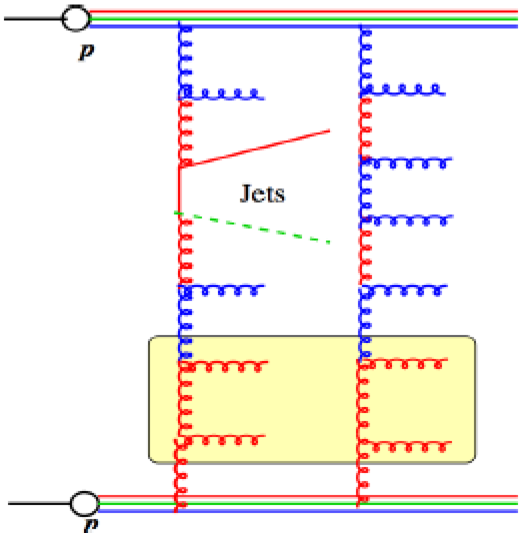
Dijet Energy Flow measurements





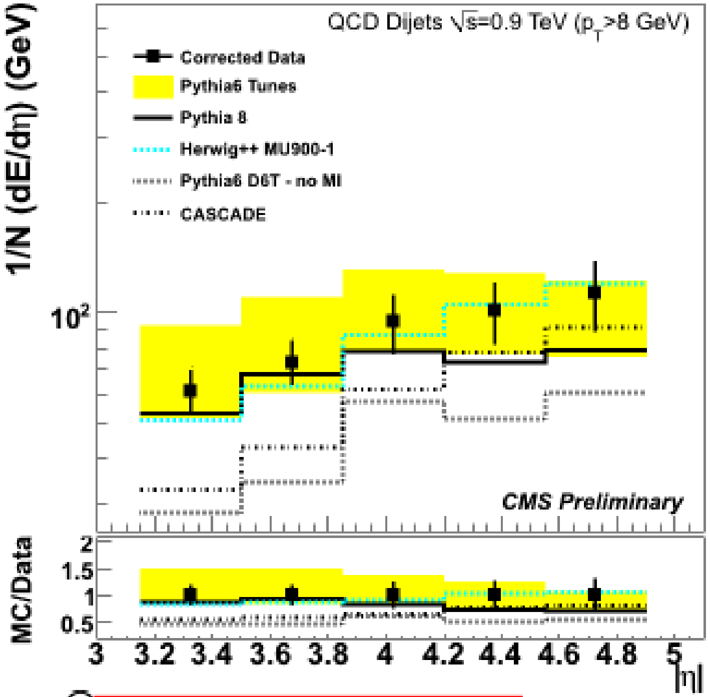
Dijets with

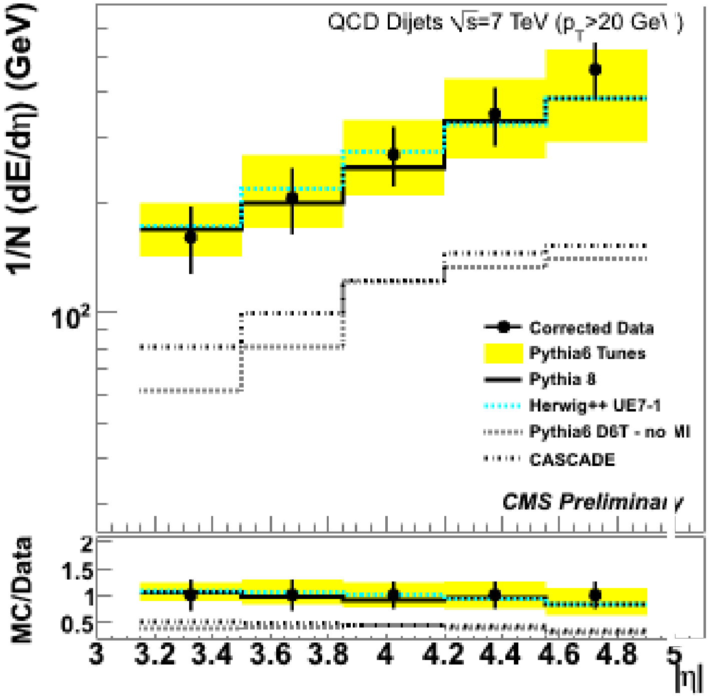
- P_t > 8 GeV for √s = 0.9 GeV
- P_t > 20 GeV for √s = 7 GeV



- Rise with η corresponds to decreasing E_t-flow with $E_t \approx 11.5$ (9) GeV at $\eta \approx 3$ (5)
- E_t-flow is much larger than observed at HERA (by a factor of 3 – 5)

