Forward physics results from CMS

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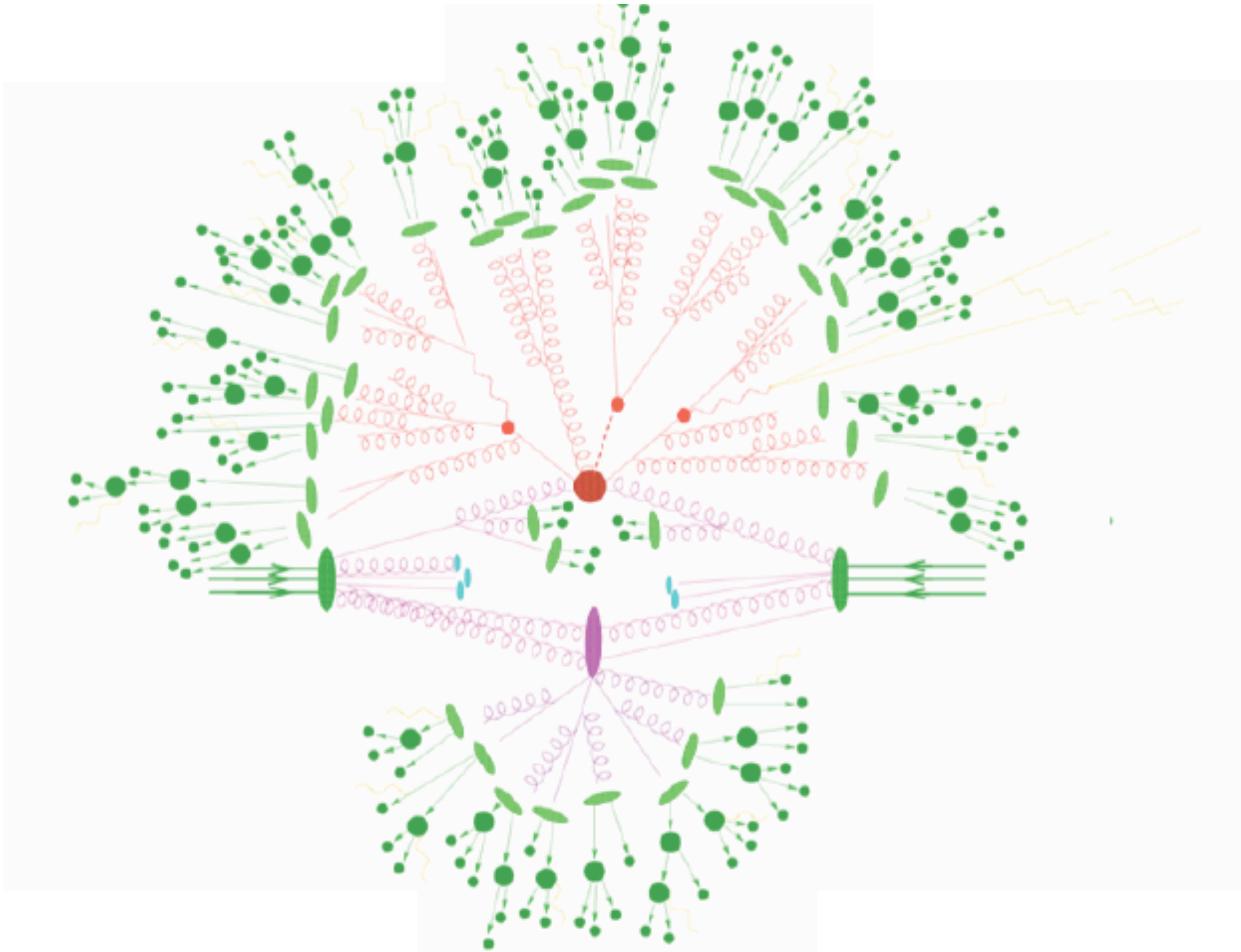
Forward physics?



Forward physics?

Proton-proton collisions are complicated..

Their understanding depends on a wide range of phenomena many of which manifest themselves by looking *forward, e.g.*:

Low-x QCD & pdf's, diffraction, γ interactions, underlying event & MPI, etc.

In this presentation will cover some of the results on these subjects from the CMS collaboration, mostly with the data set collected during 2010

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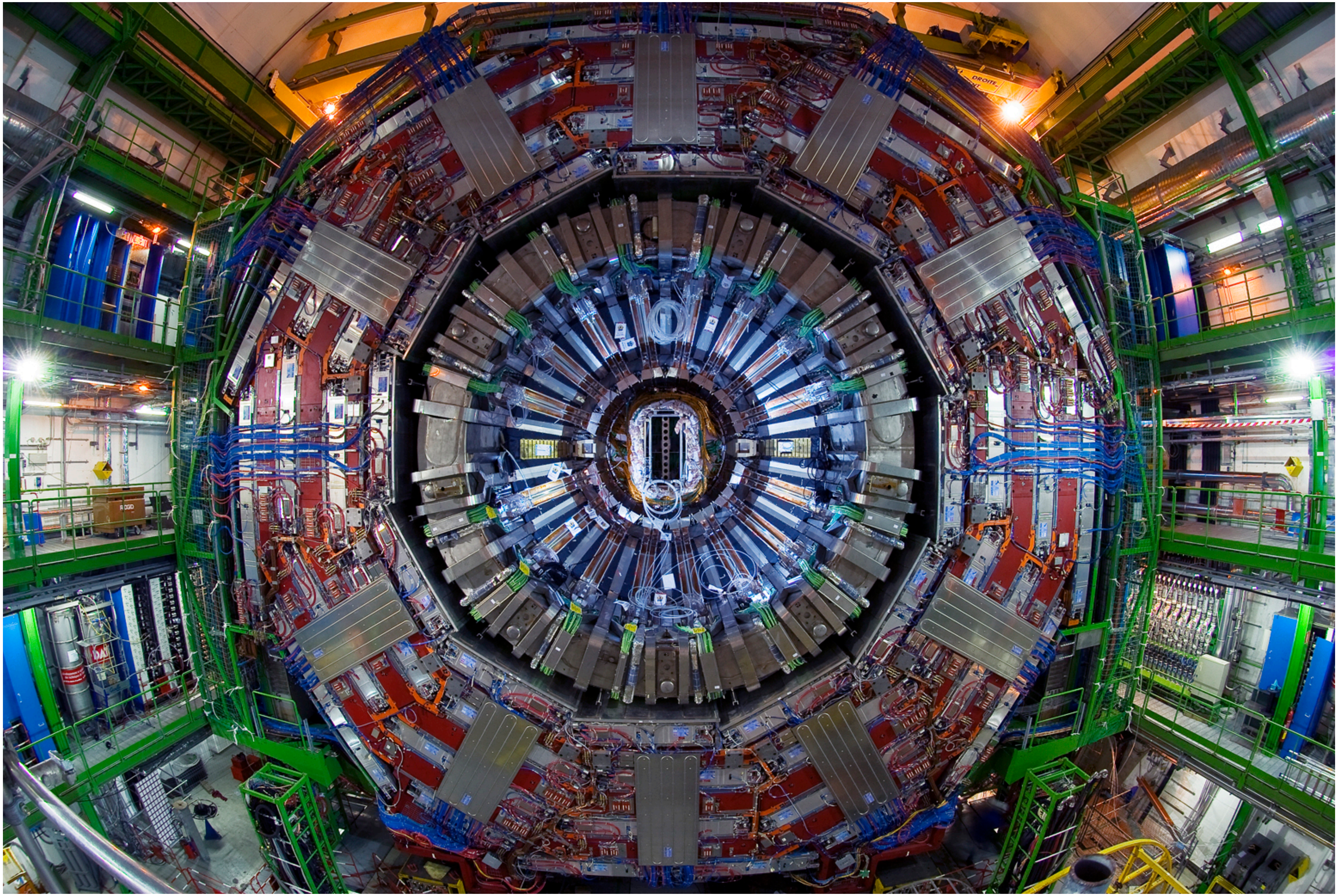
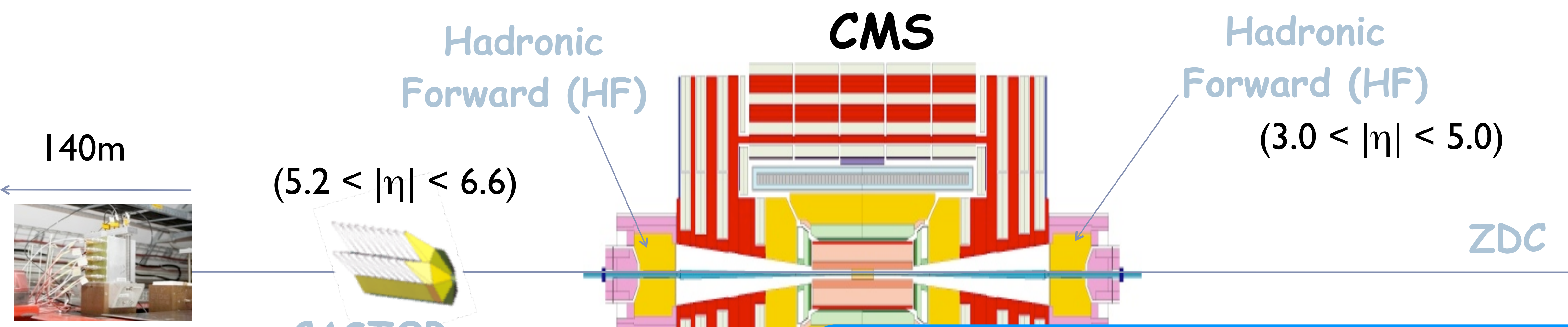
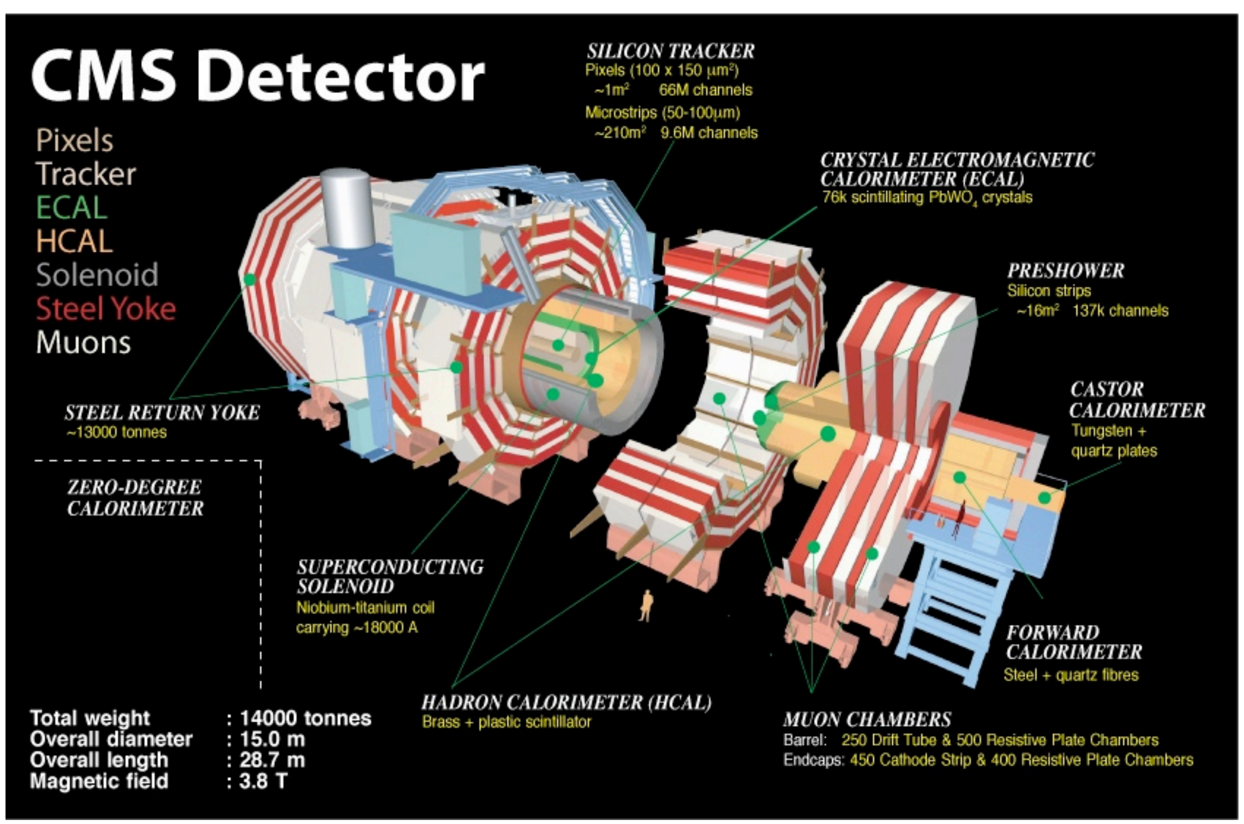
CMS PAS FWD-11-001: **Measurement of the inelastic pp cross section at 7 TeV**
CMS PAS FWD-10-005: **Measurement of the exclusive two-photon production of muon pairs**
CMS PAS FWD-10-001: **Observation of diffraction at 900 and 2360 GeV**
CMS PAS FWD-10-007: **Observation of diffraction at 7 TeV**
CMS PAS FWD-10-008: **Forward Energy Flow and Central Track Multiplicities in W and Z boson Events at 7 TeV**
CMS PAS FWD-10-011: **Forward energy flow**
CMS PAS FWD-10-003: **Measurement of forward jets at 7 TeV**
CMS PAS FWD-10-006: **Cross section measurement for simultaneous production of a central and a forward jet at 7 TeV**

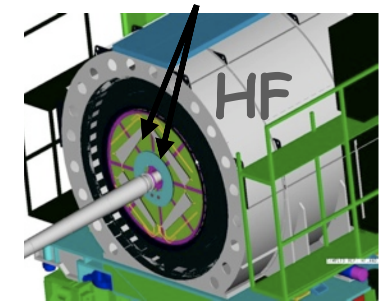
The CMS detector



Forward detectors @ CMS







Hadron Forward:

@11.2m from interaction point

Rapidity coverage: $3 < |\eta| < 5$

Steel absorbers/quartz fibers (Long+short fibers)

0.175×0.175 η/φ segmentation

pp (visible) inelastic cross section

γγ (exclusive) interactions

Soft and hard diffraction

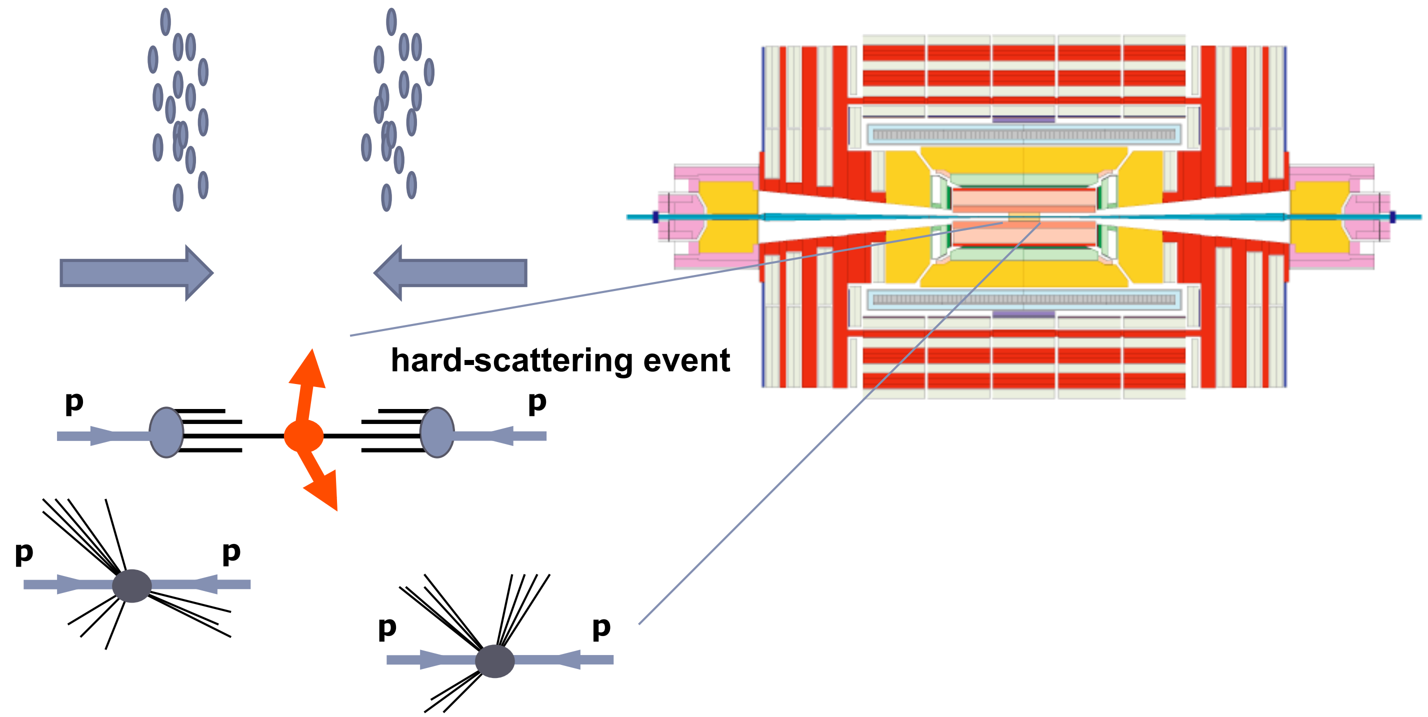
Central/forward correlations in hard interactions

Forward energy flow and multiple parton interactions

Forward and central-forward jet production

Total inelastic cross section

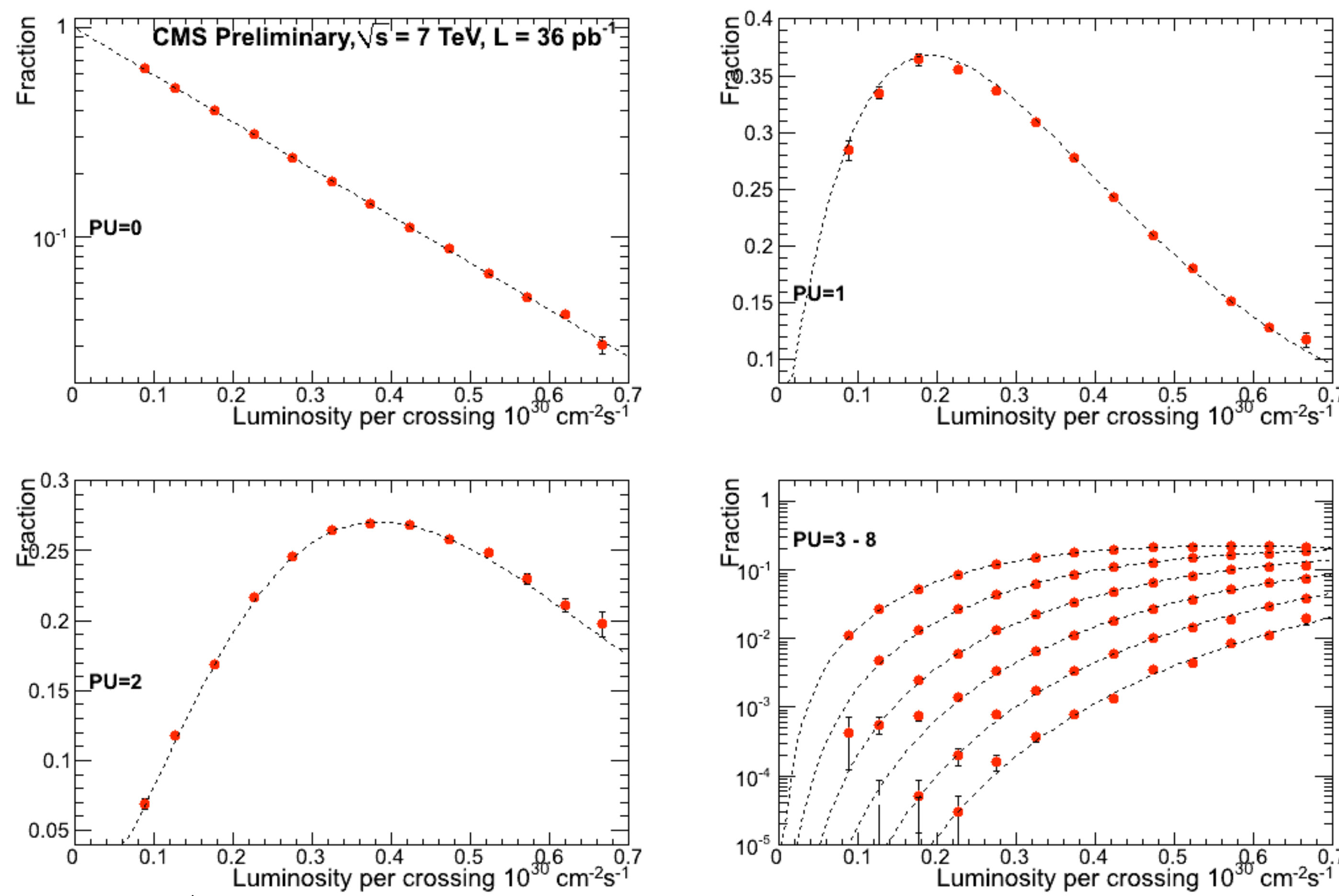
Additional (pile-up) interactions in a bunch crossing give an unbiased source of inelastic events



Probability follows a Poisson distribution that depends on the bunch luminosity and total cross section:

$$P(n) = \frac{(L\sigma)^n}{n!} \exp^{-L\sigma}$$

From the number of extra interactions versus luminosity the total (visible) cross section can be extracted



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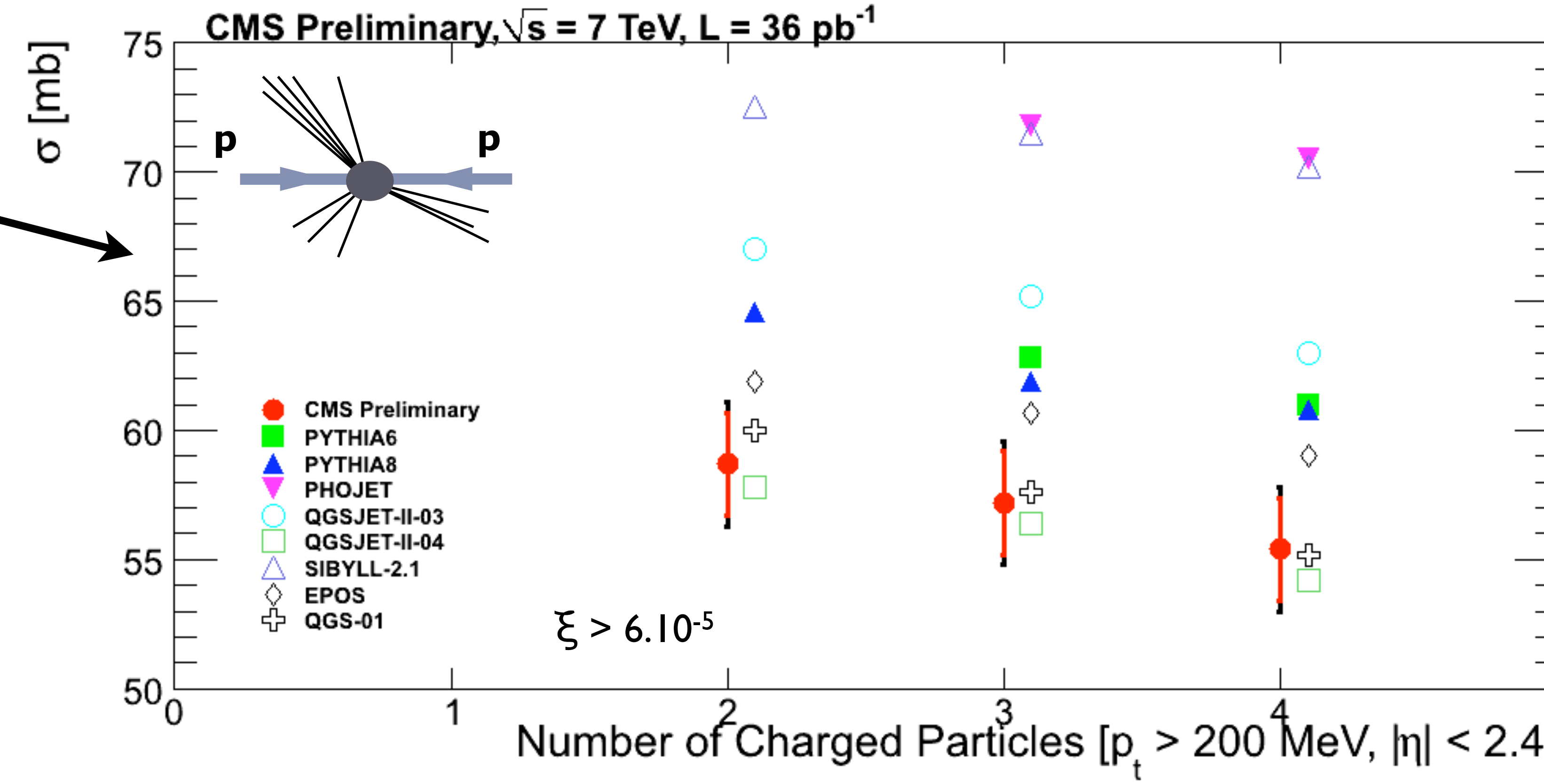
Total inelastic cross section

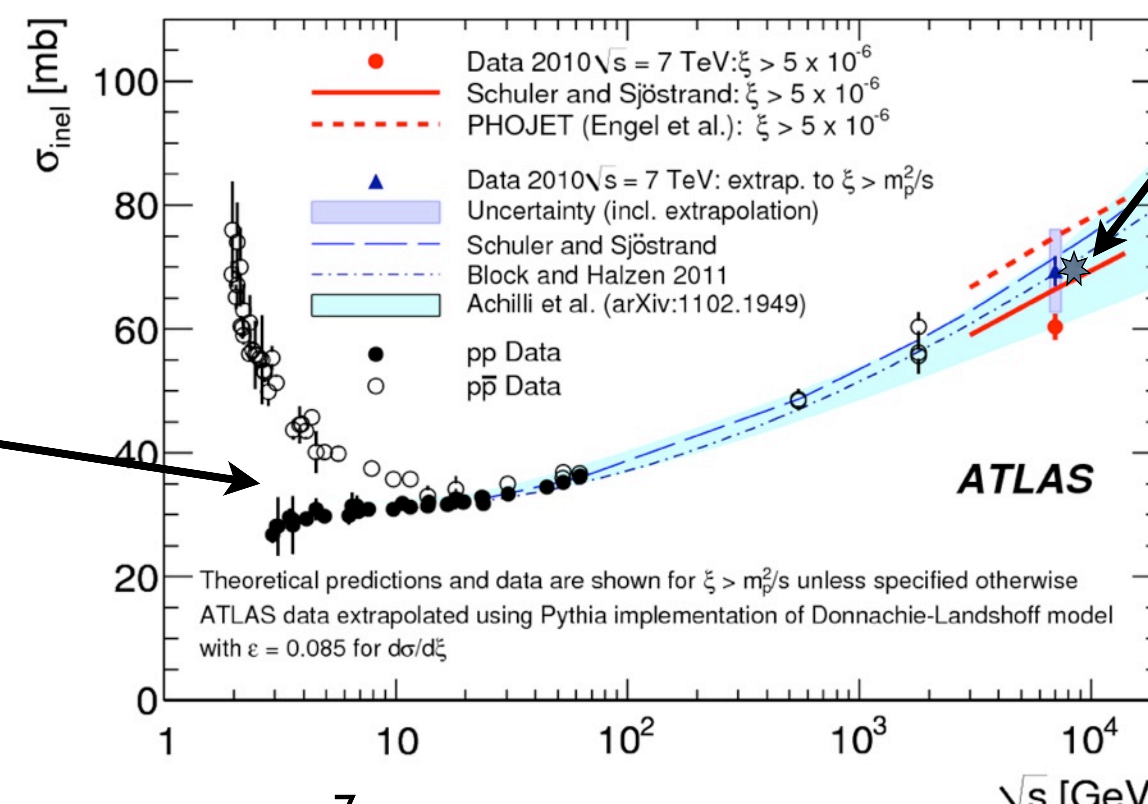
Procedure counts only (extra) events for which a vertex is reconstructed