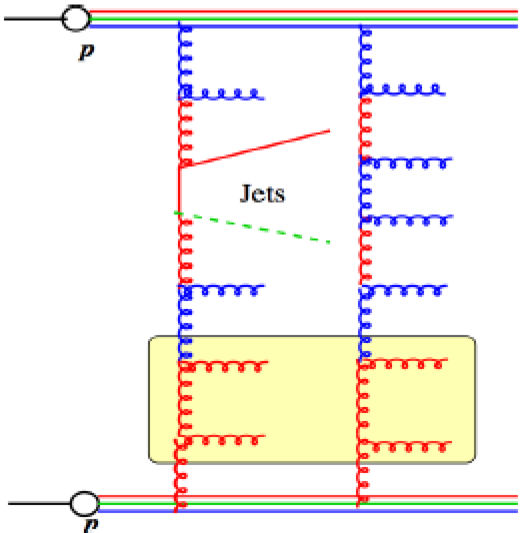
Dijet Energy Flow measurements





Dijets with

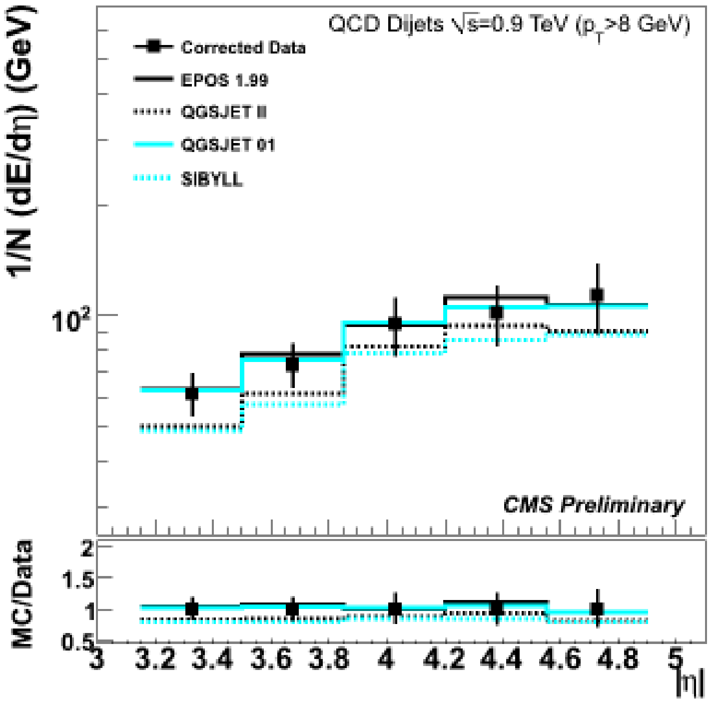
- $P_t > 8$ GeV for $\sqrt{s} = 0.9$ GeV
- $P_t > 20$ GeV for $\sqrt{s} = 7$ GeV

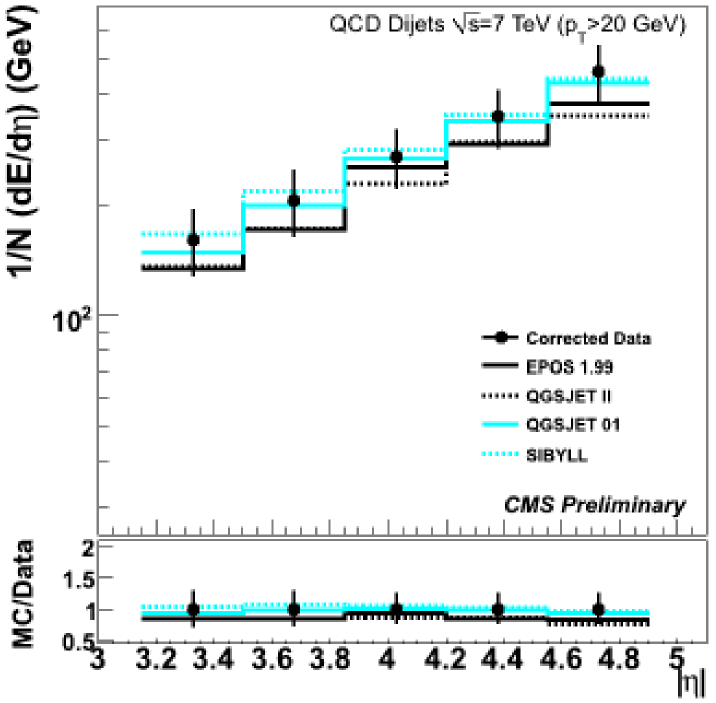


Comparison to MC predictions

- Predictions without MI too low
- Herwig
  - $\sqrt{s}$ dependent tunes work well
- Pythia
  - Different tunes cover the data