Correct for the inelastic cross section for events with a minimum number of charged particles in the central region ($p_T > 200$ MeV, $|\eta| < 2.4$)

Minimum number of (2) charged particles is roughly equivalent to a cut-off at $\xi \sim 6.10^{-5}$

MC dependent extrapolation to total inelastic cross section



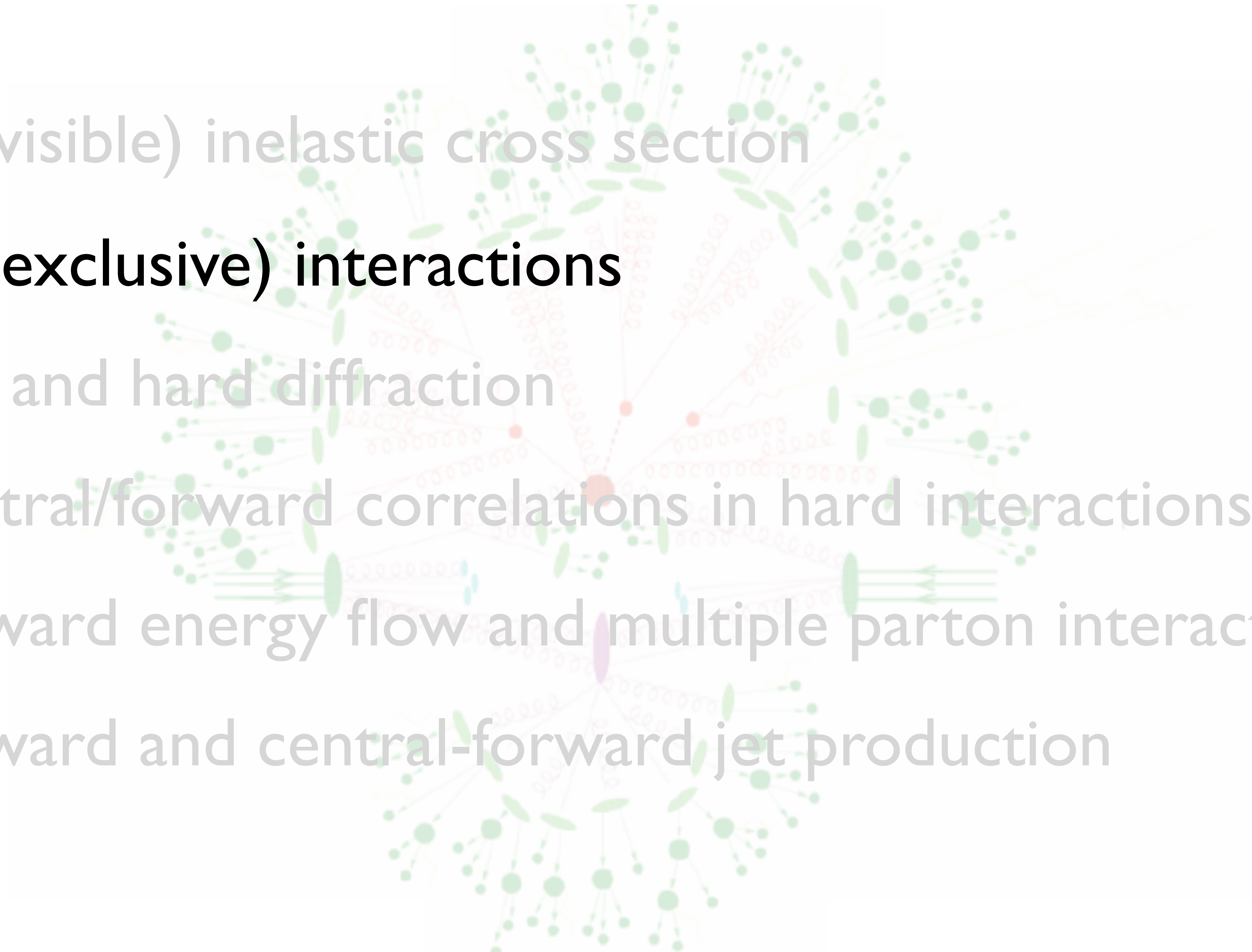


arXiv:1104.0326

CMS (ext.)

$$\sigma(pp) = 68 \pm 2.0\ (\text{Syst.}) \pm 2.4 (\text{Lum.}) \pm 4 (\text{Ext.})\ \text{mb}$$

CMS PAS FWD-11-001



pp (visible) inelastic cross section

γγ (exclusive) interactions

Soft and hard diffraction

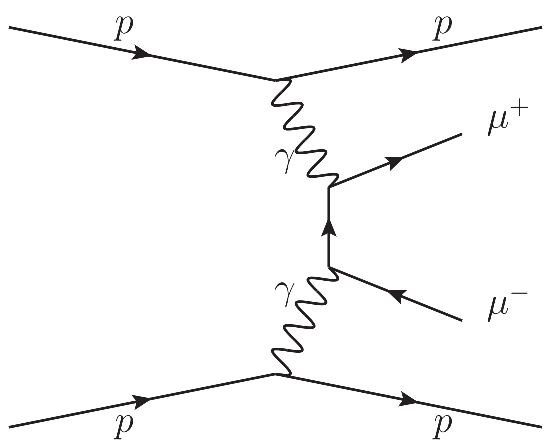
Central/forward correlations in hard interactions

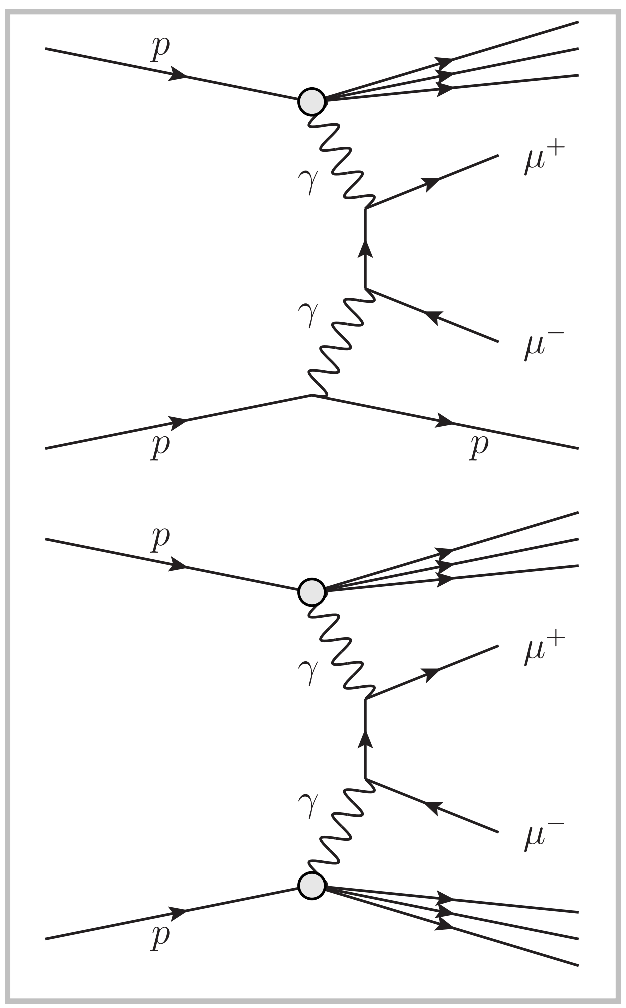
Forward energy flow and multiple parton interactions

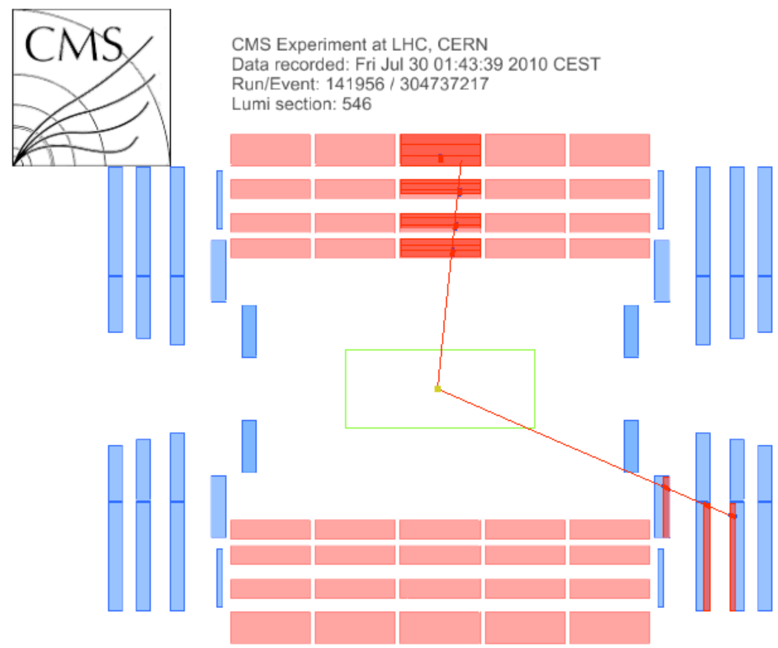
Forward and central-forward jet production

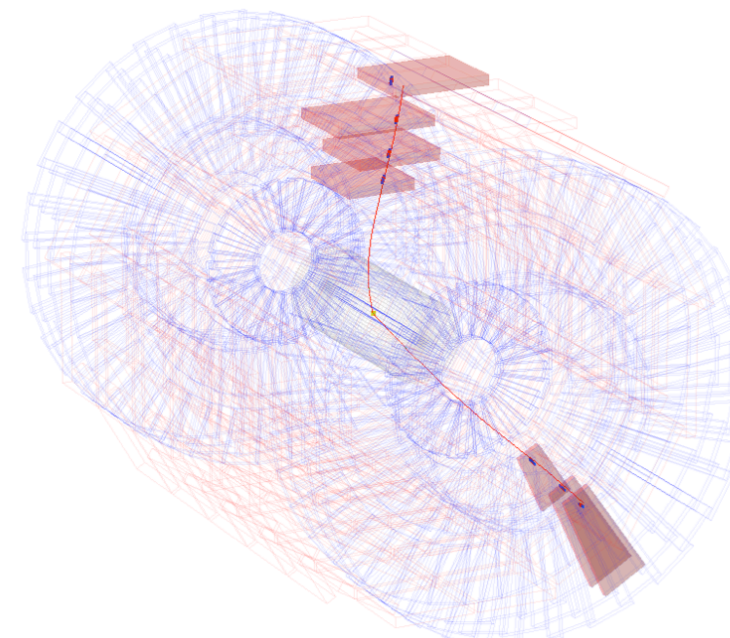
Exclusive γγ→μμ production

CMS PAS FWD-10-005







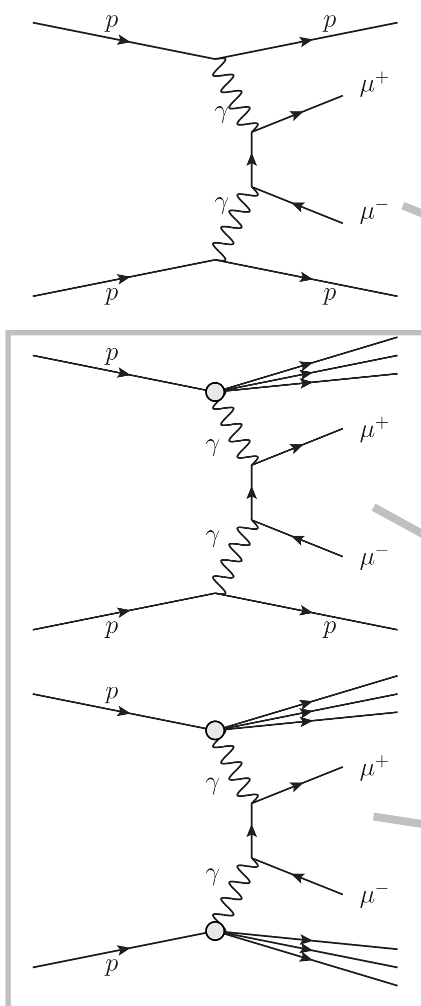


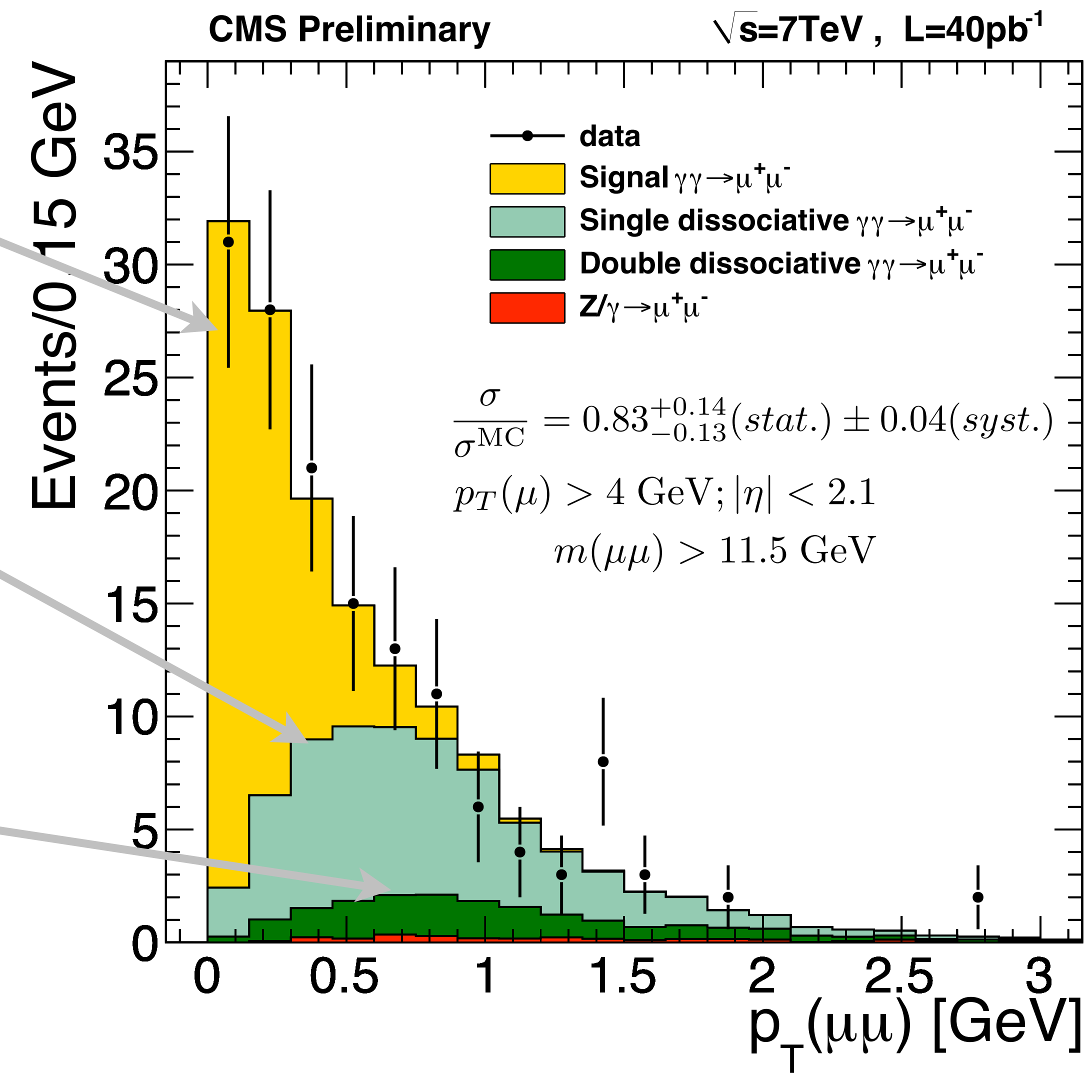
- Exclusive γγ→μμ events: 2 muons and *nothing else*
- Main background to pure QED process from single and double proton dissociation processes, where the proton fragments in a low mass state
- Standard candle for exclusive processes at the LHC and candidate for *absolute* luminosity measurement

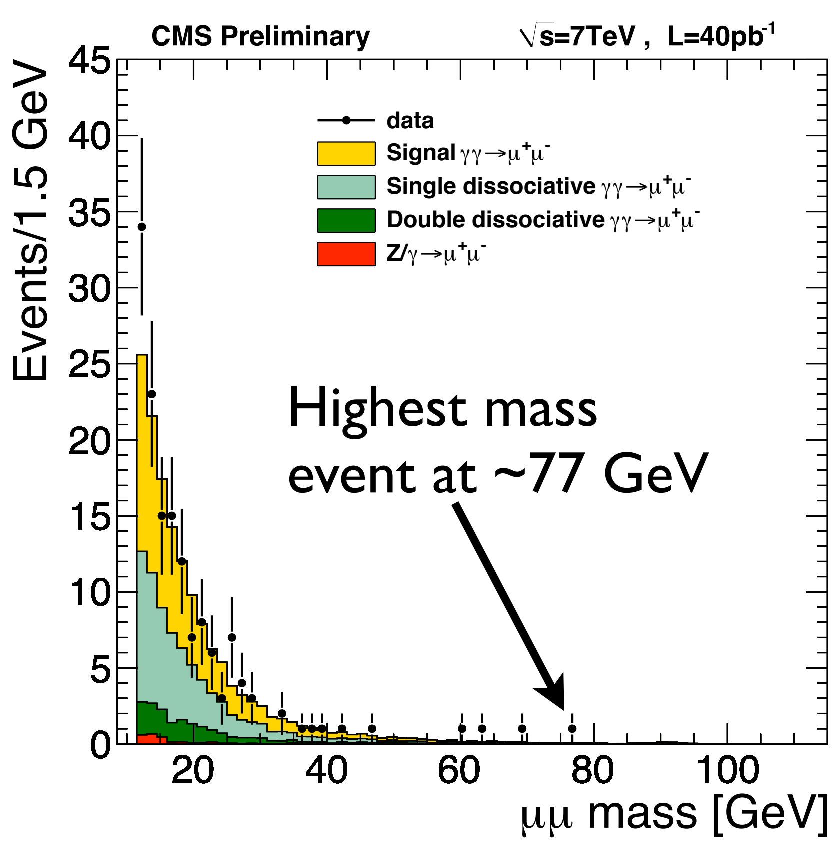
Exclusive γγ→μμ production

CMS PAS FWD-10-005

- Measurement restricted to well controlled kinematic region ($p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$), rejecting ϒ photo-production
- Exclusivity condition requires a primary vertex with exactly 2 muons and no other track within 2 mm
- Signal extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution







$$\sigma\,(p + \mu\mu + p) = 3.38^{+0.58}_{-0.55}(stat.) \pm 0.16(syst.) \pm 0.14(lum.)\text{pb}$$

- Largest systematics from track veto efficiency (data driven - pile-up sensitive)
- Good agreement between data and LPAIR MC (signal and proton dissociation)
- Potential to become competitive luminosity monitor at the LHC

pp (visible) inelastic cross section

γγ (exclusive) interactions

Soft and hard diffraction

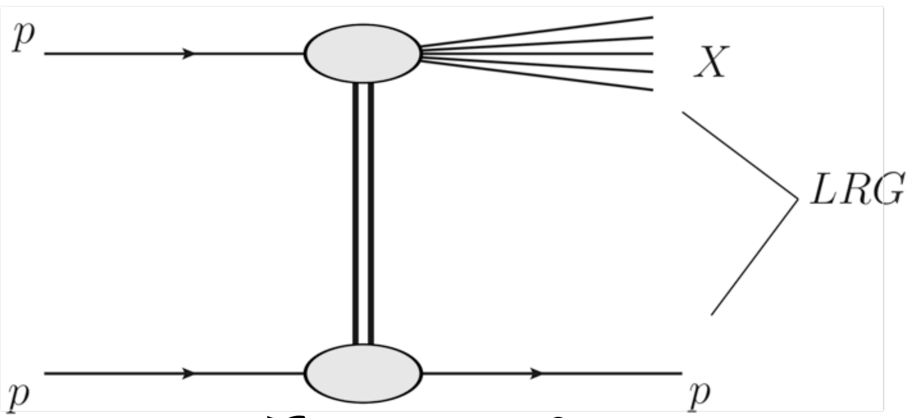
Central/forward correlations in hard interactions

Forward energy flow and multiple parton interactions

Forward and central-forward jet production

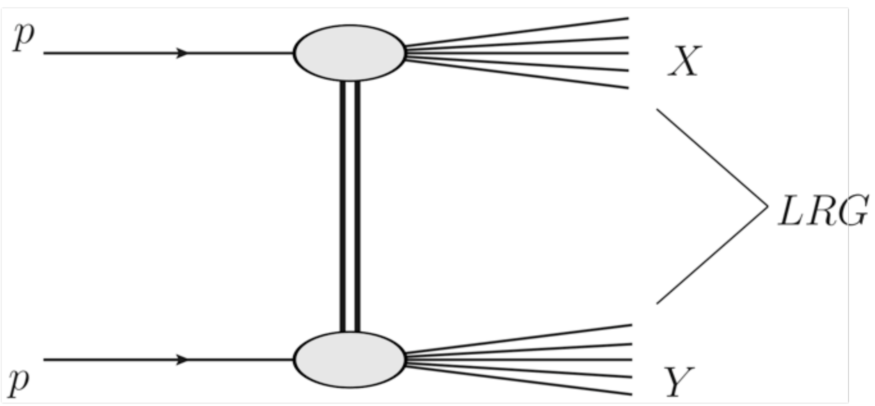
Diffraction in minimum-bias

Single-diffractive dissociation (SD):

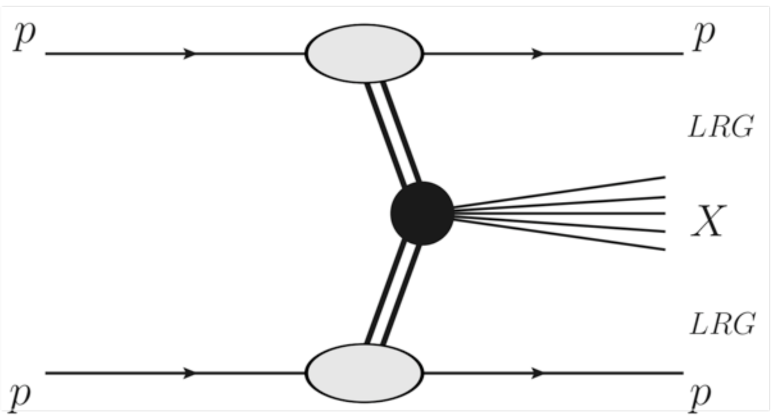


$t, \xi = (M_X)^2/s$

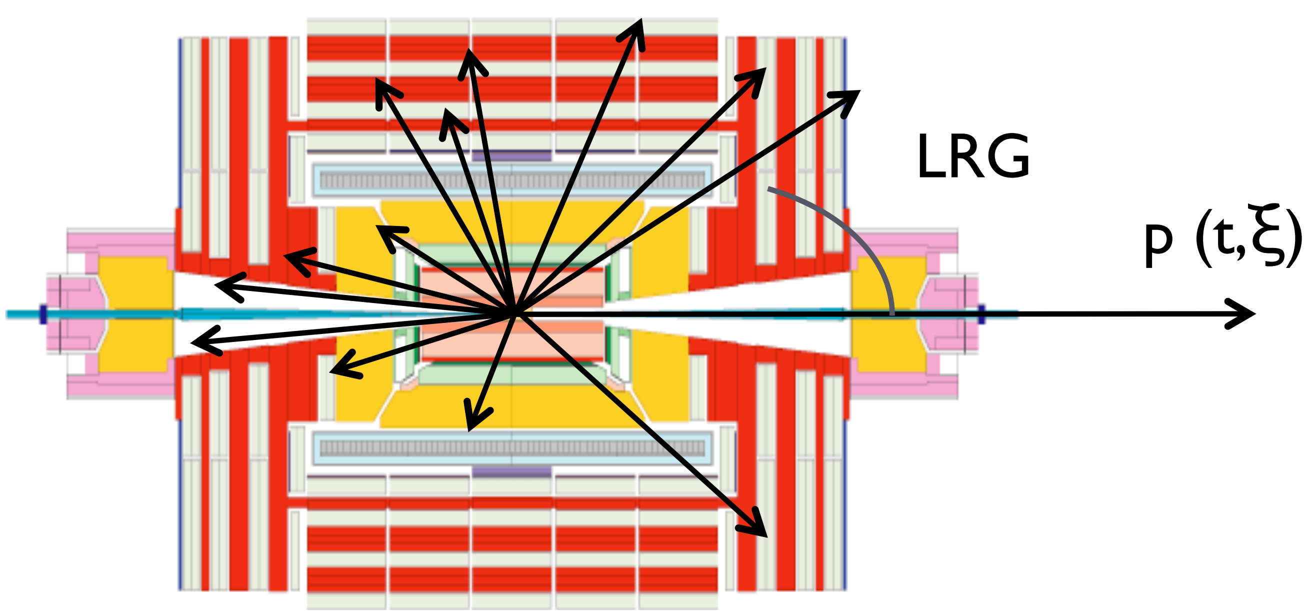
Double-diffractive dissociation (DD):



Central-diffractive dissociation (CD):



Sketch of single-diffractive event:

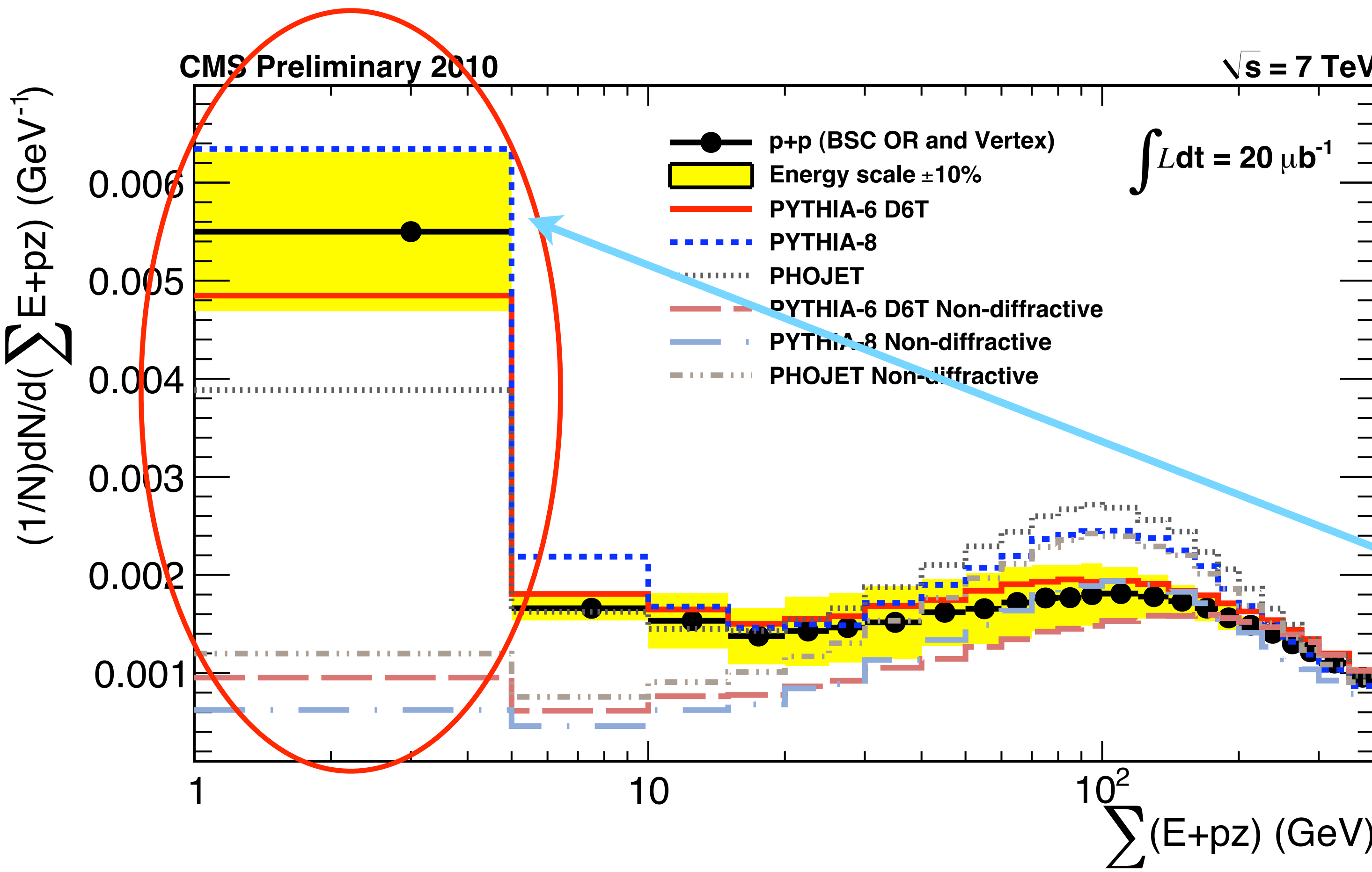


LRG: Large Rapidity Gap

Inclusive diffraction in general model dependent

Defining and constraining diffractive component important ingredient in the tuning of MC generators at the LHC

Observation of diffraction



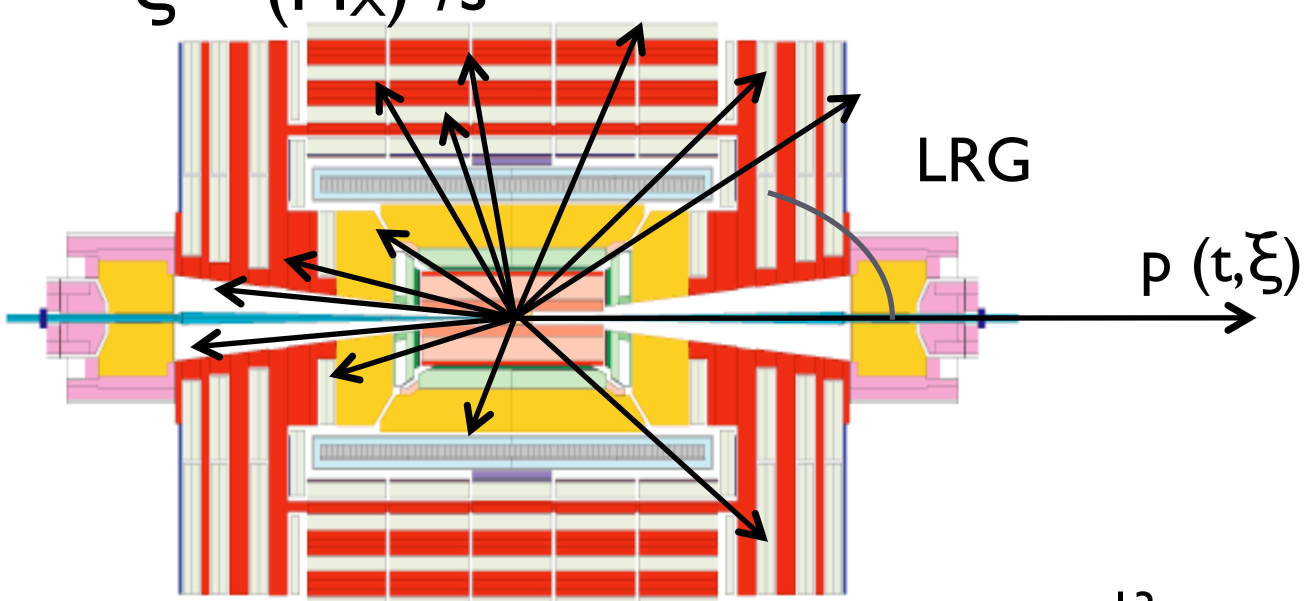
$\xi \sim \sum(E + p_z)$ when proton scattered in z-plus directions.

$\xi \sim \sum(E - p_z)$ when proton scattered in z-minus directions.

Inclusive diffractive cross section peaks at small values of ξ: $\sigma \sim 1/\xi$.

Observation of diffractive peak in data.

$\xi = (M_X)^2/s$



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

N.B. Plots are uncorrected

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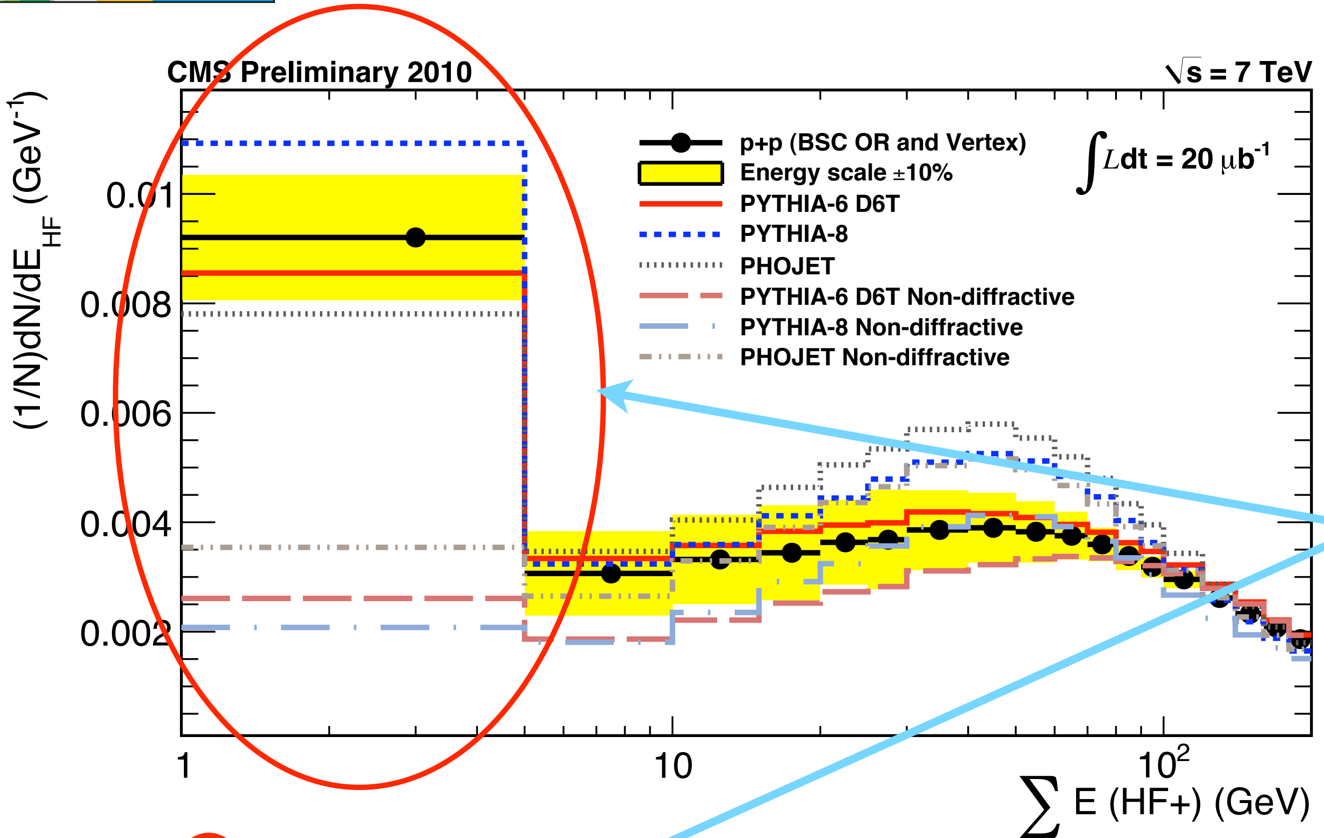
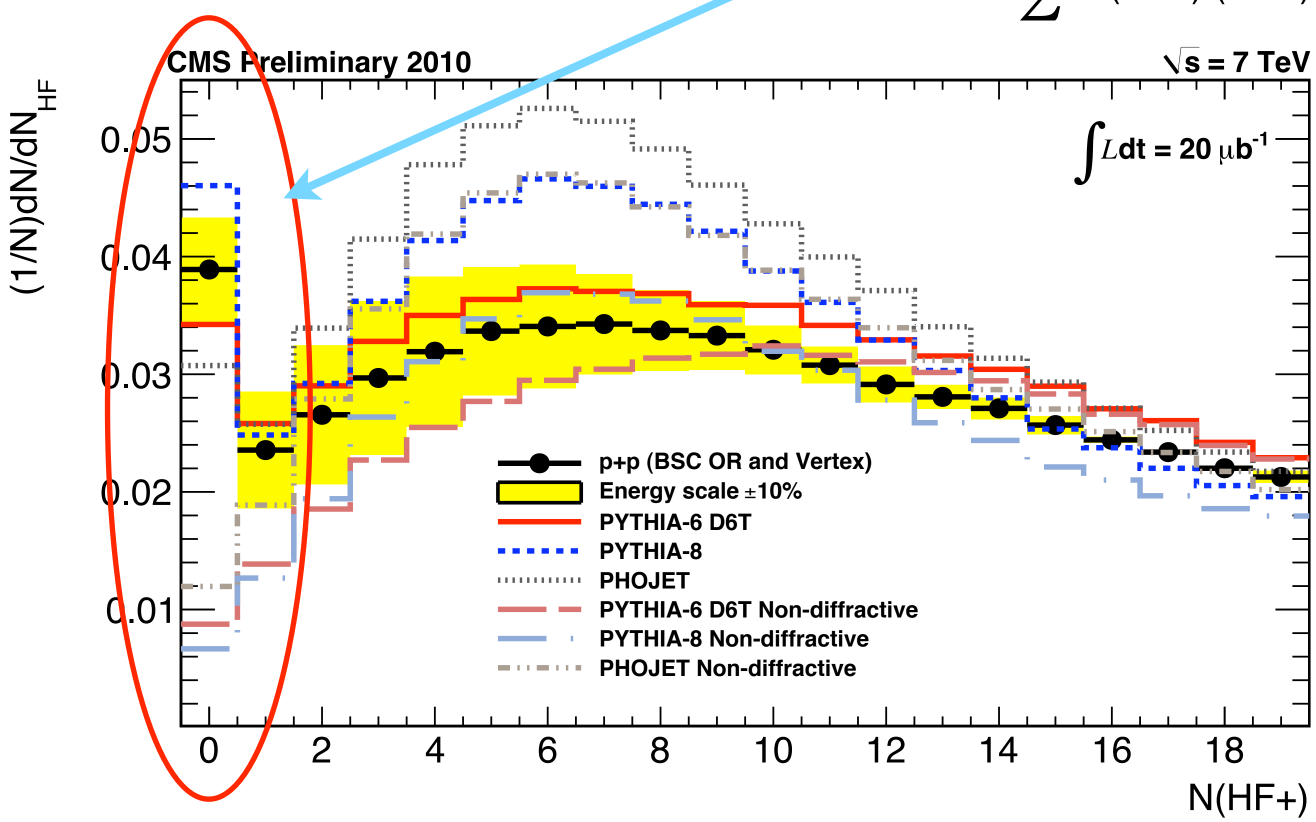
Observation of diffraction

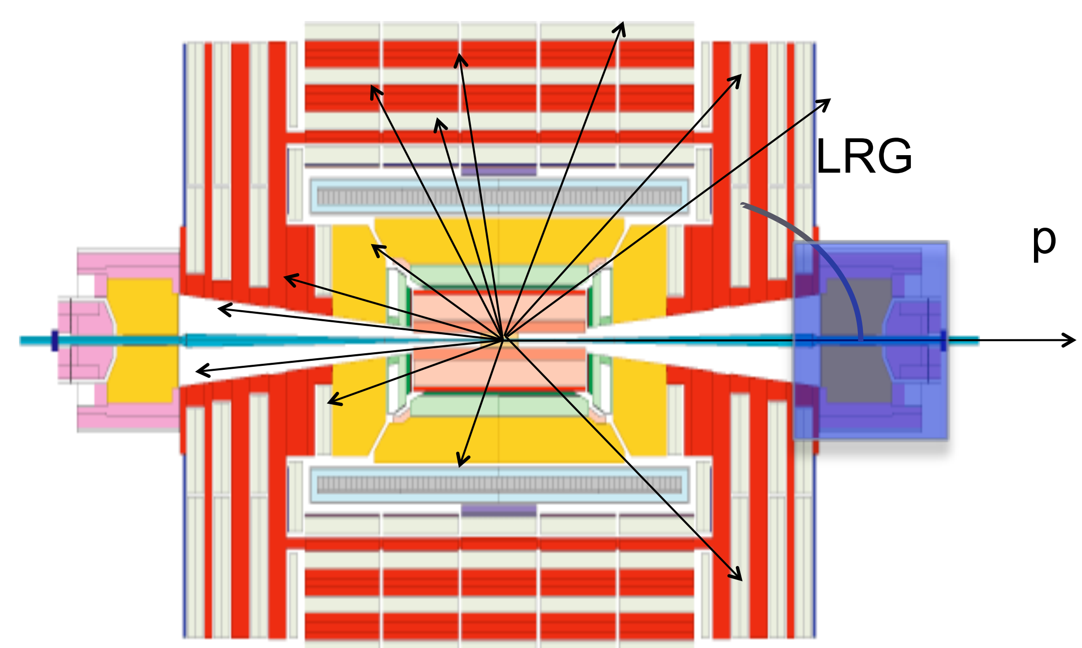




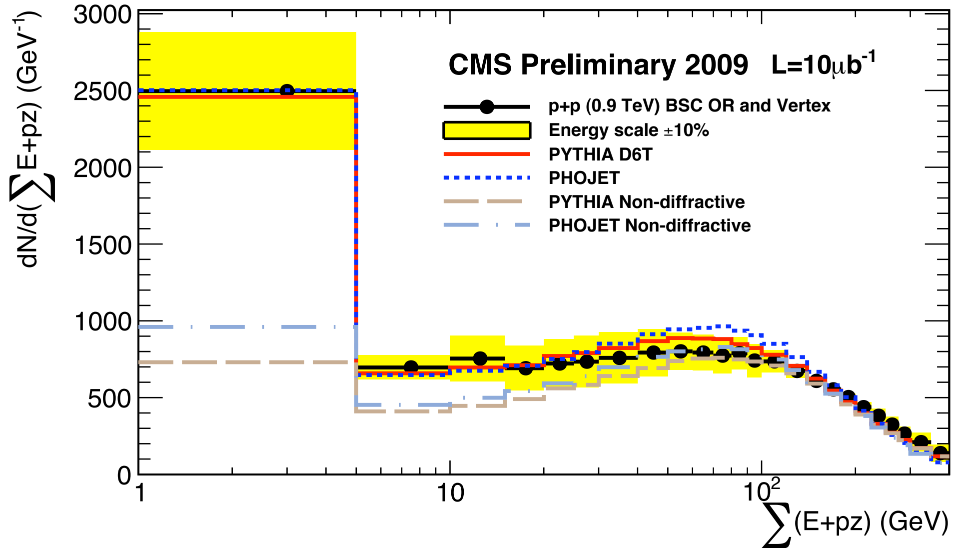
Inclusive diffraction characterized by Large Rapidity Gap (region in rapidity devoid of hadronic activity).

No energy deposition (or zero multiplicity) in HF.

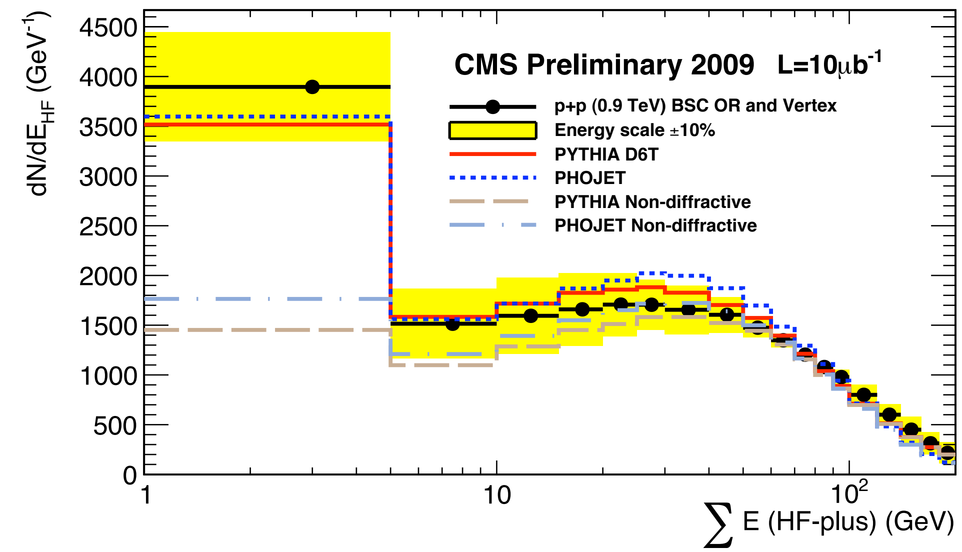
Gap definition at detector level.