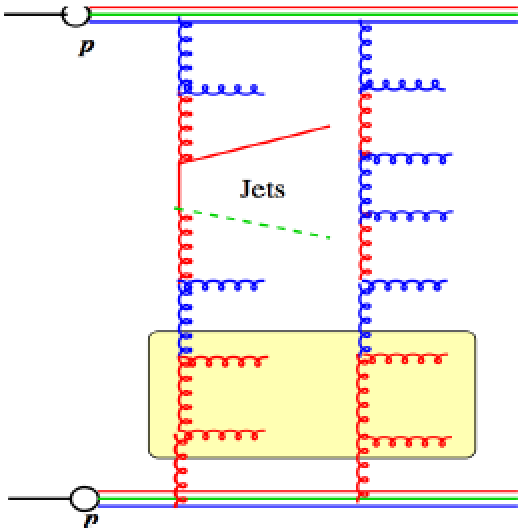
Dijet Energy Flow measurements





Dijets with

- P_t > 8 GeV for √s = 0.9 GeV
- P_t > 20 GeV for √s = 7 GeV



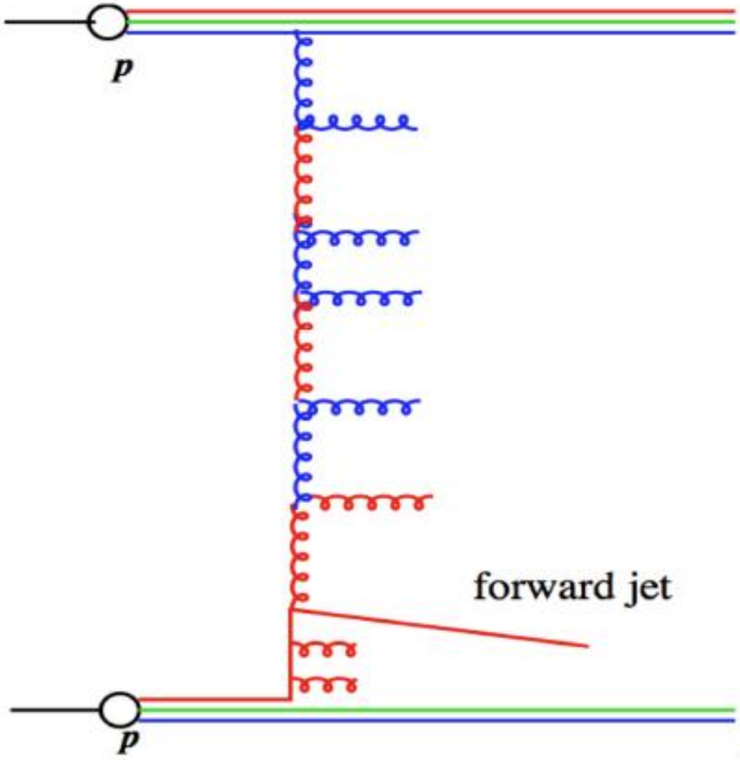
Comparison to MC predictions

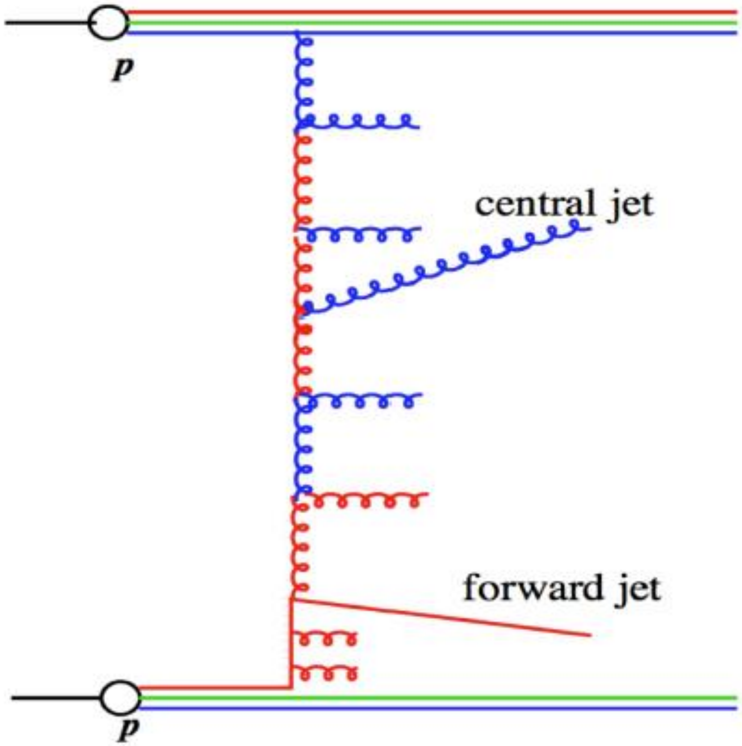
- Cosmic Ray generators
  - Describe the data fairly well (√s = 7 GeV)

Jets in the forward region

CMS PAS FWD 10-003
CMS PAS FWD 10-006

Jets in the forward region

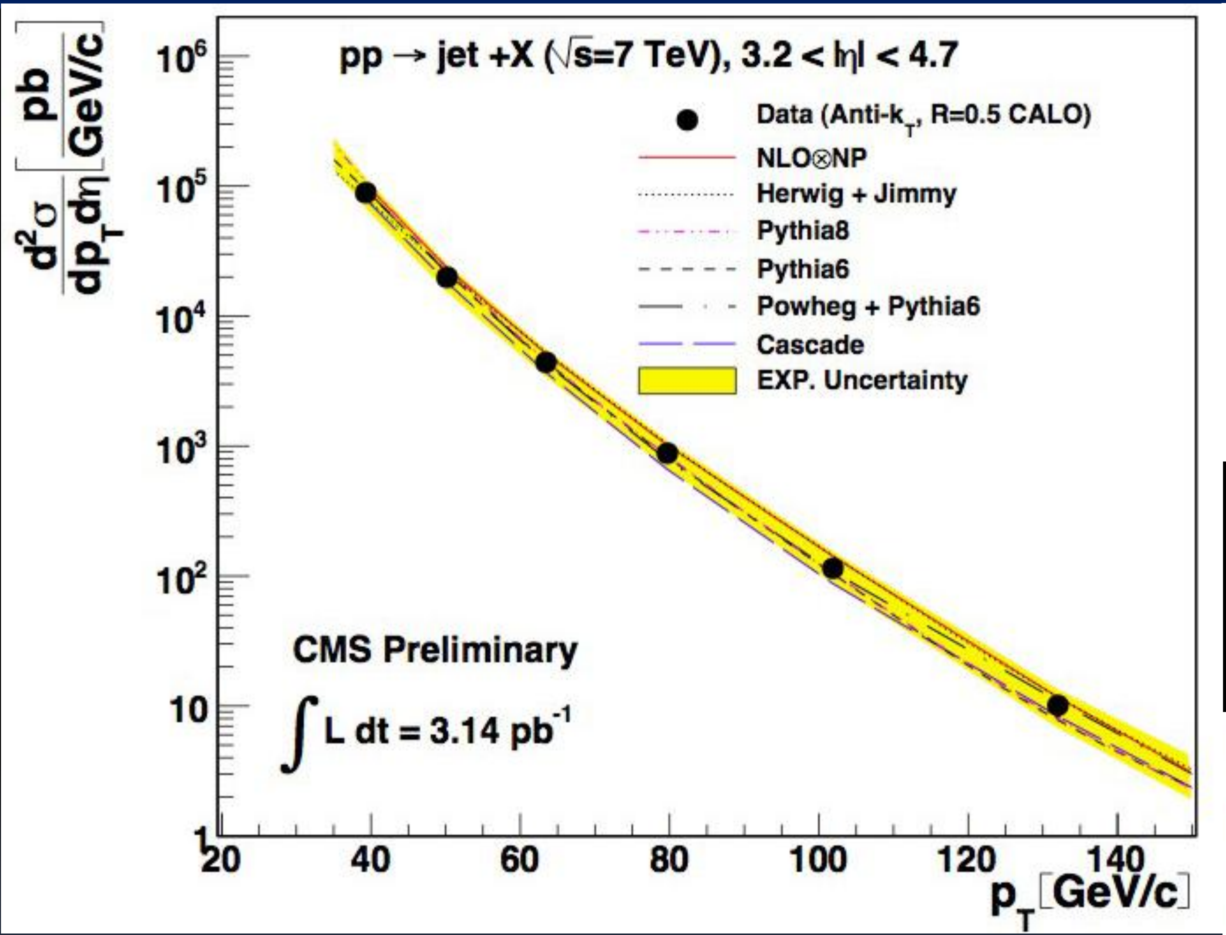


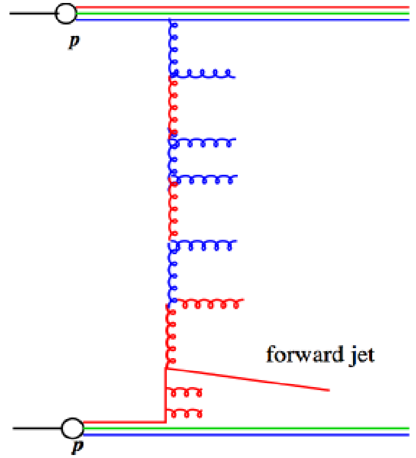


- Inclusive forward jets
  - $E_t > 35$ GeV (anti-kt, R = 0.5)
- $3.2 < |\eta_f| < 4.7$

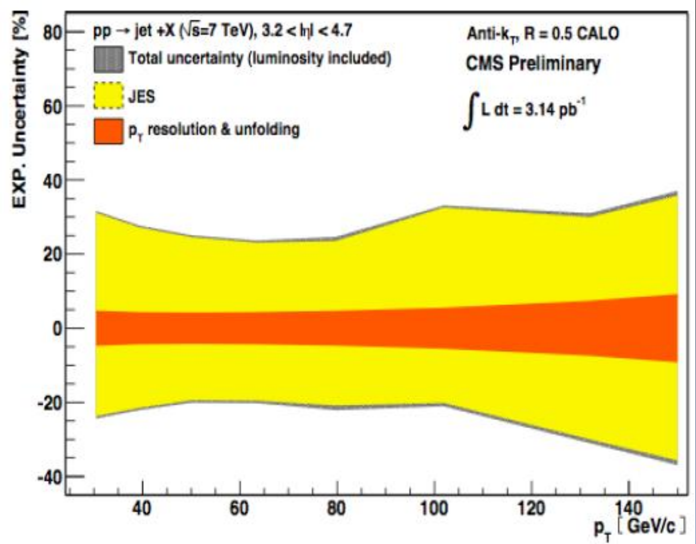
- Associated forward/central jets
  - $E_t > 35$ GeV (anti-kt, R = 0.5)
- $|\eta_c| < 2.8$ and $3.2 < |\eta_f| < 4.7$