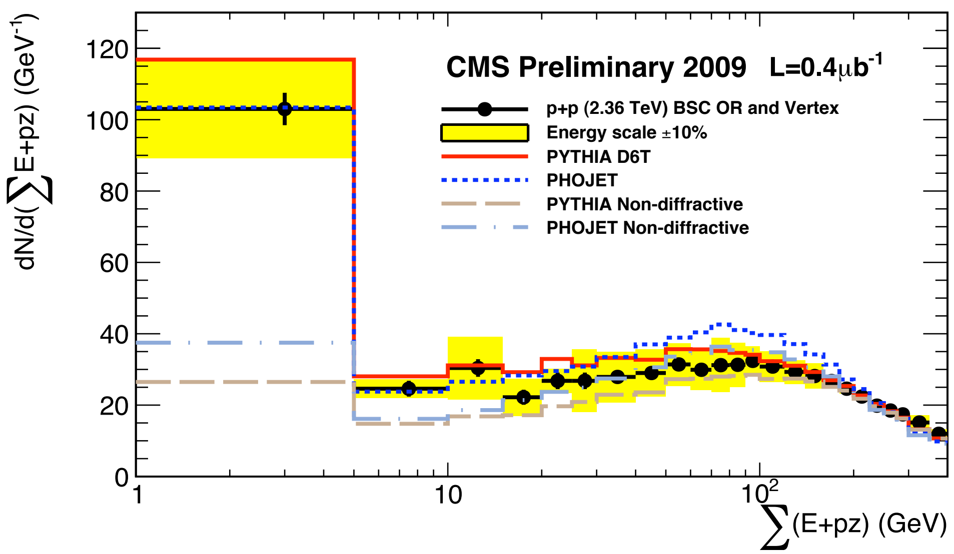


√s dependence

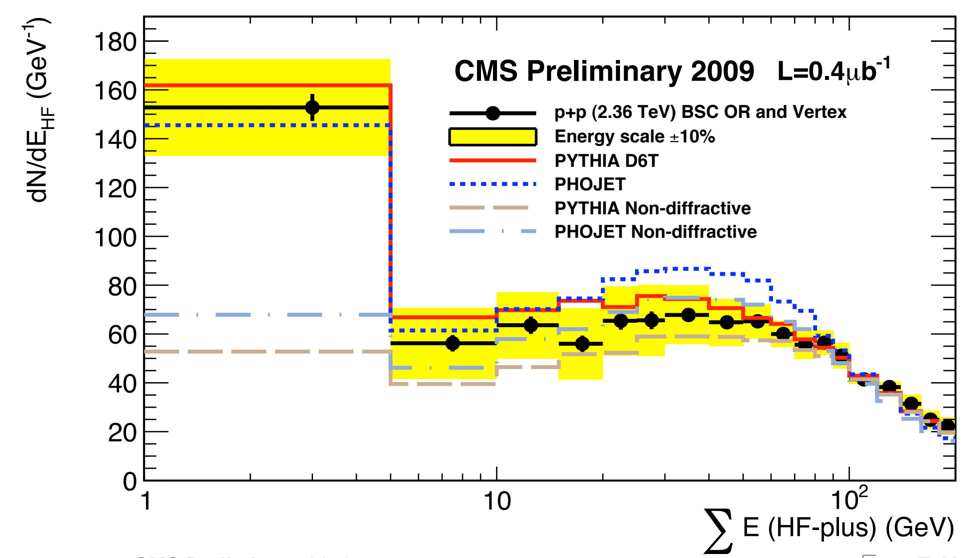


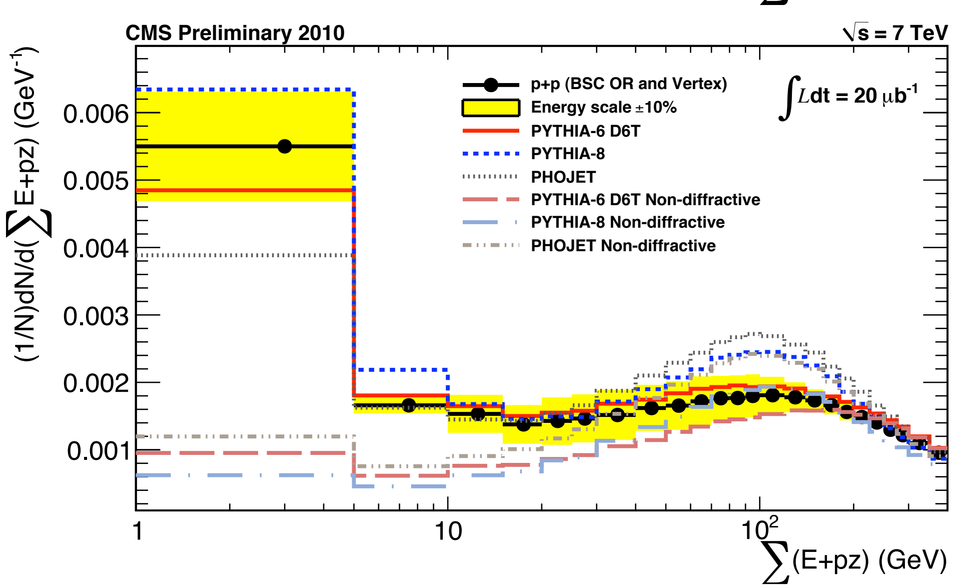
900 GeV



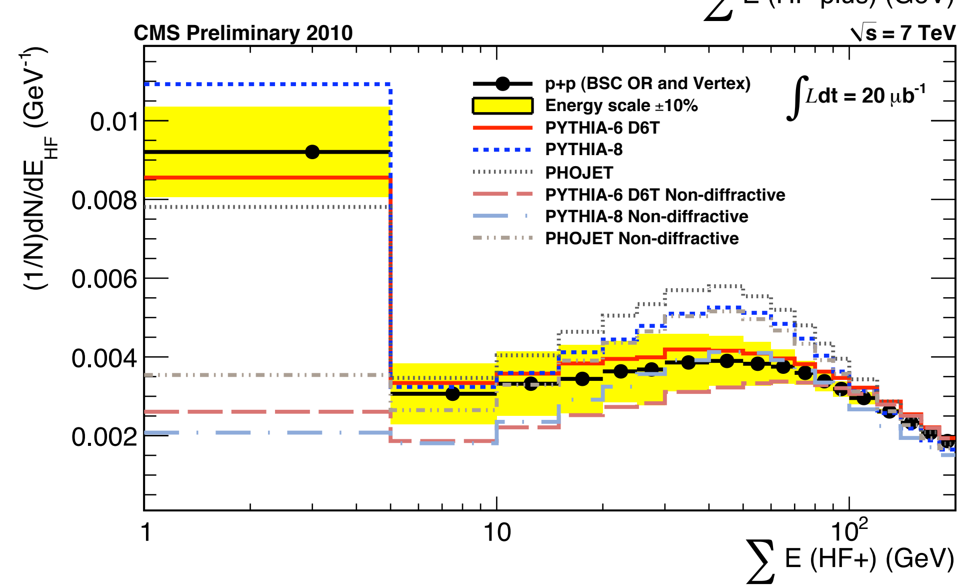


2.36 TeV





7 TeV

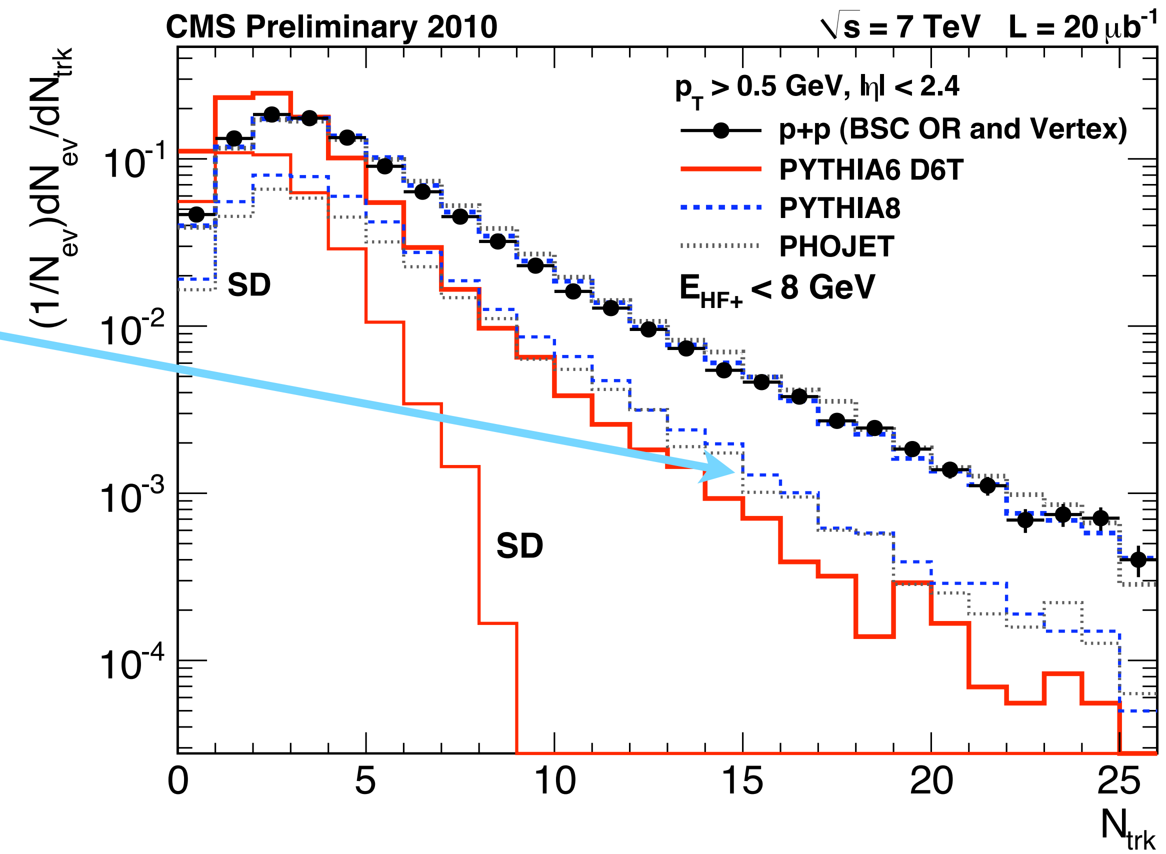


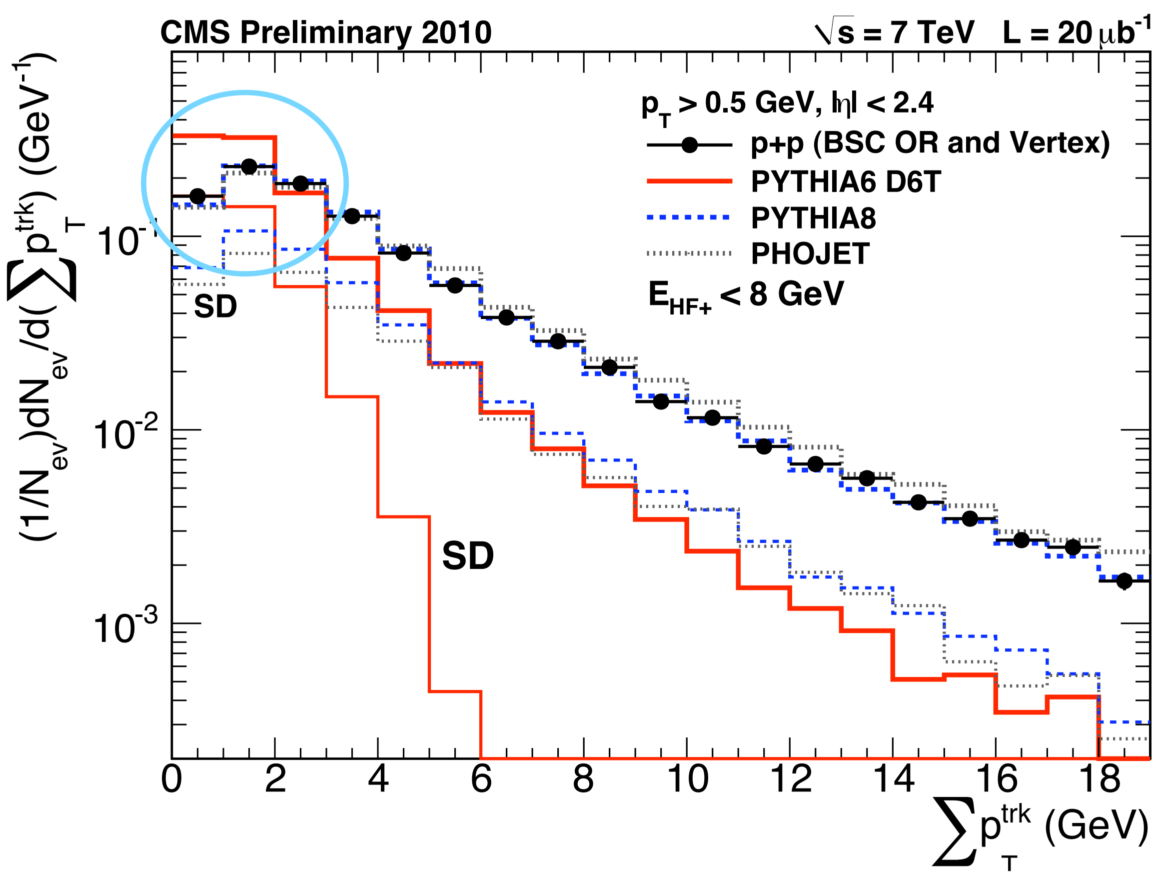
Enhancing diffractive component

High-multiplicity diffractive events in PYTHIA8 & PHOJET

PYTHIA8 & PHOJET describe fairly well the shape of the data both at low and high multiplicity region

PYTHIA6 D6T-based tunes have a relatively soft spectrum and cannot describe the data





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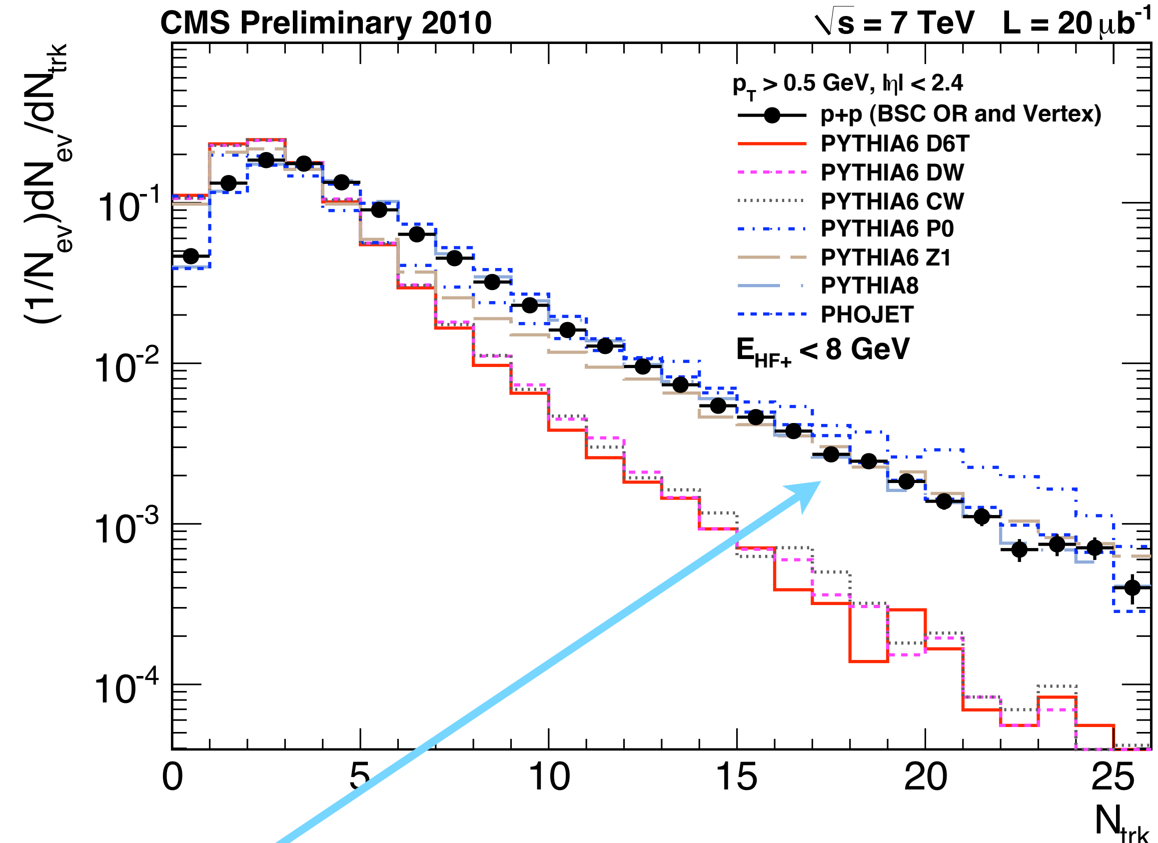
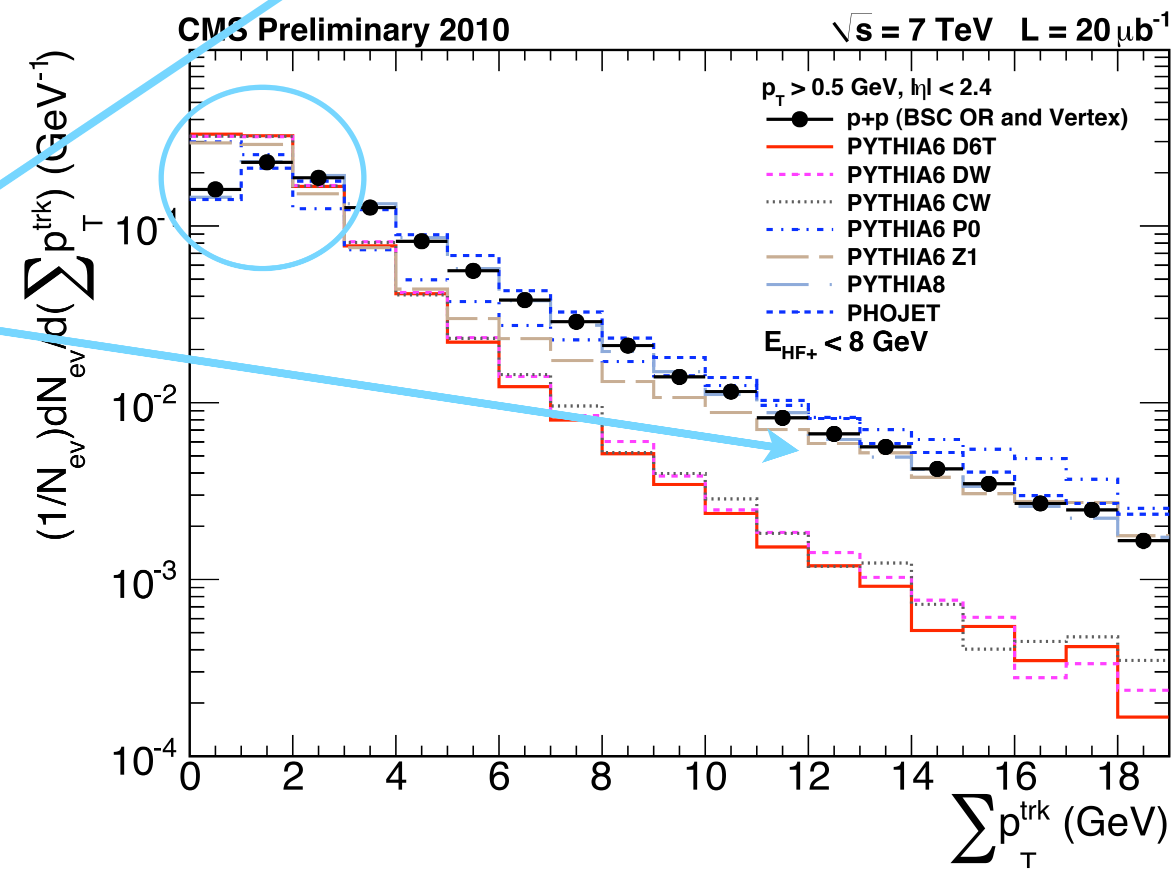
PYTHIA6 D6T-based tunes have a relatively soft spectrum and cannot describe the data

PYTHIA6 tunes P0 & Z1 are able to describe high-multiplicity region in diffractive enhanced sample, though not behavior in low energy region, where diffractive contribution is dominant





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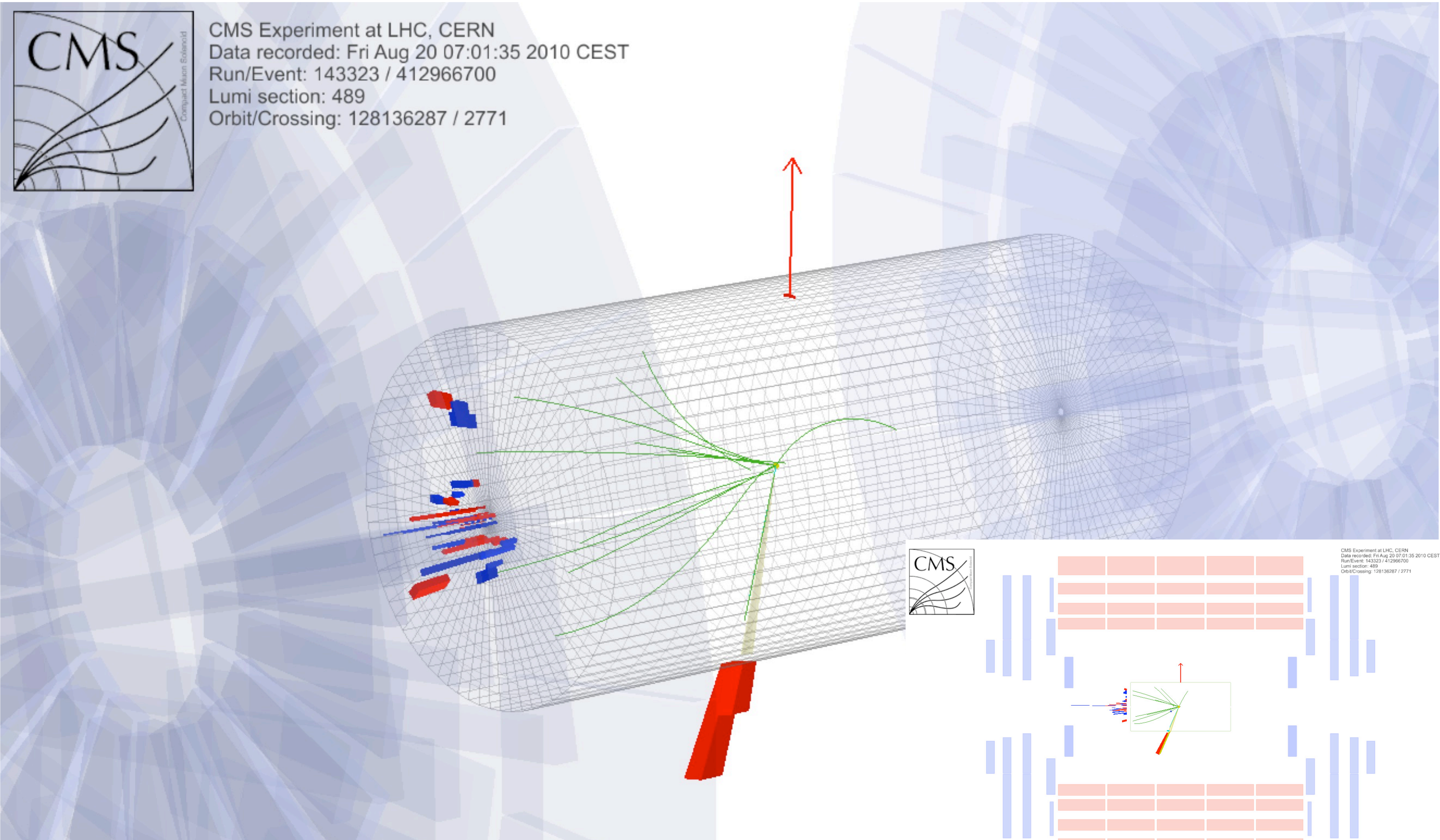
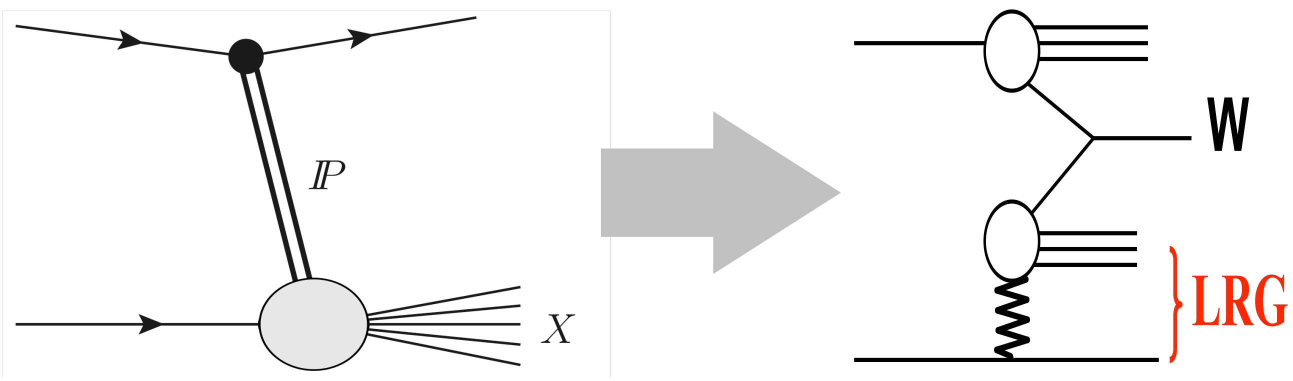
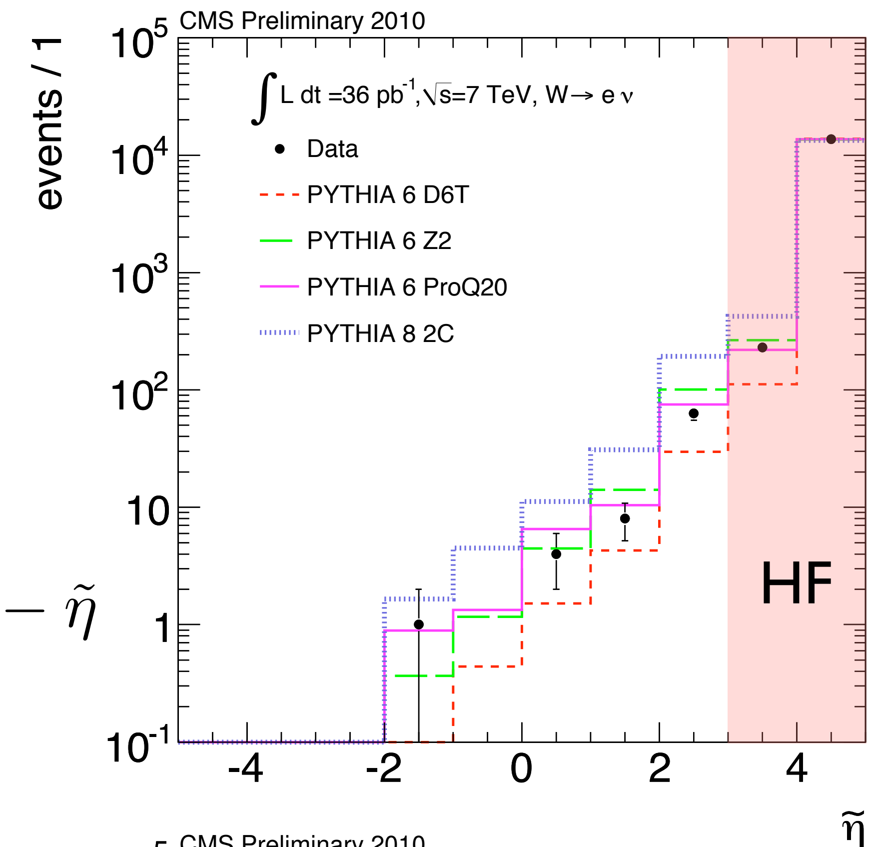
W→eν(μν) events with a LRG

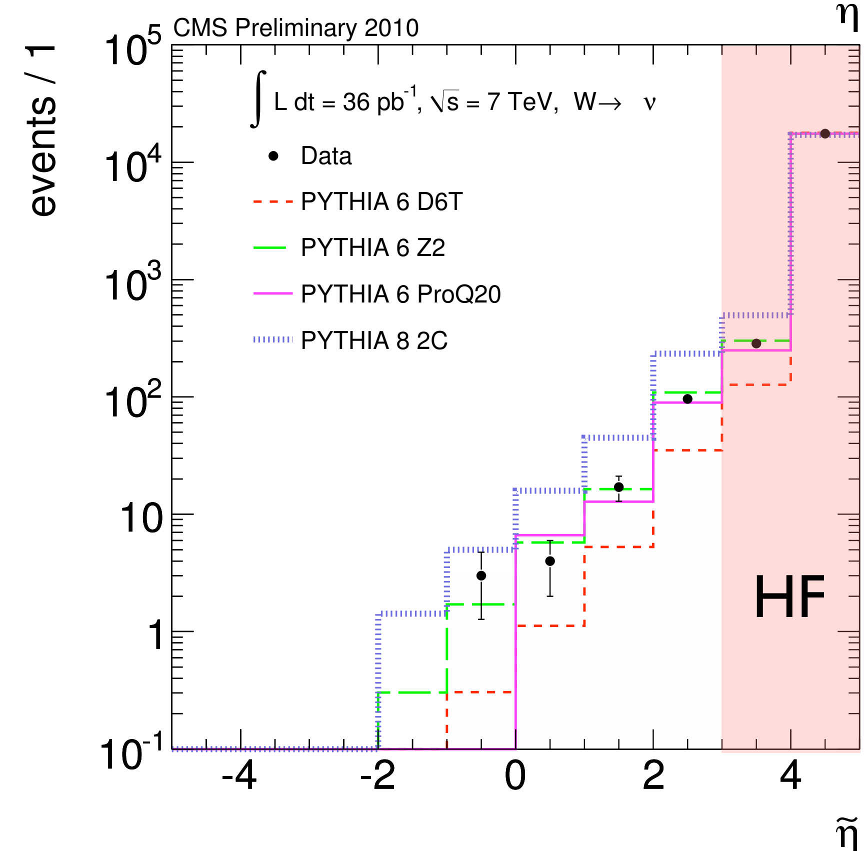


W→eν(μν) events with a LRG



$$\Delta\eta^{LRG} \equiv 5.0 - \tilde{\eta}$$



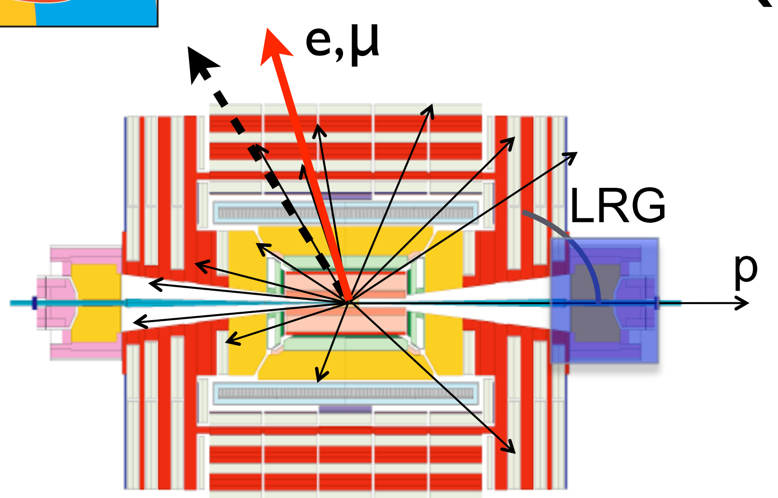


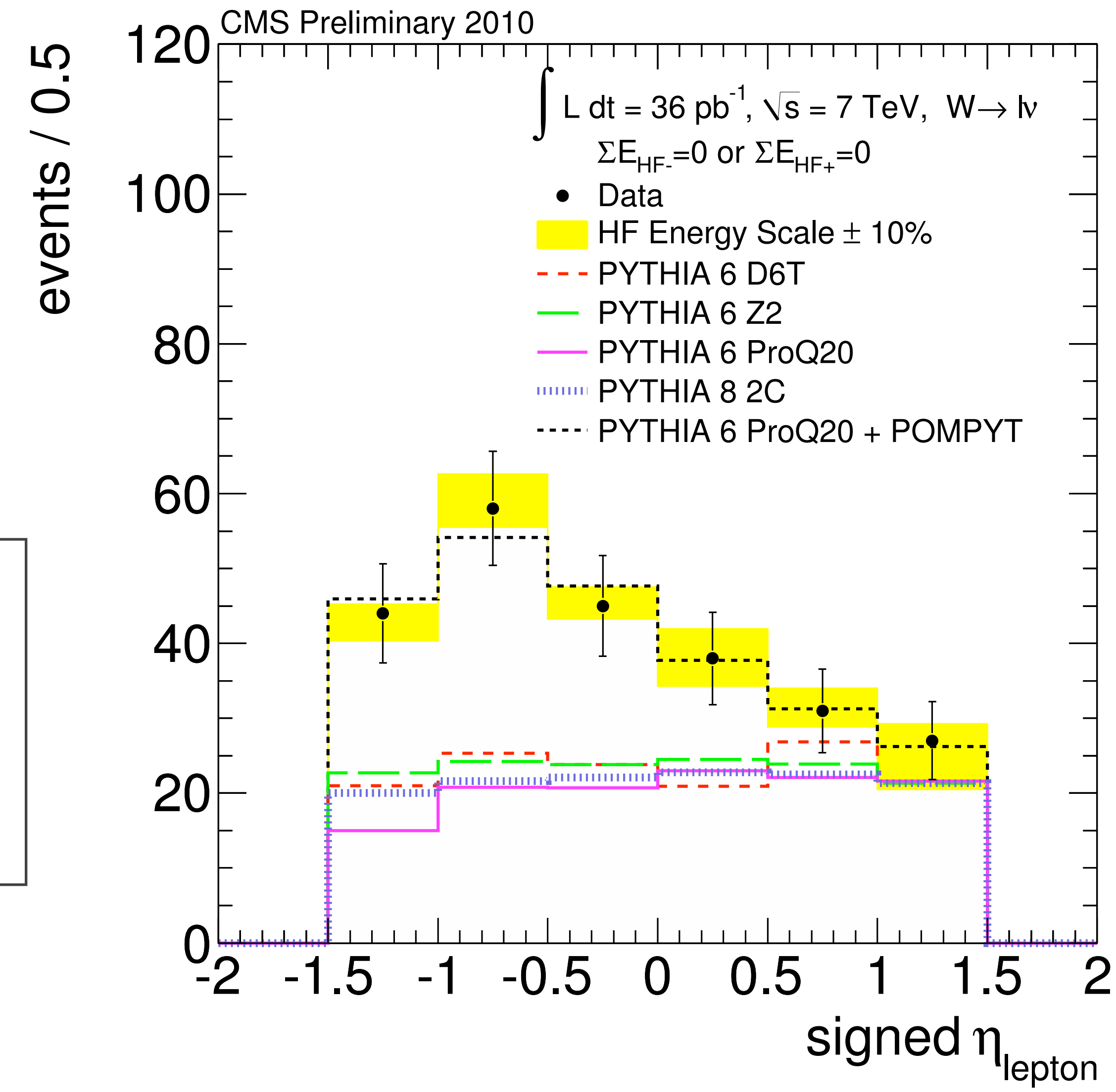
$\sum E_{HF} = 0 \Leftrightarrow \eta_{max,min} < 3$