Inclusive forward Jets



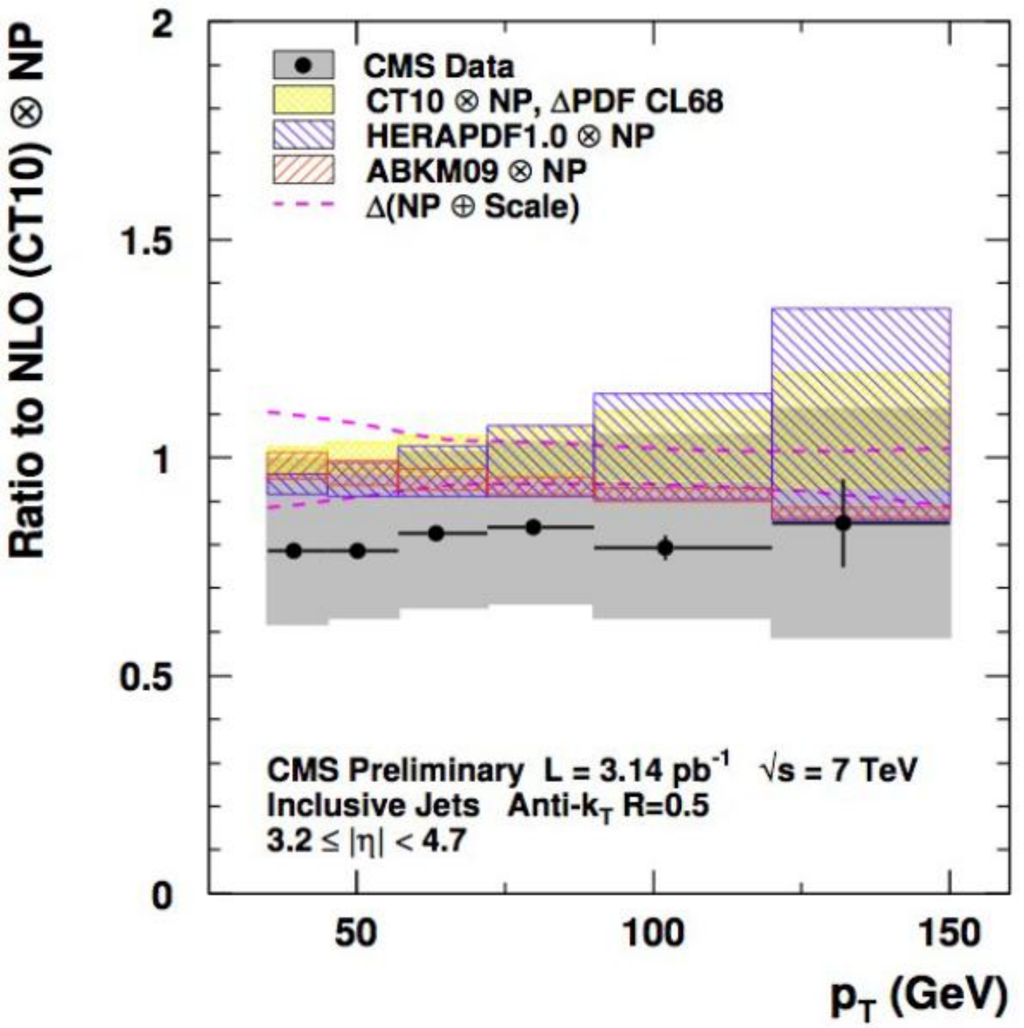


high energetic jets $p_t \sim 150$ GeV
→ $E \sim 3000$ GeV



- Jets measured in $3.2 < |\eta_f| < 4.7$
- Largest systematic uncertainty: JES
- Theory predictions agree with data within experimental uncertainties