- Single-vertex events to reject pile-up
- Gap size (Δη) distributions for W candidate events
- Note that LRG events from non-diffractive MC events as well
- Large dependence on MC tune

CMS PAS FWD-10-008

W→eν(μν) events with a LRG





LRG selection in HF ($3 < |\eta| < 5$)

Signed η_{lepton} distribution ($\eta_{lepton} < 0$ when e,μ opposite to the LRG)

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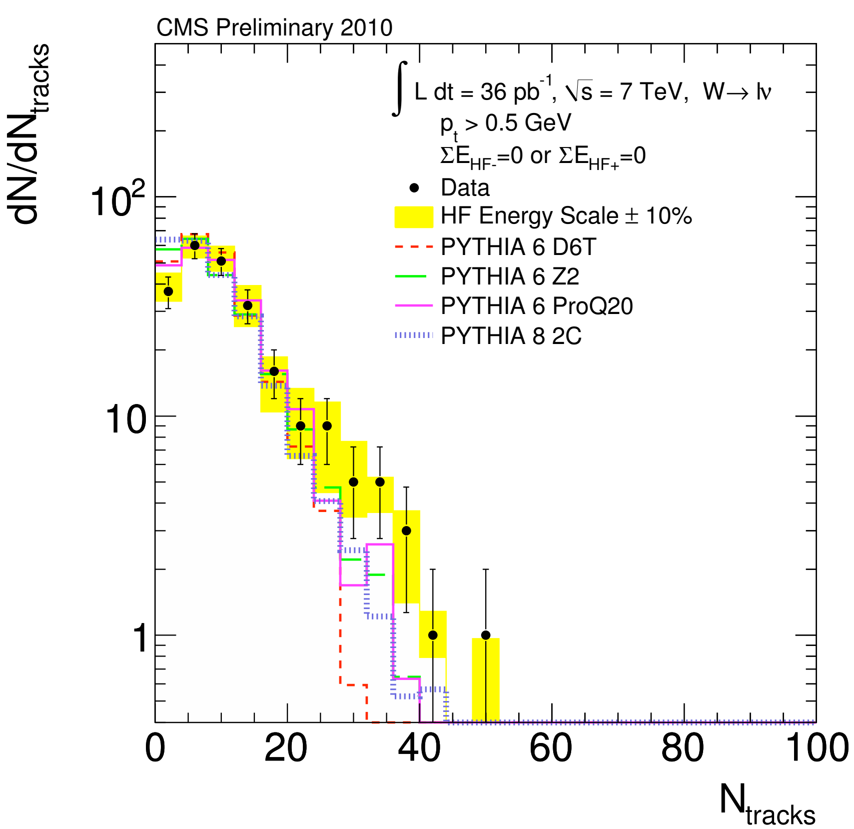


Flat for non-diffractive, asymmetric for diffractive events

Evidence of diffractive W production in the data

Fit for PYTHIA (ND) + POMPYT (SD):

$$f_{SD} = 50 \pm 9.3(stat.) \pm 5.2(syst.)\%$$

(uncorrected)

pp (visible) inelastic cross section

γγ (exclusive) interactions

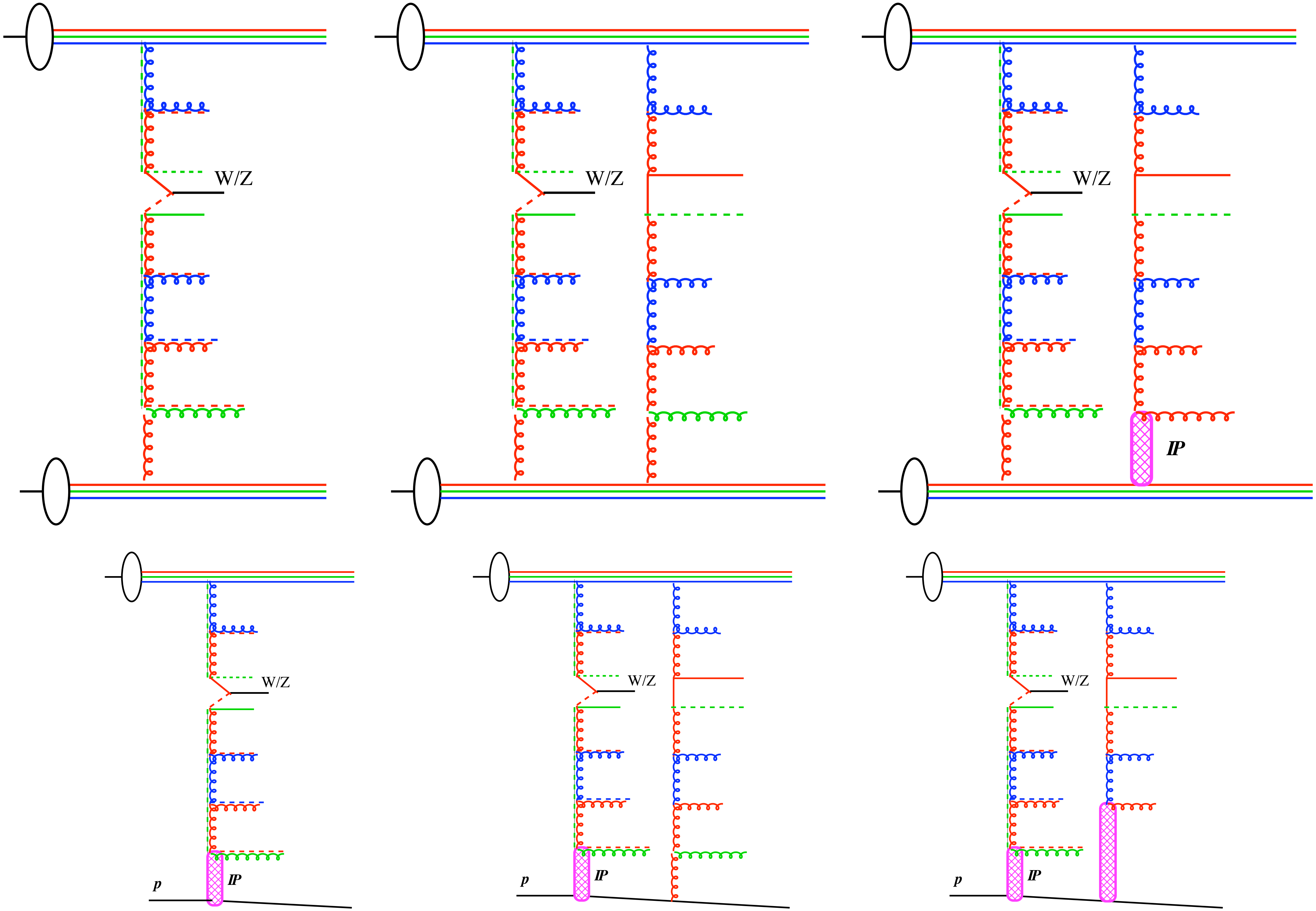
Soft and hard diffraction

Central/forward correlations in hard interactions

Forward energy flow and multiple parton interactions

Forward and central-forward jet production

Underlying event in hard interactions

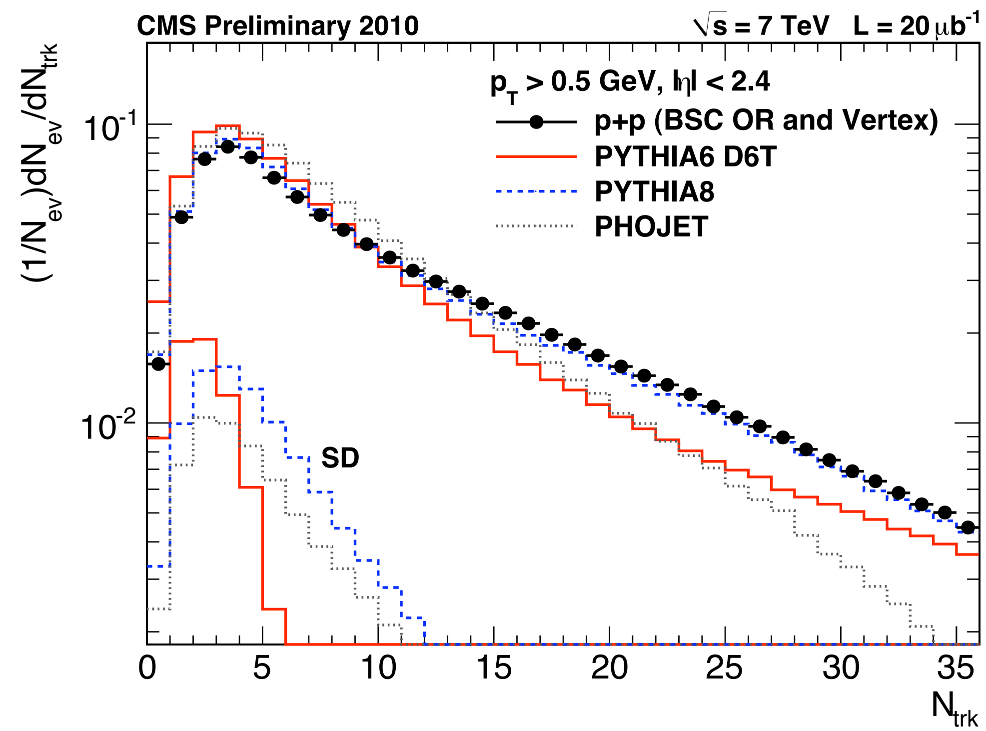


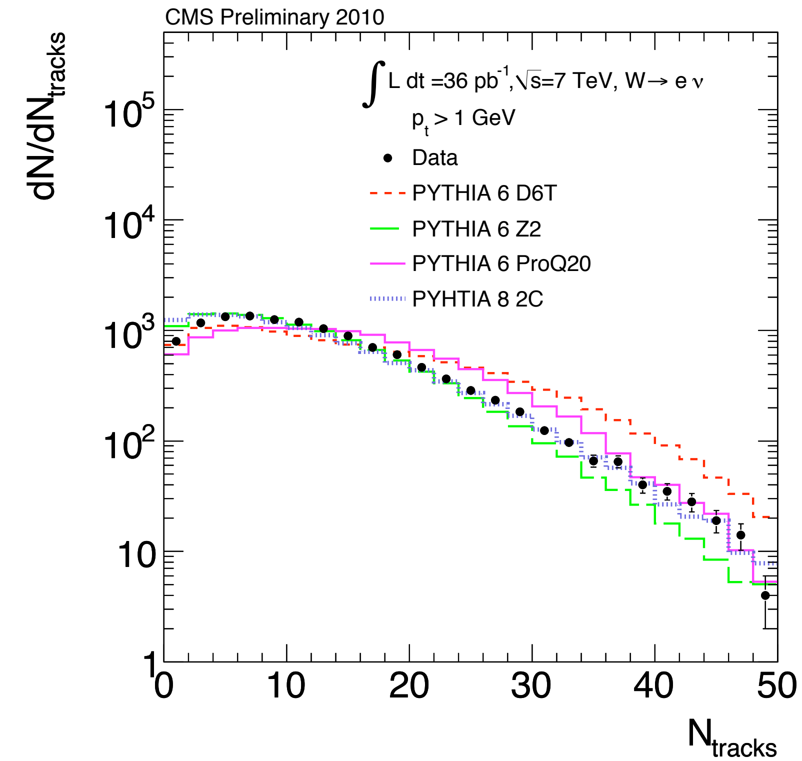
Central vs Forward energy flow

Minimum bias

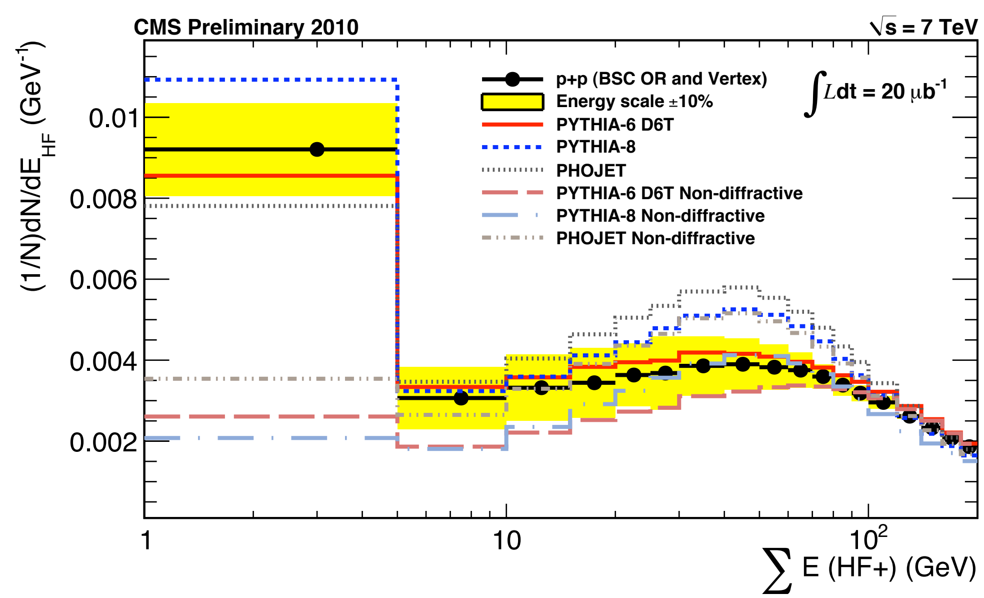
$pp \to WX$

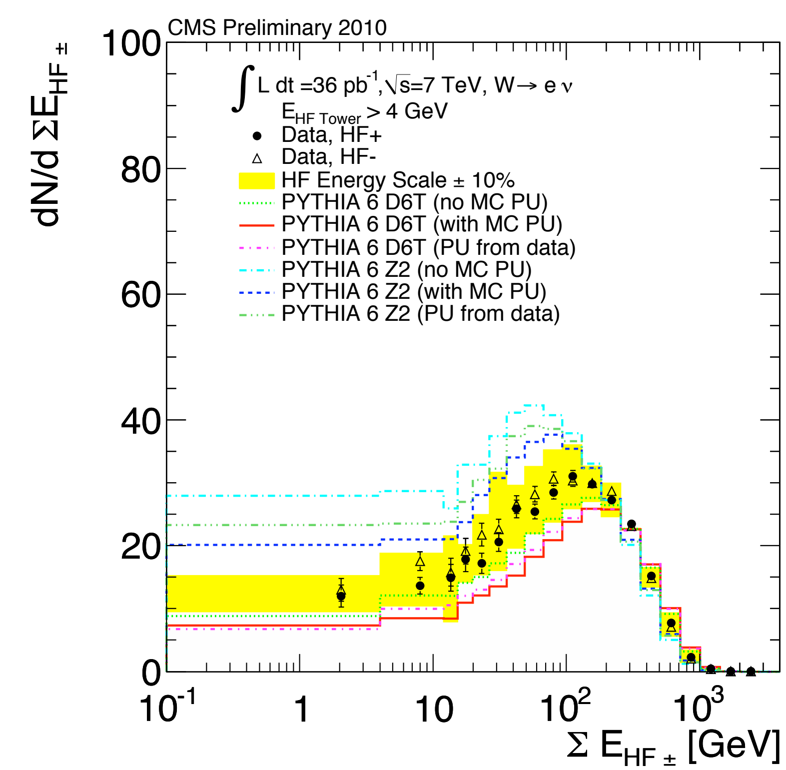
Central track multiplicity





Forward energy





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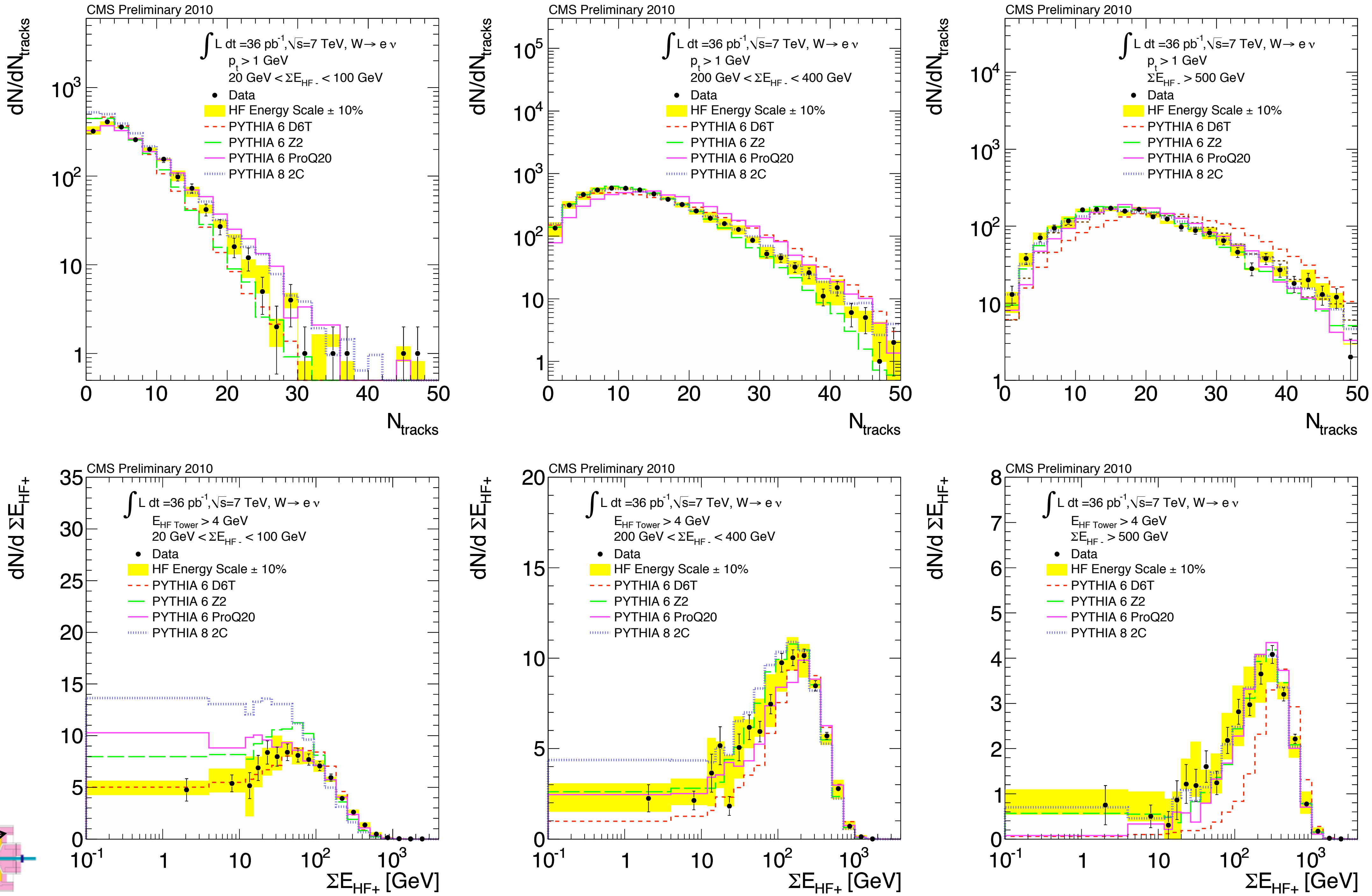
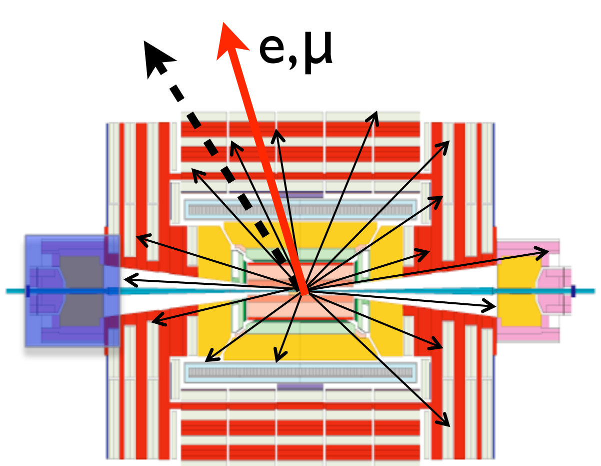
Central vs Forward energy flow

Central and forward activity with increasing forward deposition in the opposite side





$\sum E_{HF-}$

CMS PAS FWD-10-008

pp (visible) inelastic cross section

γγ (exclusive) interactions

Soft and hard diffraction

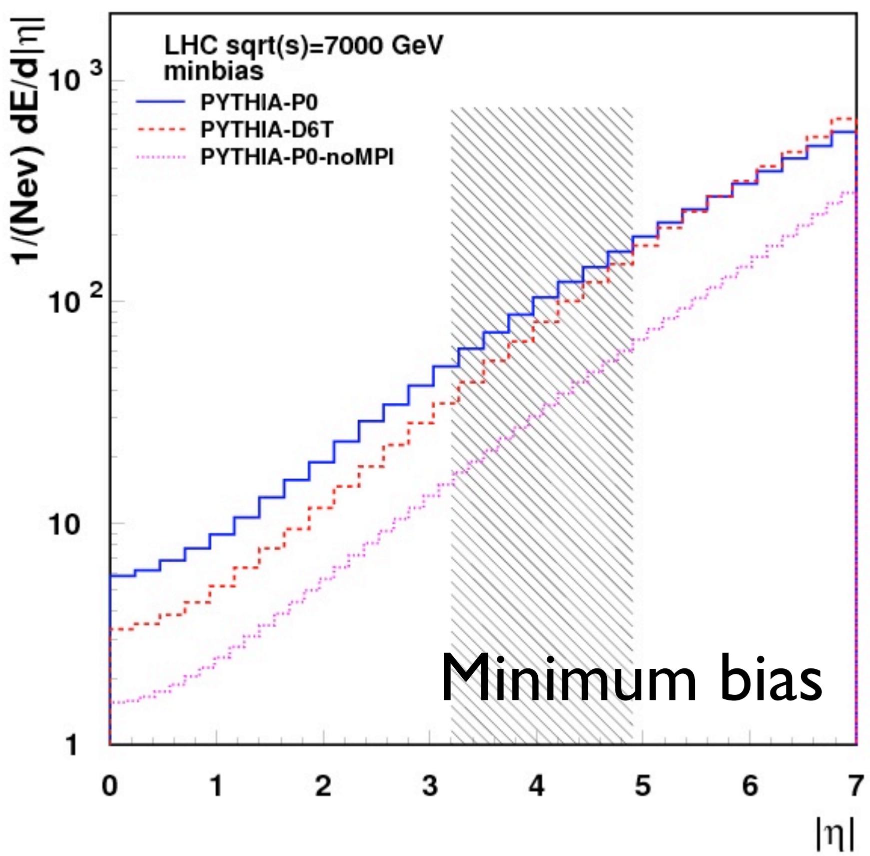
Central/forward correlations in hard interactions

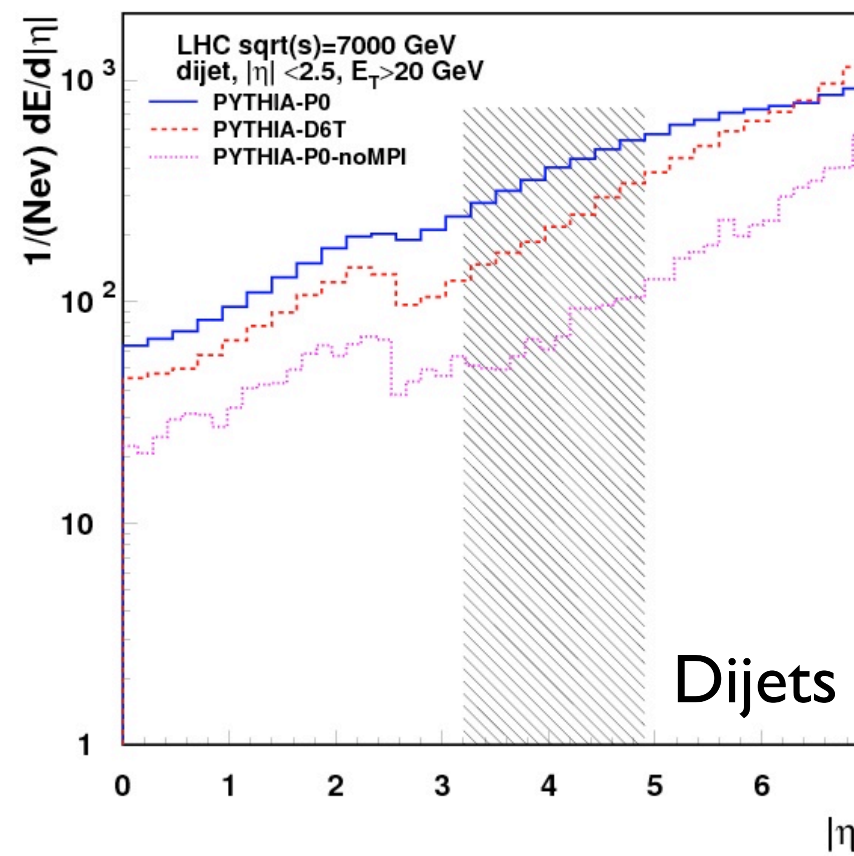
Forward energy flow and multiple parton interactions

Forward and central-forward jet production

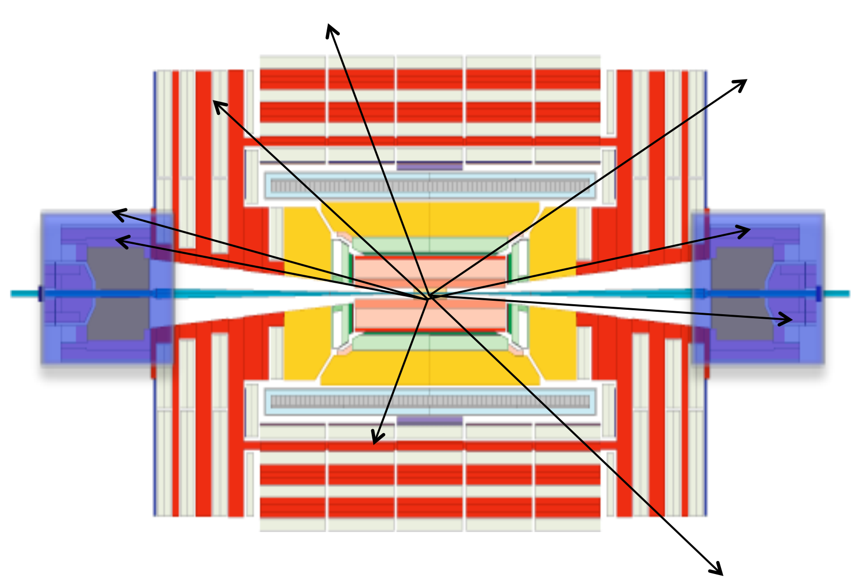
Forward energy flow

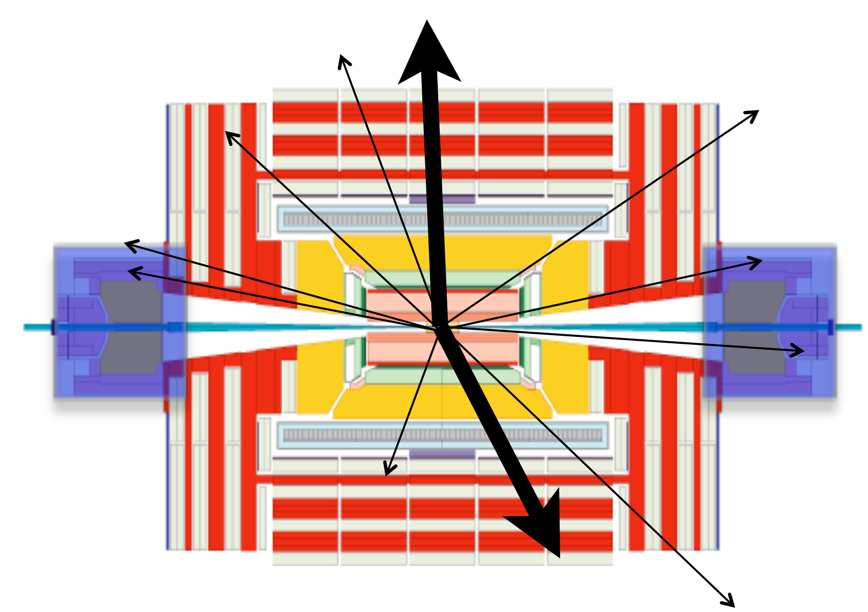
- Energy flow in the forward region particularly sensitive to the underlying event (UE) dynamics
- Important input in the tuning of multi-parton interactions (MPI) models at the LHC
- Measurement of the forward energy flow (dE/dη) in minimum bias and dijet events
- Performed in the range covered by the HF calorimeter (3 < |η| < 5)
- √s dependence from results at both 0.9 and 7 TeV





Generator level





CMS PAS FWD-10-011

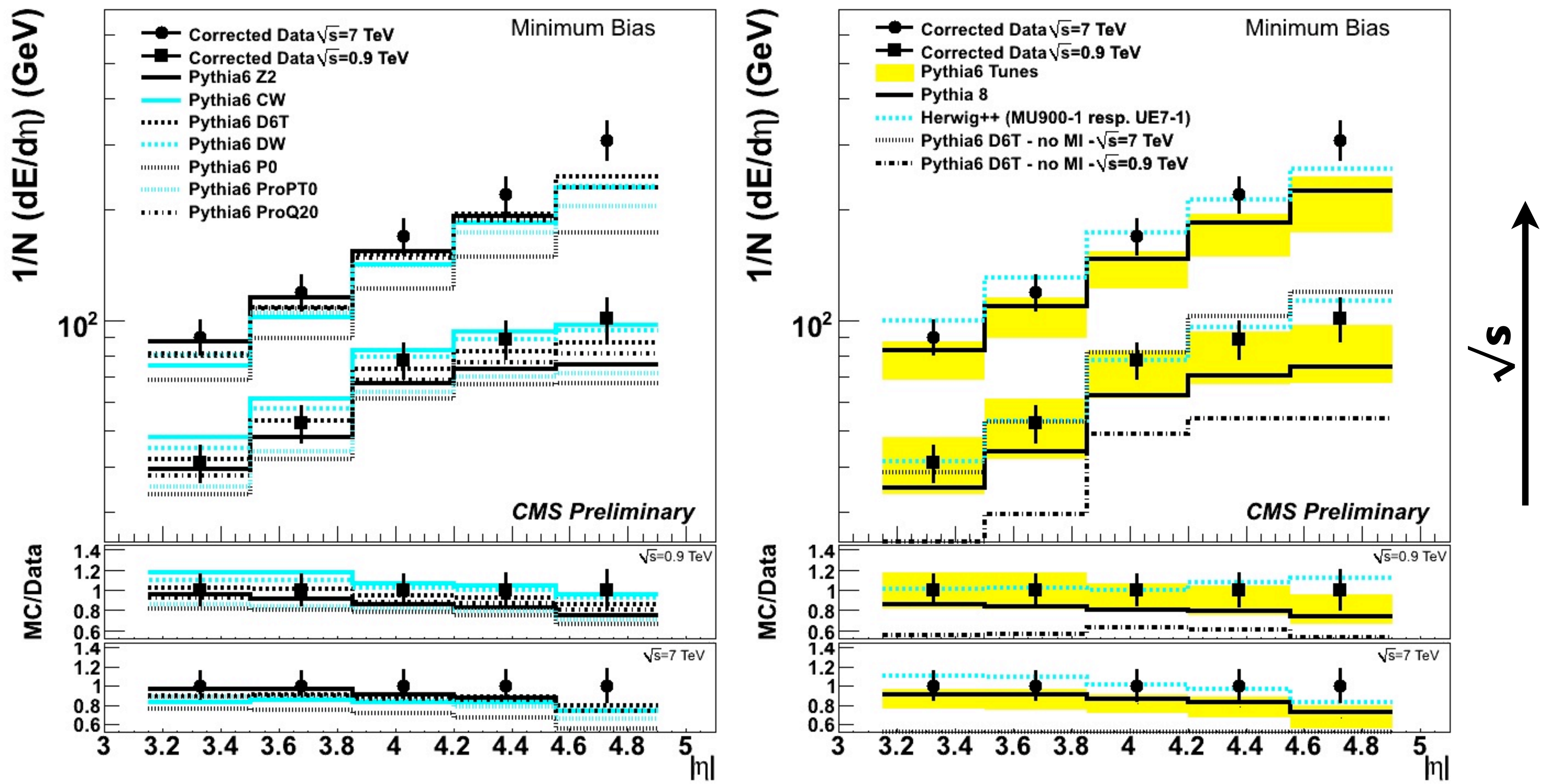
Forward energy flow

dE/dη increases with η

√s dependence

Slightly steeper spectrum compared to most MC generators

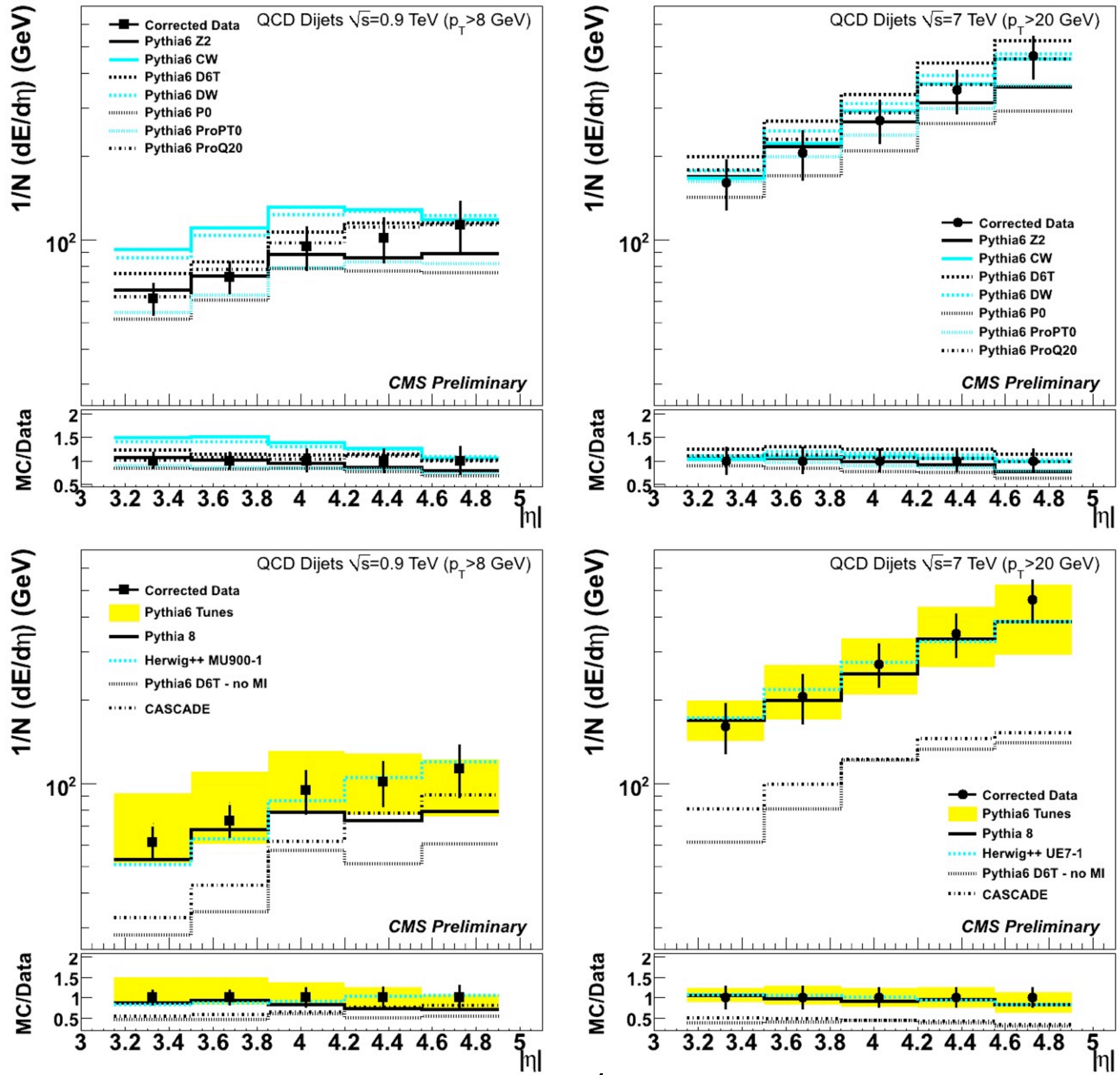
Clear effect of multi-parton interactions in MC's



CMS PAS FWD-10-011

Forward energy flow

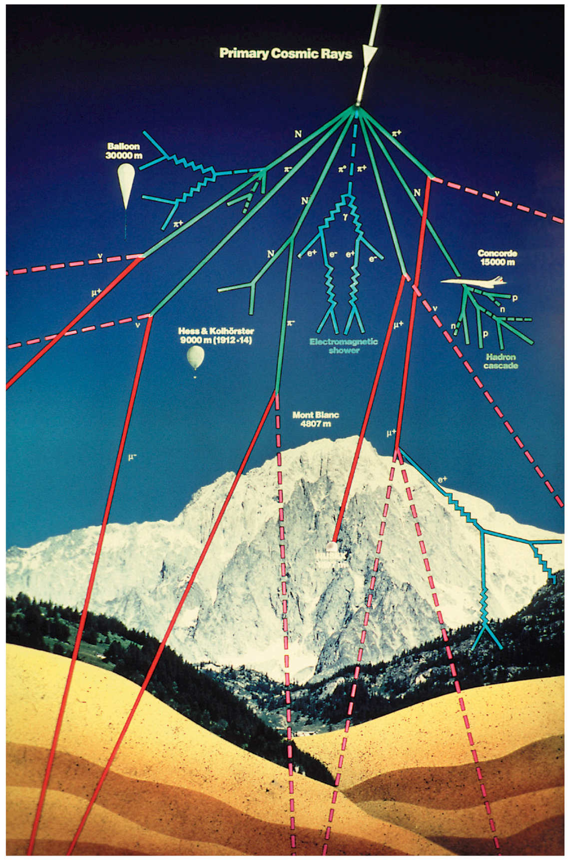
- dE/dη increases with η
- √s dependence
- Slightly steeper spectrum compared to most MC generators
- Clear effect of multi-parton interactions in MC's
- Higher dE/dη for events in which a hard scale is present
- No generator/tune fully describes the data



√s →

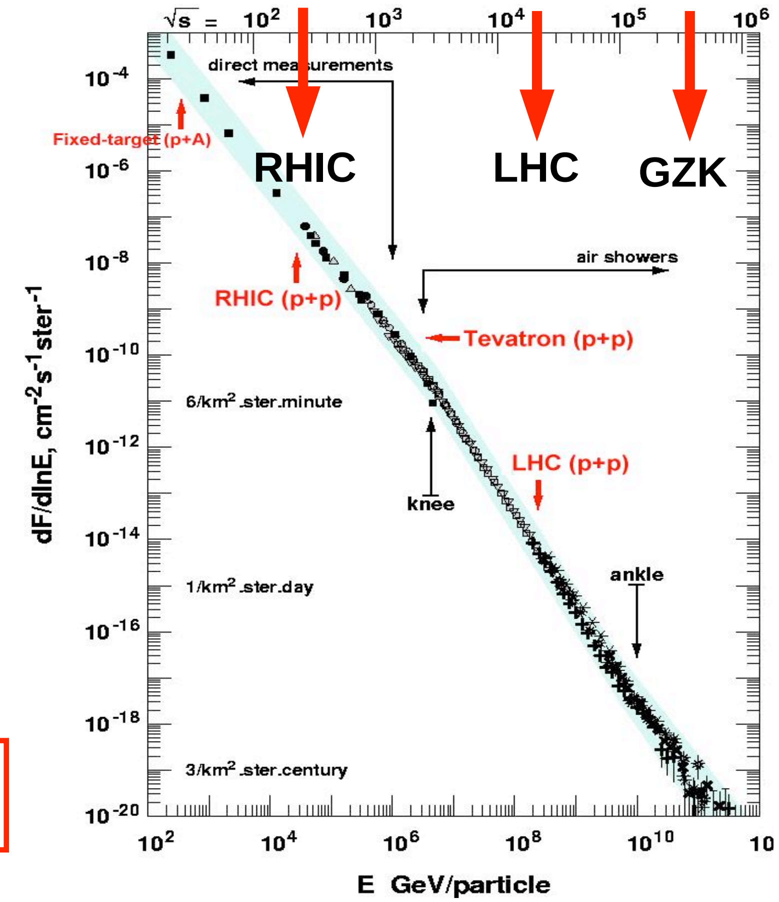
[CMS PAS FWD-10-011]()

dE/dη and cosmic rays MC's



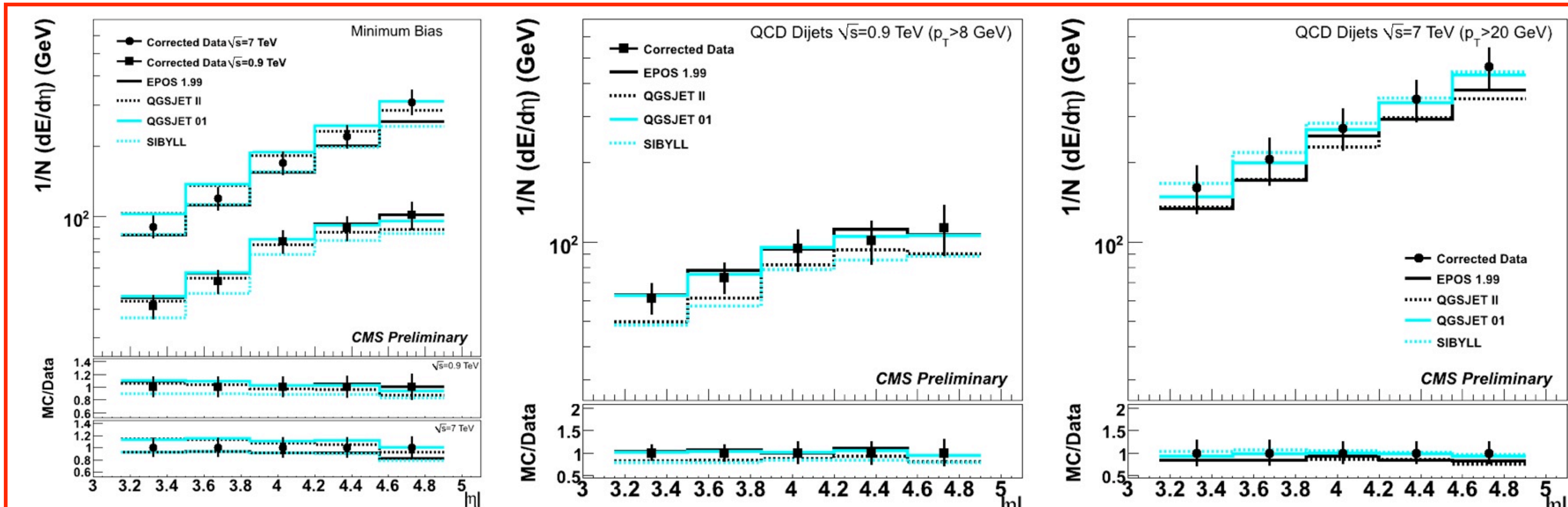
Regge-based Monte Carlo generators for cosmic ray (proton) interactions in the atmosphere (EPOS, QGSJET, SIBYLL)

LHC data important for model extrapolations to ultra high energies



Very good agreement with the dE/dη data

CMS PAS FWD-10-011



pp (visible) inelastic cross section

γγ (exclusive) interactions

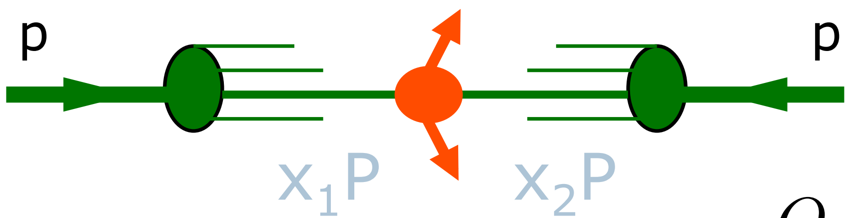
Soft and hard diffraction

Central/forward correlations in hard interactions

Forward energy flow and multiple parton interactions

Forward and central-forward jet production

Forward jets

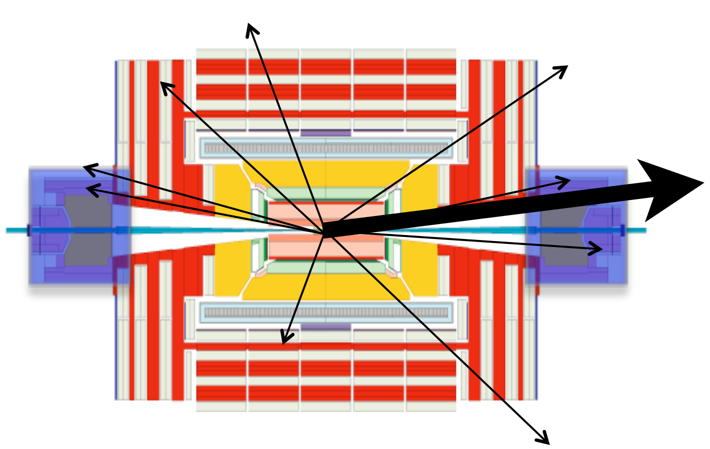


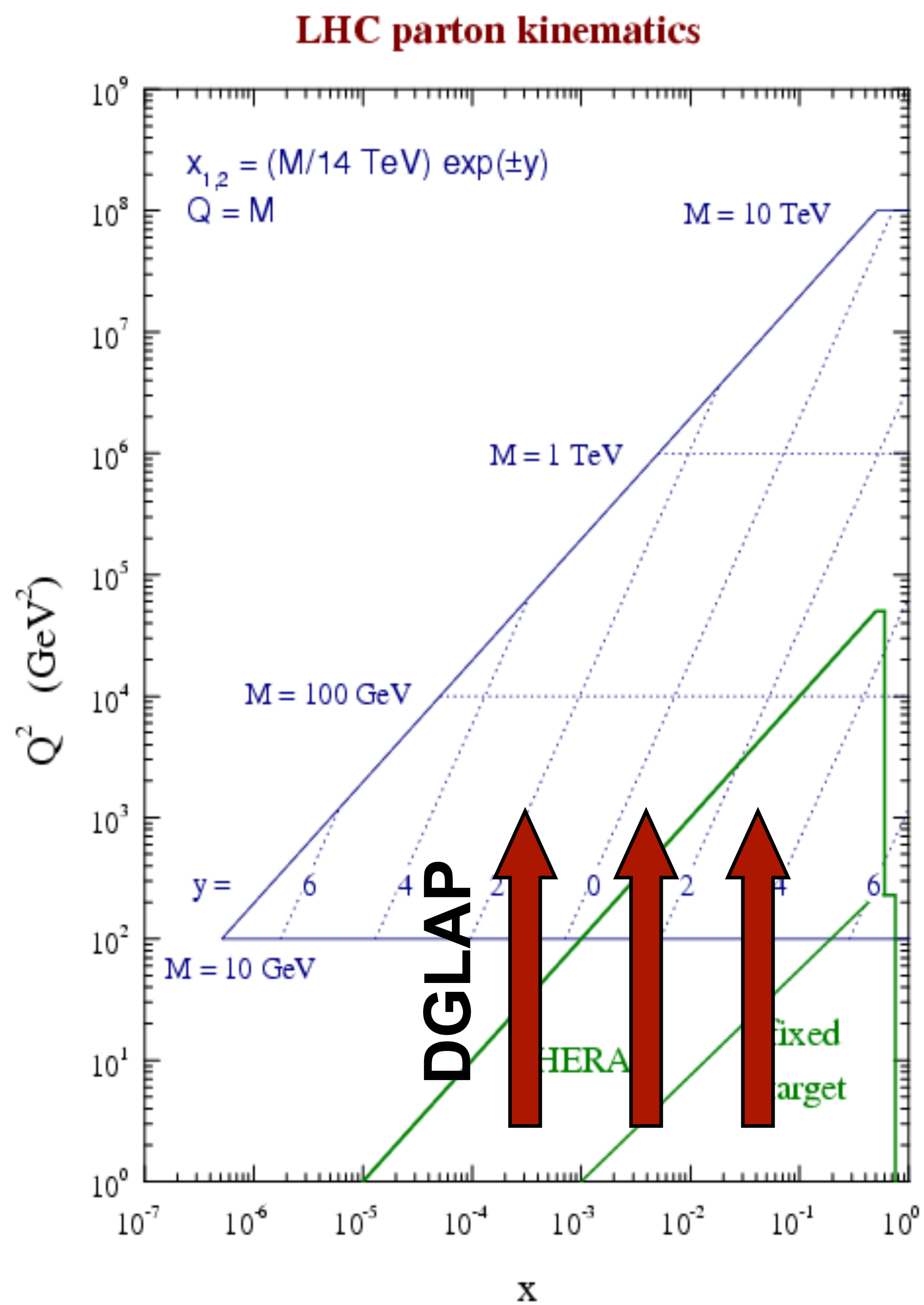
$$x = \frac{Q}{\sqrt{s}} e^{-y}$$

Access to low-x region by measuring very forward jets

Sensitive to low-x gluon pdf's down to x ~ 10^{-5}

Test of perturbative QCD evolution (DGLAP, BFKL)





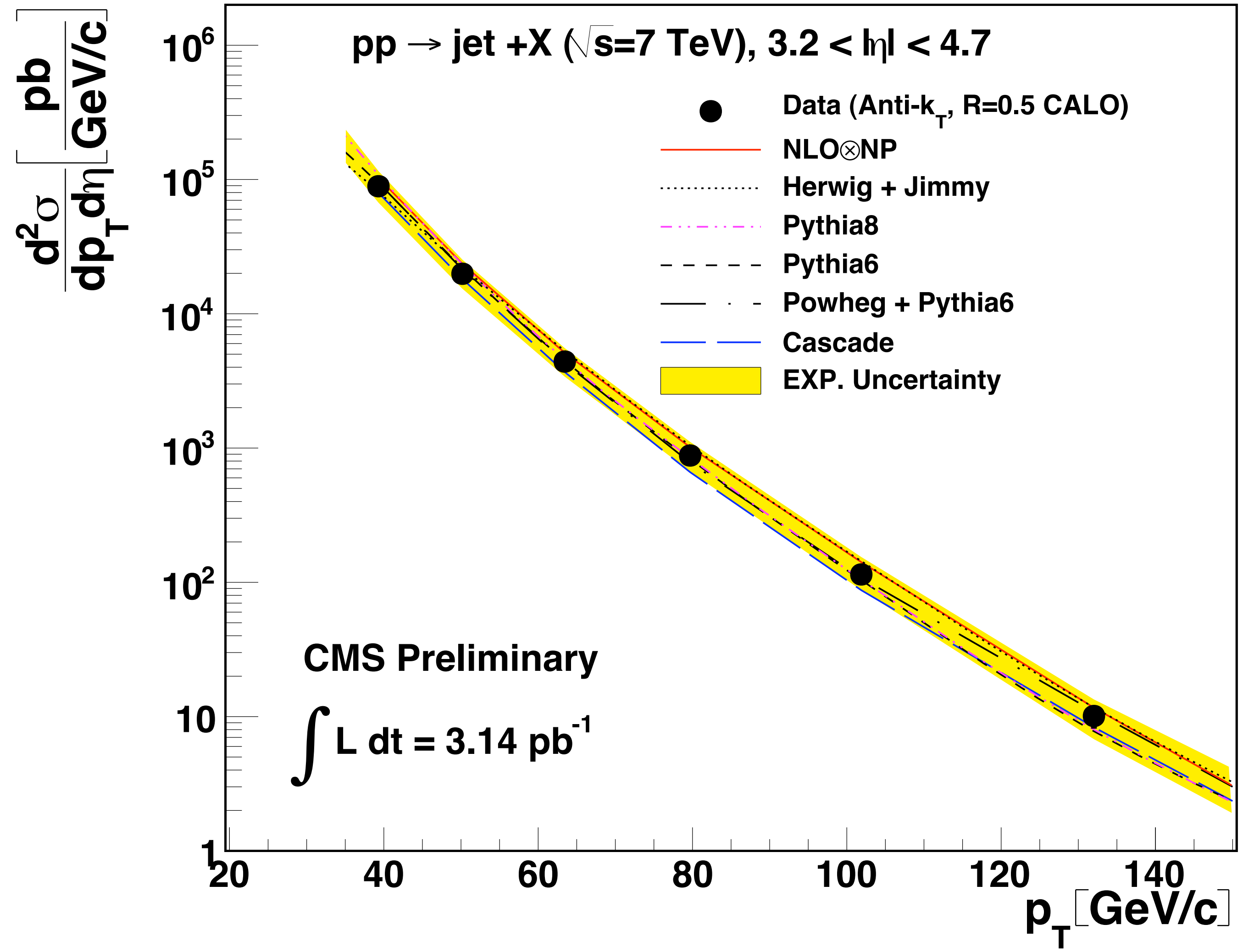
Inclusive forward jet cross section

[CMS PAS FWD-10-003]