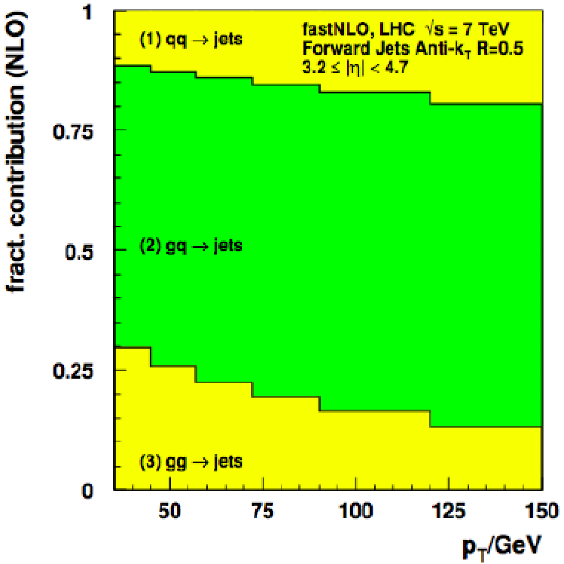
Inclusive forward Jets

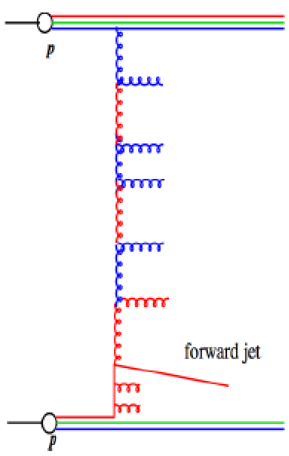


- Forward Jet measurements can constrain high and low x parton distributions

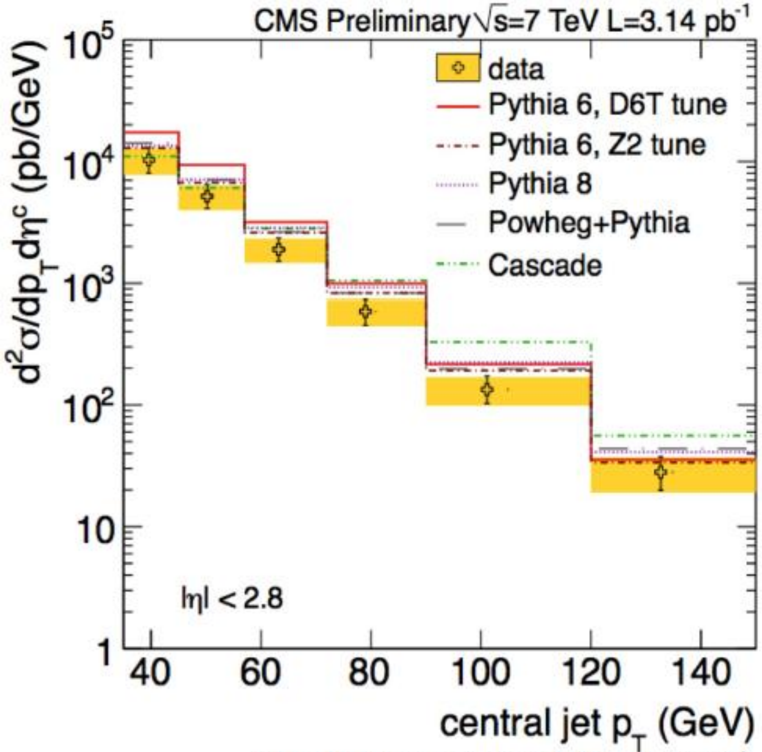
CMS Note 2011-004

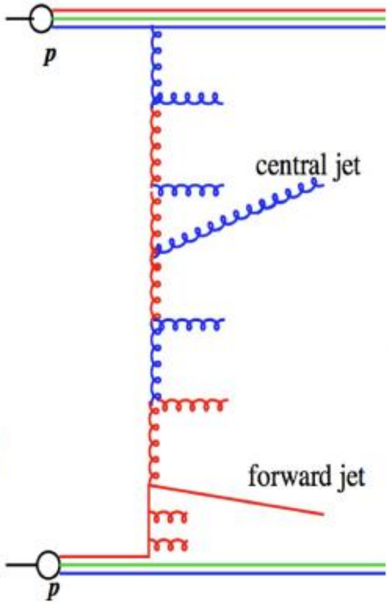
- Non-perturbative (NP) corrections
  - Hadronization and MPI
- Scales: μ_f & μ_r varied independently (x2)
- ≈ 10% uncertainty
- PDF uncertainties largest at high p_t → high x partons
- ≈ 10 – 30%