Anti-k$_T$ (R=0.5) jets

$3.2 < |\eta| < 4.7$, $35 < p_T < 150$ GeV

Agreement within errors to theoretical prediction, LO & NLO MC's

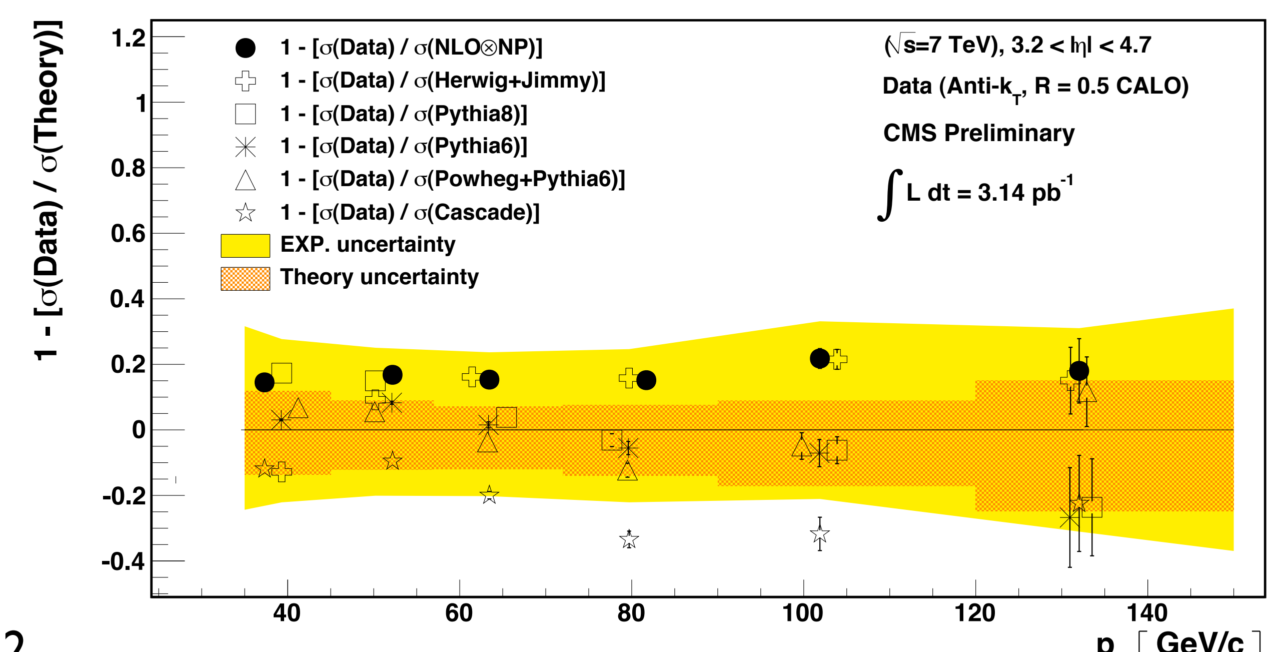


Systematic uncertainty dominated by Jet Energy Scale (20 - 30%)

Jet pT resolution: 3-6%

Model (unfolding): 3%

Luminosity: 4%

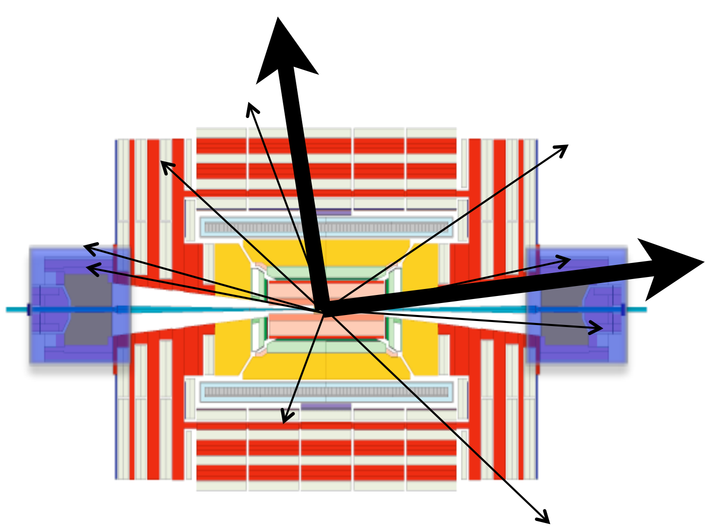


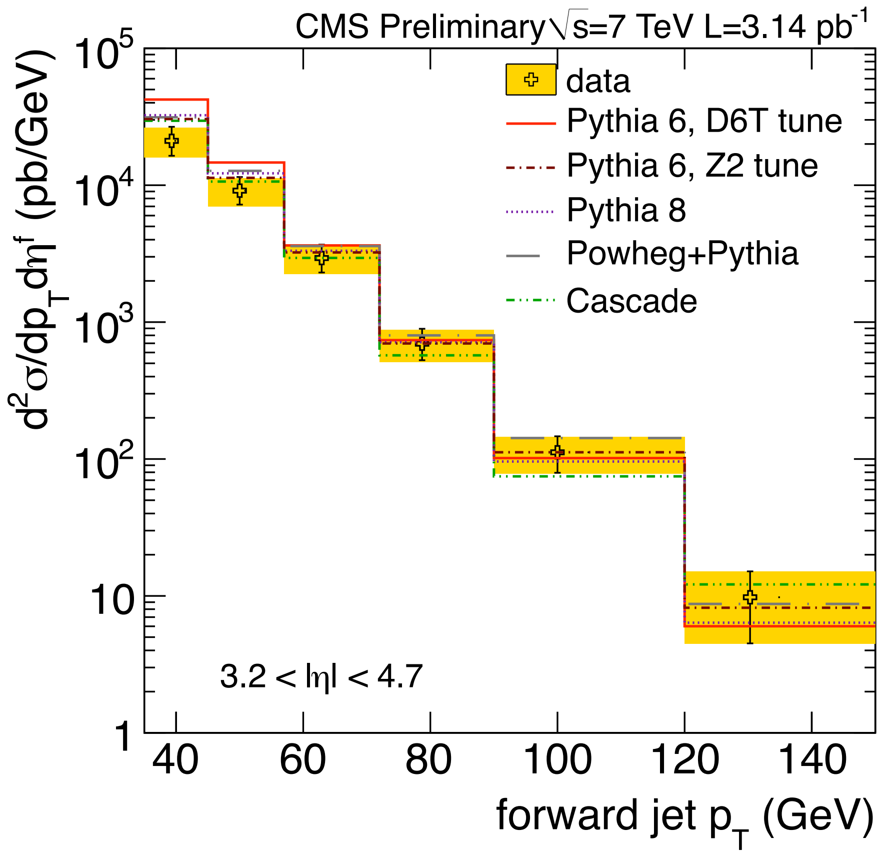
Central-forward jets

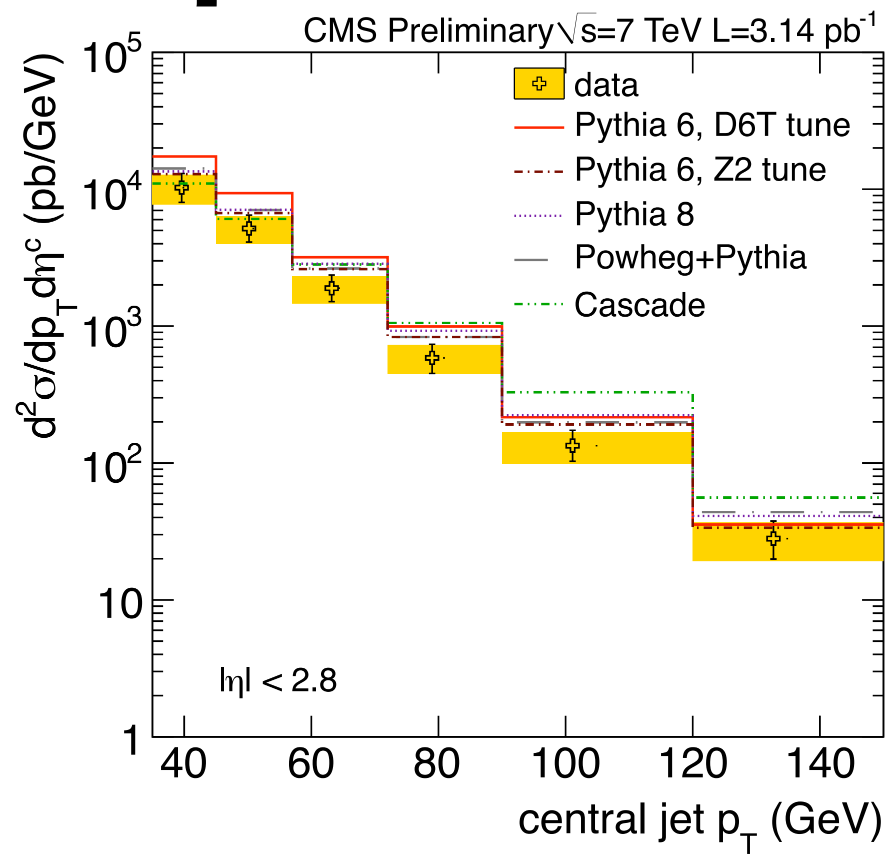
Simultaneous production of a central and forward jet

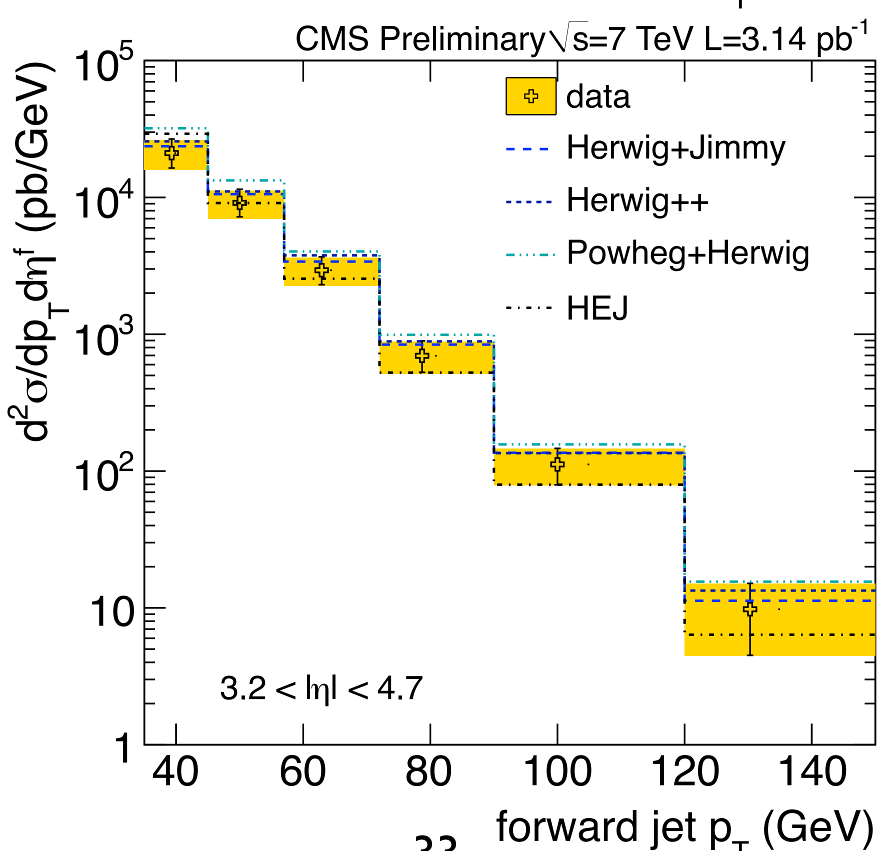
Analogous selection as in inclusive forward jet measurement (extra central jet with |η| < 2.8)

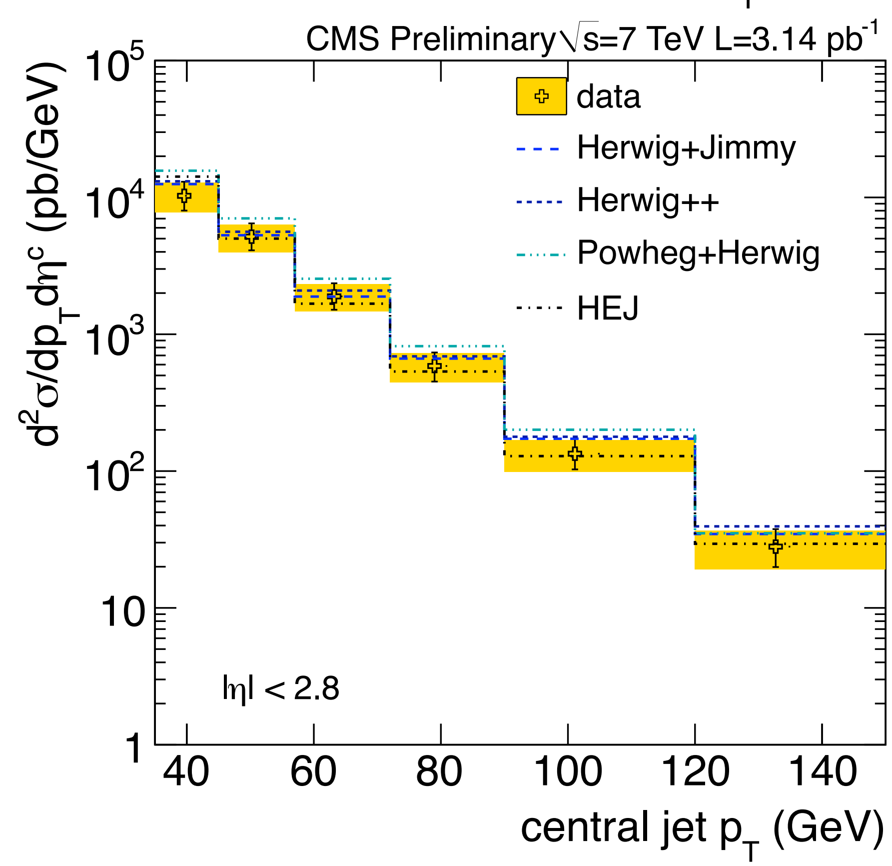
PYTHIA in general overestimates the data, with a steeper spectrum, while HERWIG describes the data better











CMS PAS FWD-10-006

Central-forward jets

Simultaneous production of a central and forward jet

Analogous selection as in inclusive forward jet measurement (extra central jet with $|\eta| < 2.8$)

PYTHIA in general overestimates the data, with a steeper spectrum, while HERWIG describes the data better

Systematic uncertainty dominated by Jet Energy Scale: ~25%

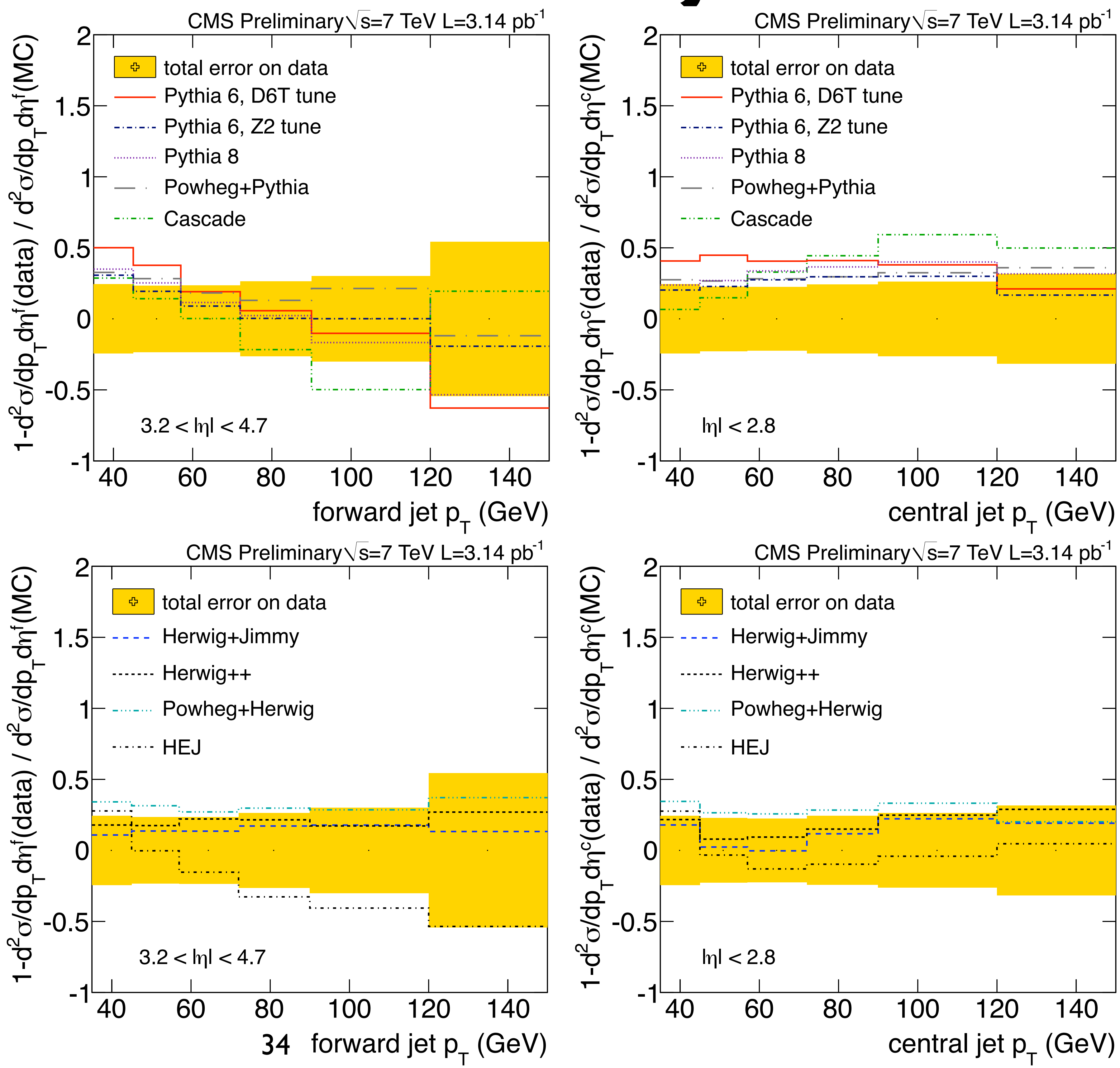
Jet pT resolution: < 5%

Model (unfolding): ~2-5% (central) < 10% (forward)

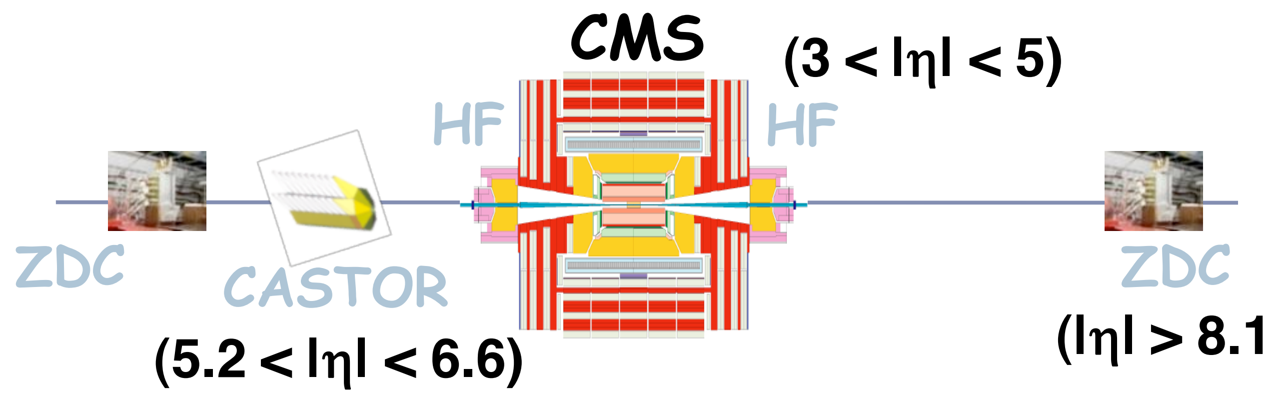
Pile-up: < 5%

Luminosity: 4%

CMS PAS FWD-10-006



Forward physics @ CMS



- Low-x QCD with forward jets
- Underlying event tuning & cosmic rays shower modeling
- Exclusive di-muon production & absolute luminosity measurements
- Vector meson photoproduction
- Observation of hard-diffraction

Physics with 1 pb^{-1} - 100 pb^{-1}

N.B. No pile-up assumed

All results assume $\sqrt{s}$ = 14 TeV

- Physics with proton taggers @ high-luminosity

A look at the past..

~1yr BC (Before Collisions)

Summary

The CMS Forward Physics program covers a wide range of measurements:

- ➡ pp inelastic cross section
- ➡ γγ interactions
- ➡ diffraction
- ➡ central & forward energy flow
- ➡ forward jet production

which enrich our knowledge of proton-proton interactions at the highest energies and give unique information for the modeling & tuning of Monte Carlo generators at the LHC

Benchmark channels for exclusive & diffractive physics with near beam proton detectors at the LHC - see talk on AFP (ATLAS) & HPS (CMS)

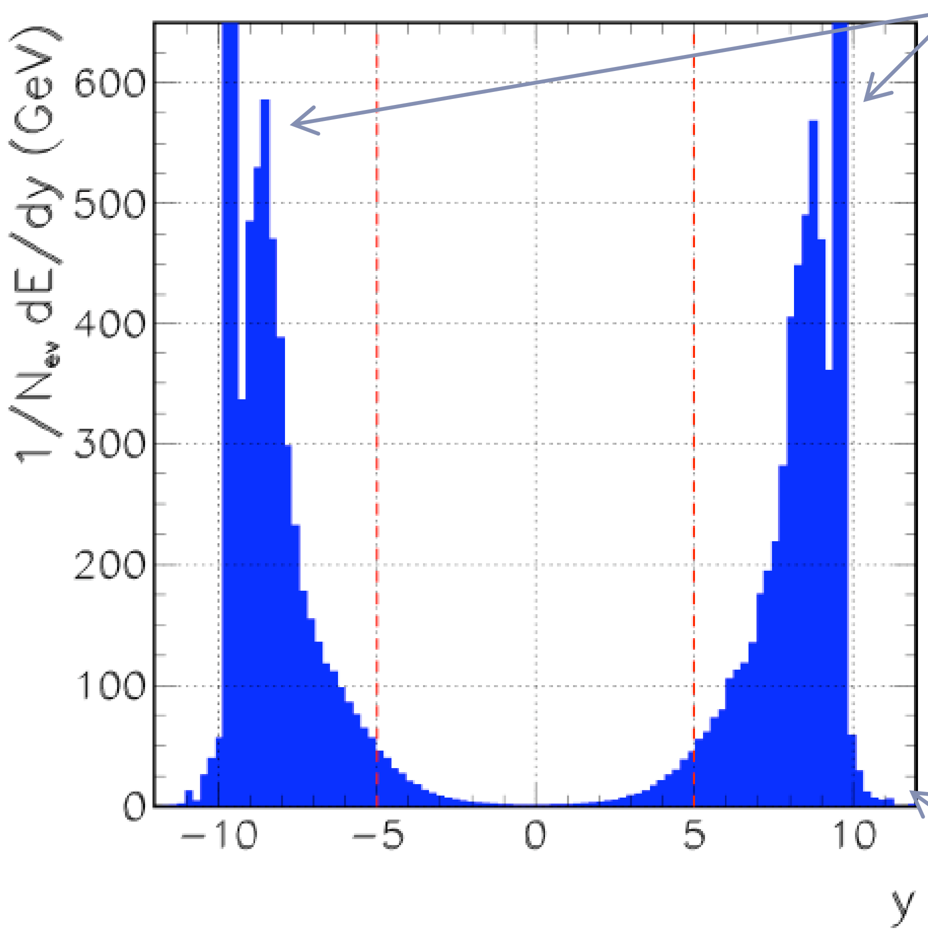
Forward instrumentation around CMS essential to fully develop such a physics program

Backup

Forward physics

- Most energy deposited between 8 < |y| < 9
- Main CMS/ATLAS calorimeters: |y| < 5

Energy flow at LHC



$$y_{max} = \ln \frac{\sqrt{s}}{m} \approx 11.5$$

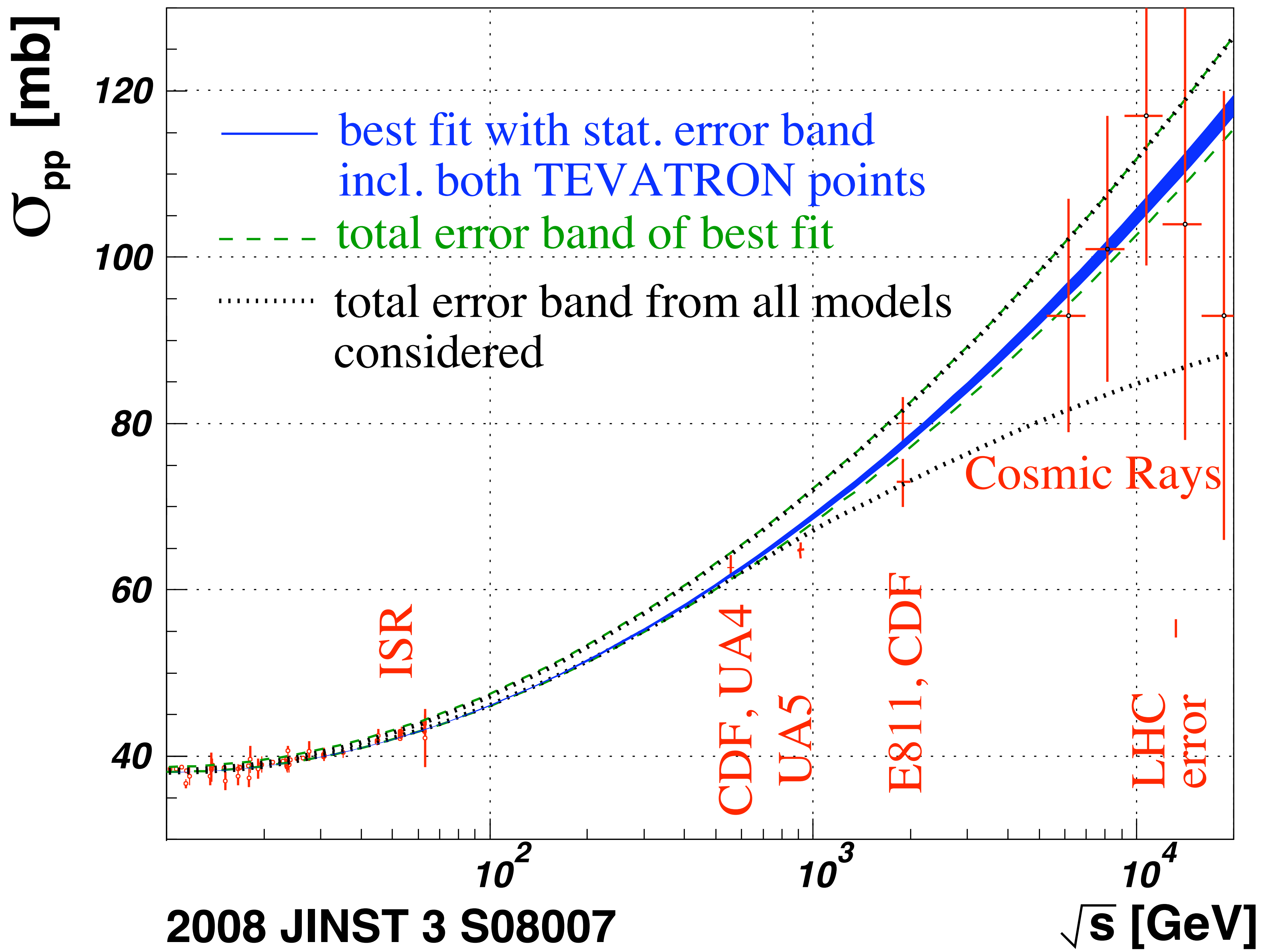
Low-x QCD & BFKL dynamics studies

Monte Carlo tuning

γ-mediated processes & absolute luminosity determination

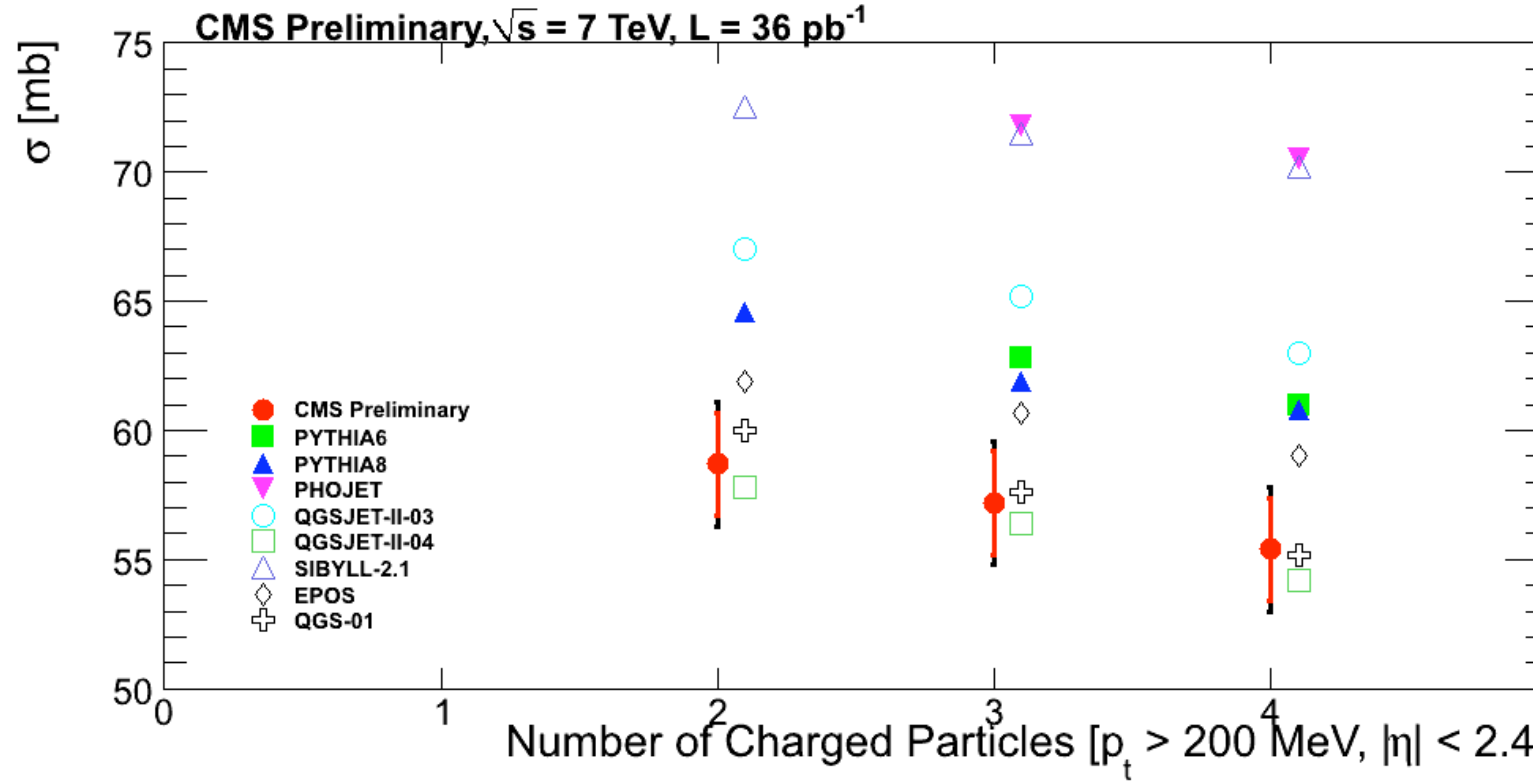
Hard diffraction and rapidity gap survival determination