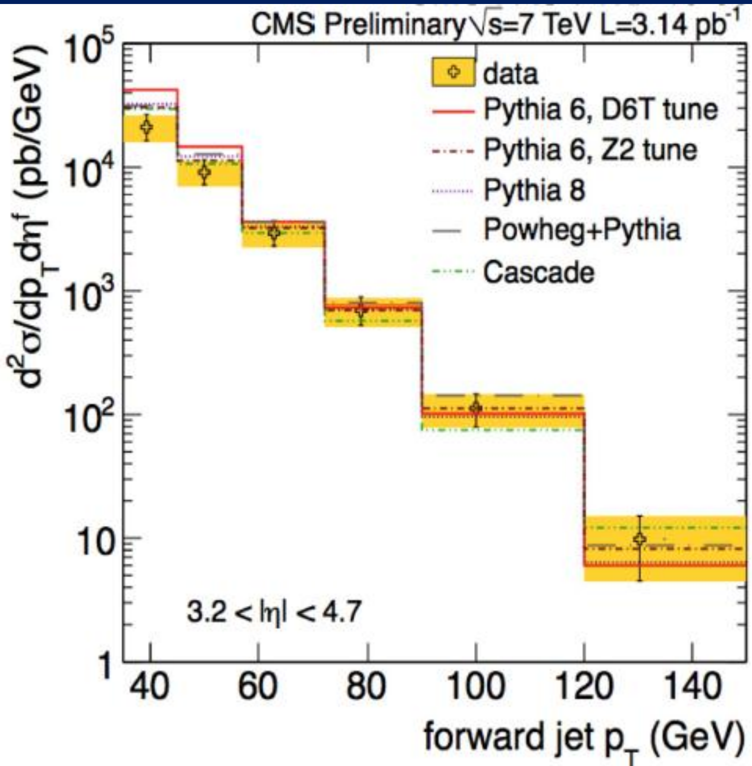


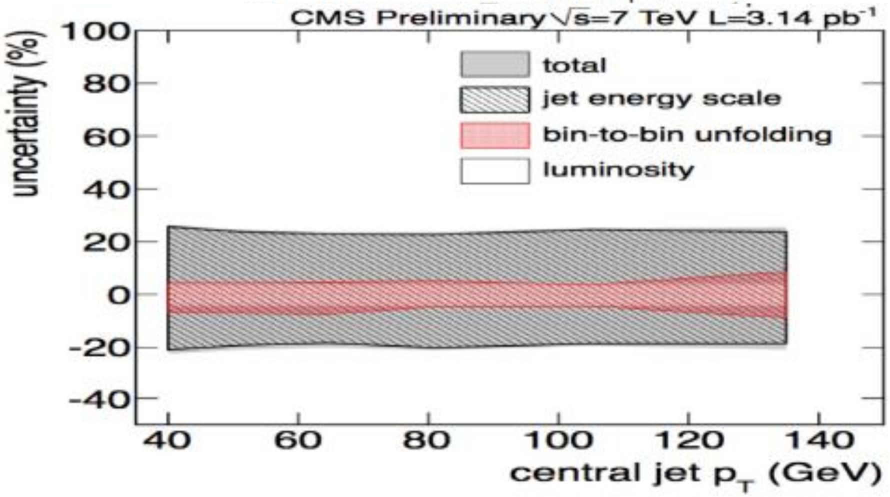


Forward and central Jets



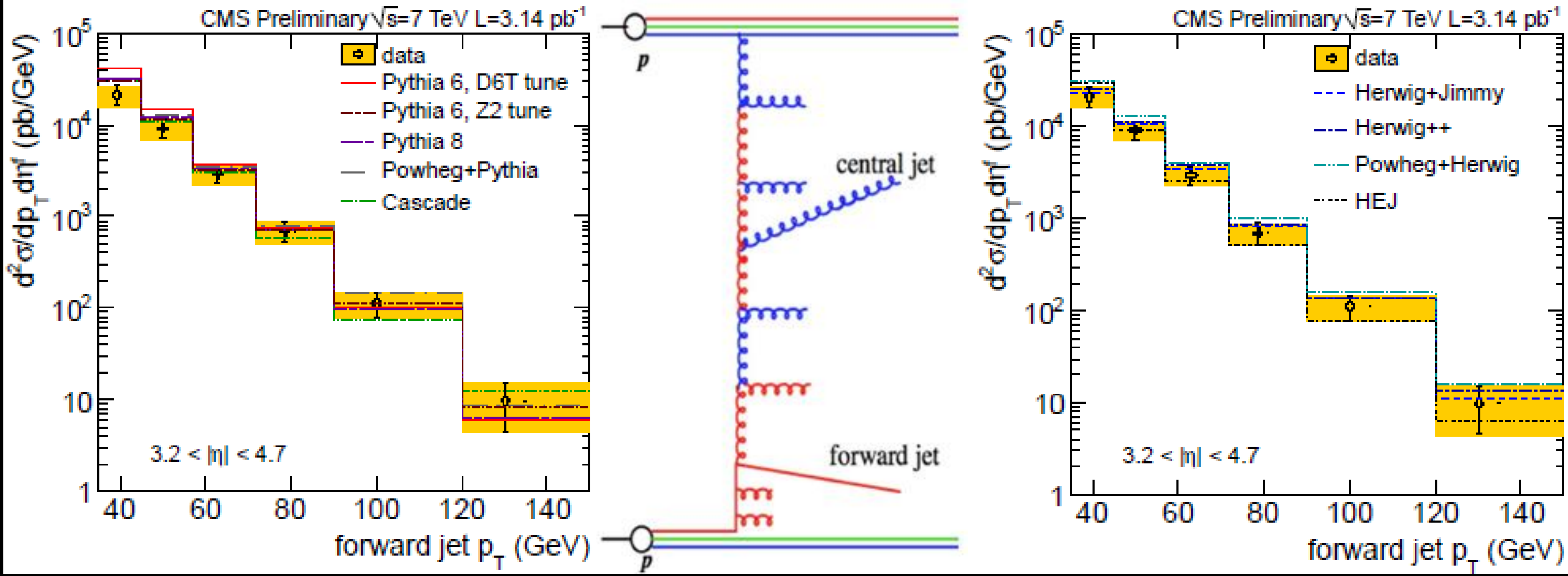






- Forward and central jets measured with $p_t > 35$ GeV
- Largest uncertainty : JES
- Large spread in theory predictions

Forward and central Jets



- Predictions from collinear approach:
- Differences between Pythia - Herwig
- Differences also in POWHEG predictions using Pythia/ Herwig for PS

- Predictions from small x calculations:
- HEJ (at parton level): within experimental uncertainties
- CASCADE: large deviation from data

→ Room for improvement

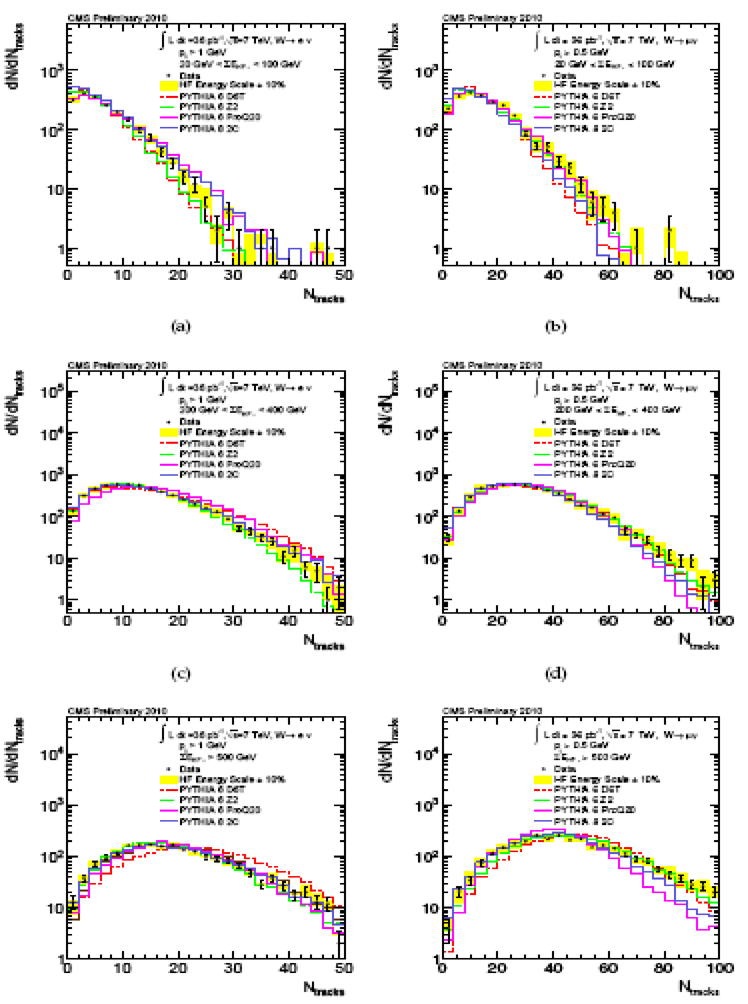
Conclusions

- Inelastic cross-section
  - New measurement based on counting vertices in pileup events
- Inclusive diffraction at 7 TeV
  - No models completely describe calorimeter and charged track distributions
- *W/Z*
  - No models completely describe energy flow and charged track distributions
  - Study of LRG events, and measurement of diffractive component from η_{lepton}
- Exclusive production
  - Observation of $\gamma\gamma\rightarrow\mu\mu$ standard candle, data well-described by LPAIR MC
- Inclusive forward and forward/central jets
  - Test small x predictions and PDFs
- Correlations between central and forward region – challenge to the theory
- More data (2011) currently being analysed

Extra

W/Z Distributions

- Measurements of
    - Energy flow in HF ($3 < |\eta| < 4.9$), summing calorimeter towers above4GeV
    - Track multiplicities ($|\eta| < 2.4$), for p_T>0.5 GeV and p_T>1.0 GeV
    - Correlations – track multiplicities in bins of energy flow, energy deposits in HF+ vs. HF-
- Comparison to a range of Pythia6 and Pythia8 tunes
    - No tune simultaneously describes all multiplicity and energy flow distributions in data



LHC as a small x machine

- LHC can access lowest x values
  - for central W/Z production at
    - 7 TeV: $x \sim 0.01$
    - 14 TeV: $x \sim 0.005$
  - at forward rapidities ($\eta \sim 5$):
    - 7 TeV $x \sim 6 \cdot 10^{-5}$
    - 14 TeV $x \sim 3 \cdot 10^{-5}$
  - for central jets with p_t > 20 GeV
    - 7 TeV : $x \sim 0.006$
    - 14 TeV : $x \sim 0.003$
  - at forward rapidities ($\eta \sim 5$):
    - 7 TeV: $x \sim 4 \cdot 10^{-5}$
    - 14 TeV: $x \sim 2 \cdot 10^{-5}$

J. M. Campbell, J. W. Huston, and W. J. Stirling.
Hard Interactions of Quarks and Gluons: A Primer for LHC Physics.
Rept. Prog. Phys., 70:89, 2007.