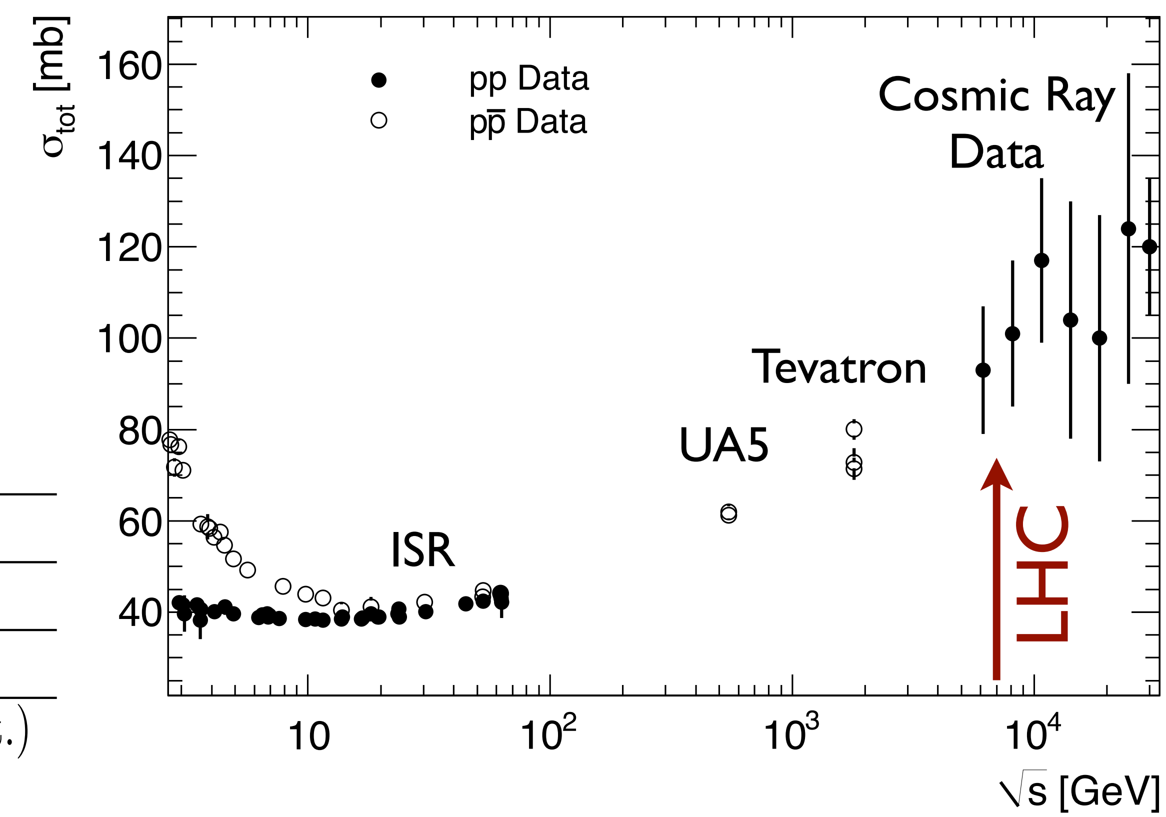
Discovery physics w/ near beam detectors



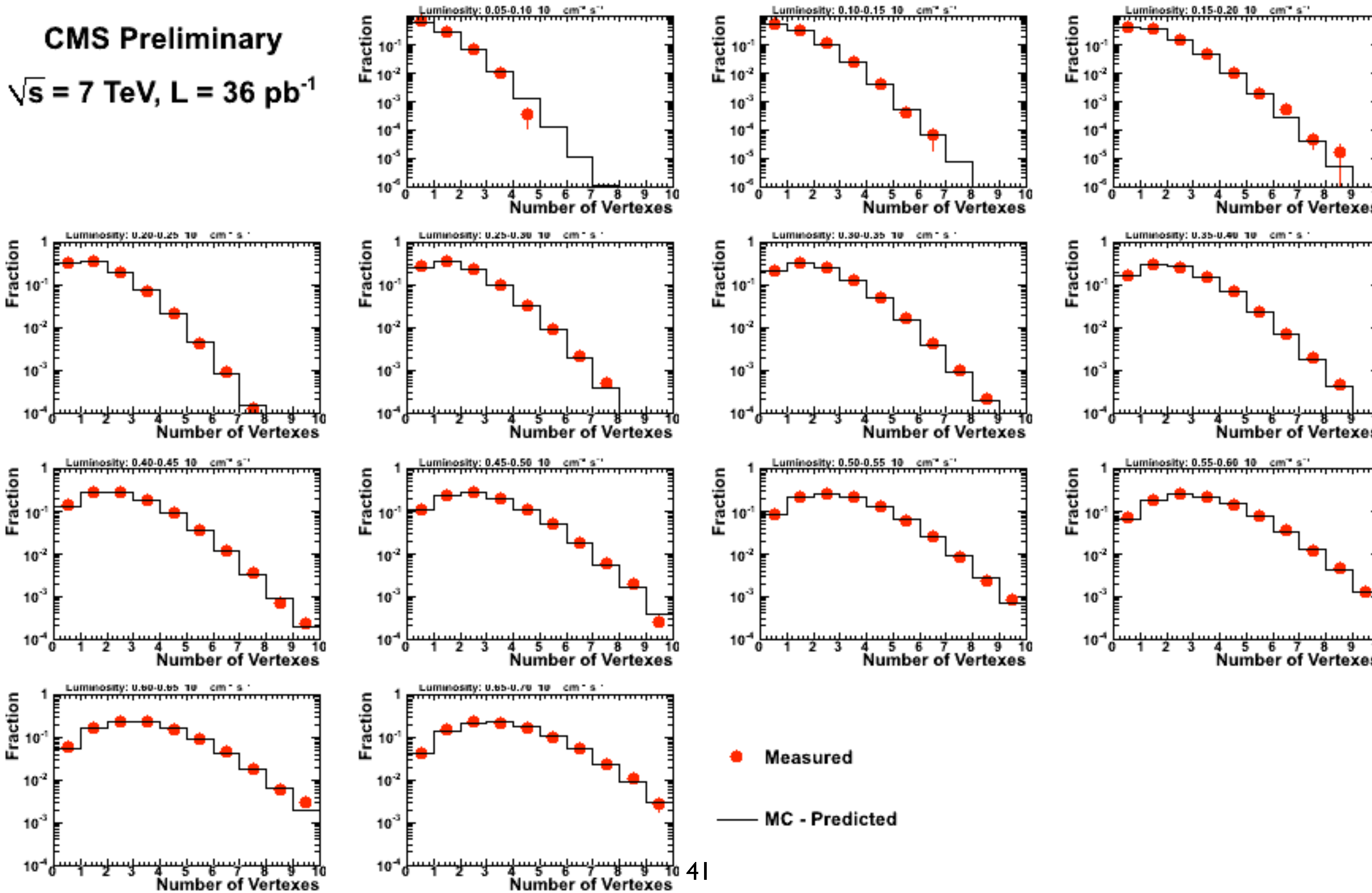
σ_{pp} [mb]
120
100
80
60
40
best fit with stat. error band
incl. both TEVATRON points
total error band of best fit
total error band from all models
considered
Cosmic Rays
ISR
CDF, UA4
UA5
E811, CDF
LHC
error
10^2
10^3
10^4
2008 JINST 3 S08007
$\sqrt{s}$ [GeV]

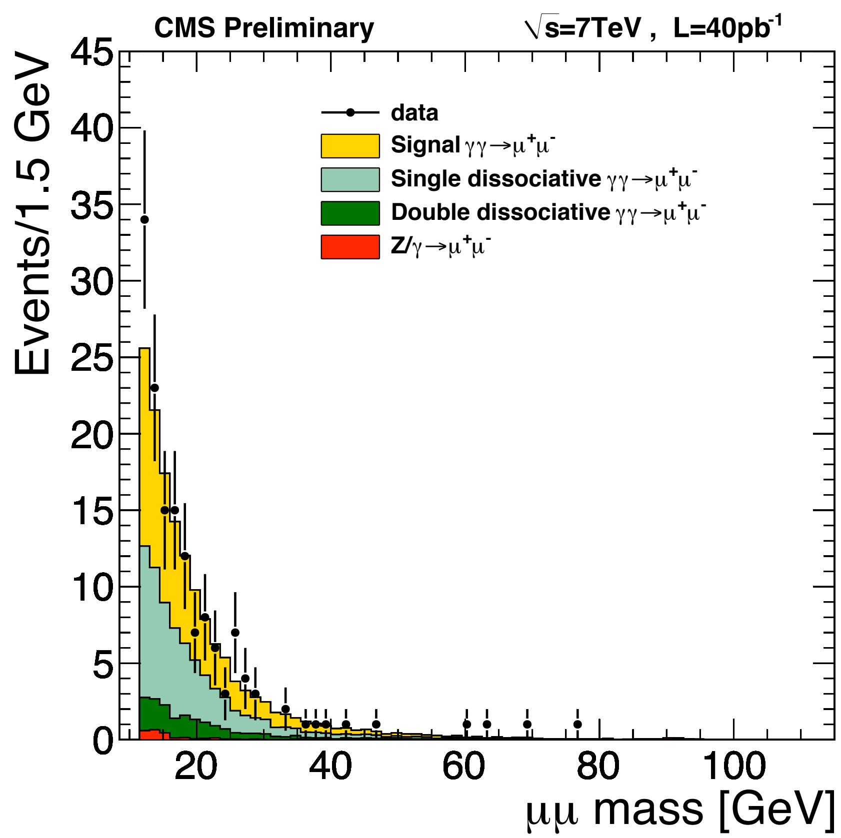
Total inelastic cross section



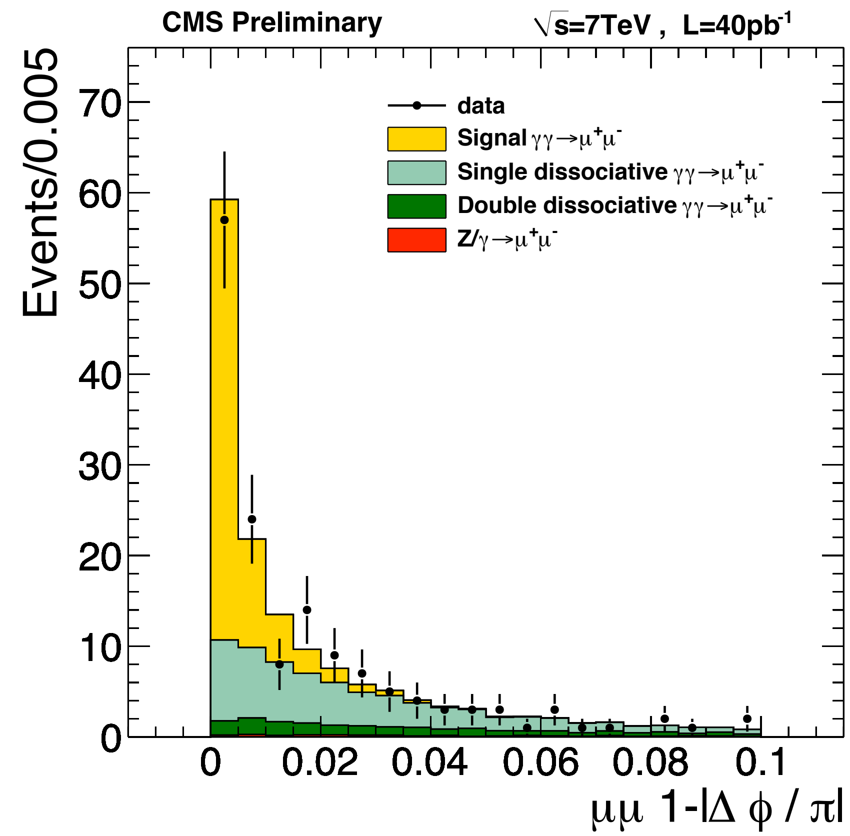


$\sigma(N_{\rm chg} \geq 2;\ p_T > 200\ {\rm MeV};\ \|\eta\| < 2.4)$	$58.7 \pm 2.0\ ({\rm Syst.}) \pm 2.4({\rm Lum.})$
$\sigma(N_{\rm chg} \geq 3;\ p_T > 200\ {\rm MeV};\ \|\eta\| < 2.4)$	$57.2 \pm 2.0\ ({\rm Syst.}) \pm 2.4({\rm Lum.})$
$\sigma(N_{\rm chg} \geq 4;\ p_T > 200\ {\rm MeV};\ \|\eta\| < 2.4)$	$55.4 \pm 2.0\ ({\rm Syst.}) \pm 2.4({\rm Lum.})$
$\sigma(N_{\rm part} \geq 3;\ p_T > 200\ {\rm MeV};\ \|\eta\| < 2.4)$	$59.7 \pm 2.0\ ({\rm Syst.}) \pm 2.4({\rm Lum.})$
$\sigma_{\rm inel.}(pp)$	$68 \pm 2.0\ ({\rm Syst.}) \pm 2.4({\rm Lum.}) \pm 4({\rm Ext.})$

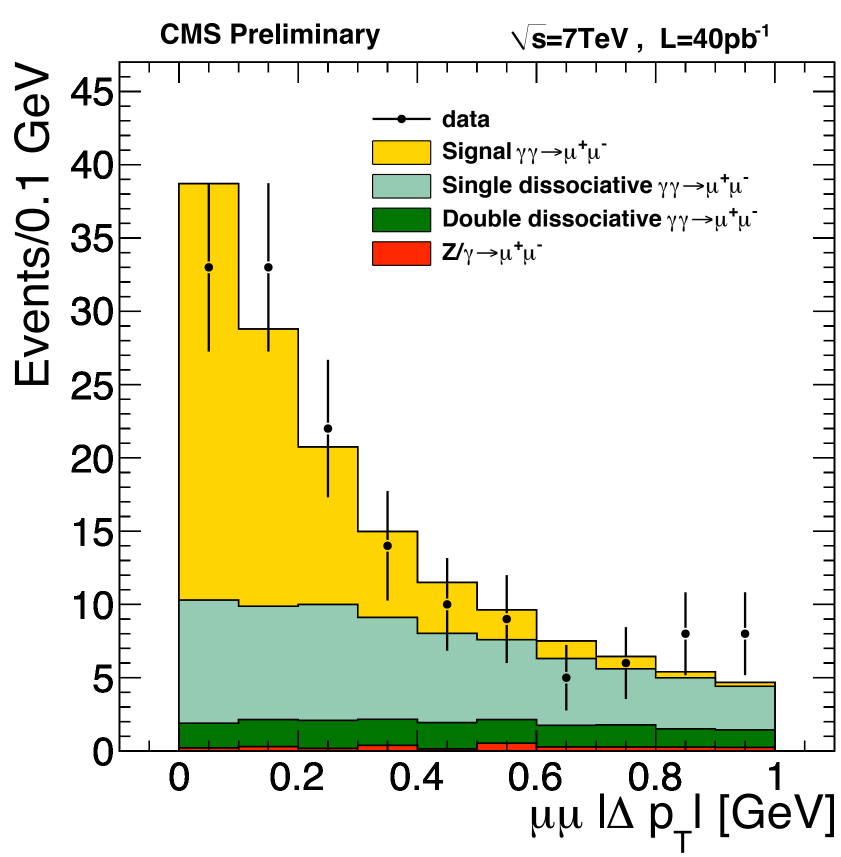

CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 36 pb^{-1}
Luminosity: 0.05-0.10
Luminosity: 0.10-0.15
Luminosity: 0.15-0.20
Luminosity: 0.20-0.25
Luminosity: 0.25-0.30
Luminosity: 0.30-0.35
Luminosity: 0.35-0.40
Luminosity: 0.40-0.45
Luminosity: 0.45-0.50
Luminosity: 0.50-0.55
Luminosity: 0.55-0.60
Luminosity: 0.60-0.65
Luminosity: 0.65-0.70
Fraction
Number of Vertexes
Measured
MC - Predicted



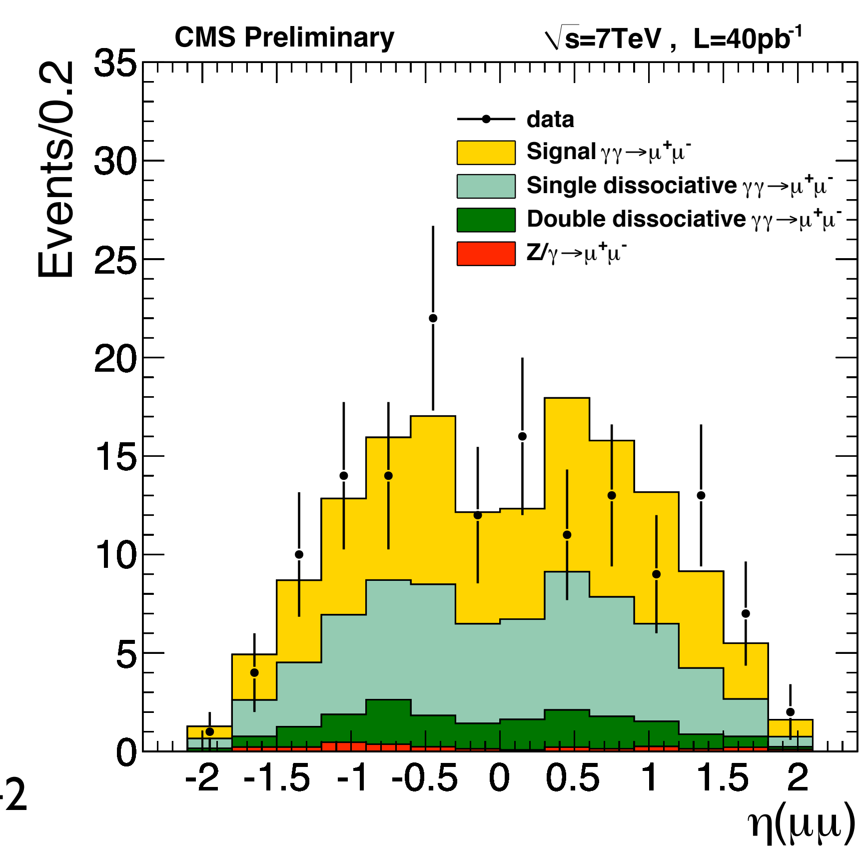
CMS Preliminary
√s=7TeV , L=40pb-1
data
Signal γγ→μ+μ-
Single dissociative γγ→μ+μ-
Double dissociative γγ→μ+μ-
Z/γ→μ+μ-
Events/1.5 GeV
μμ mass [GeV]



CMS Preliminary
√s=7TeV , L=40pb-1
data
Signal γγ→μ+μ-
Single dissociative γγ→μ+μ-
Double dissociative γγ→μ+μ-
Z/γ→μ+μ-
Events/0.005
μμ 1-|Δ φ / π|

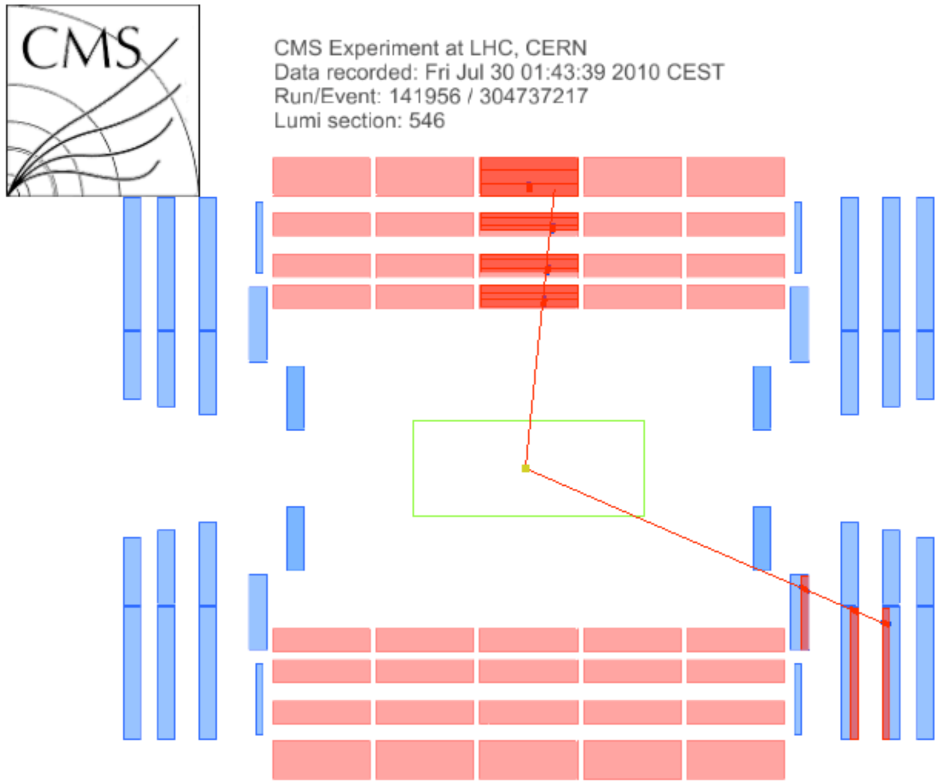


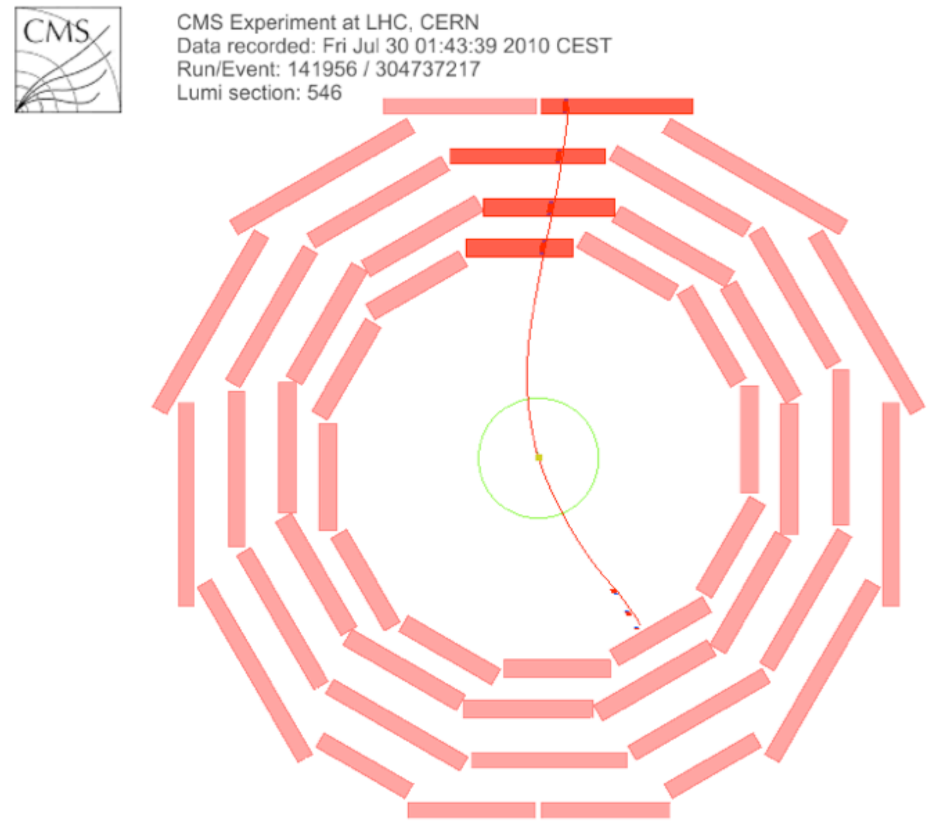
CMS Preliminary
√s=7TeV , L=40pb-1
data
Signal γγ→μ+μ-
Single dissociative γγ→μ+μ-
Double dissociative γγ→μ+μ-
Z/γ→μ+μ-
Events/0.1 GeV
μμ |Δ pT| [GeV]

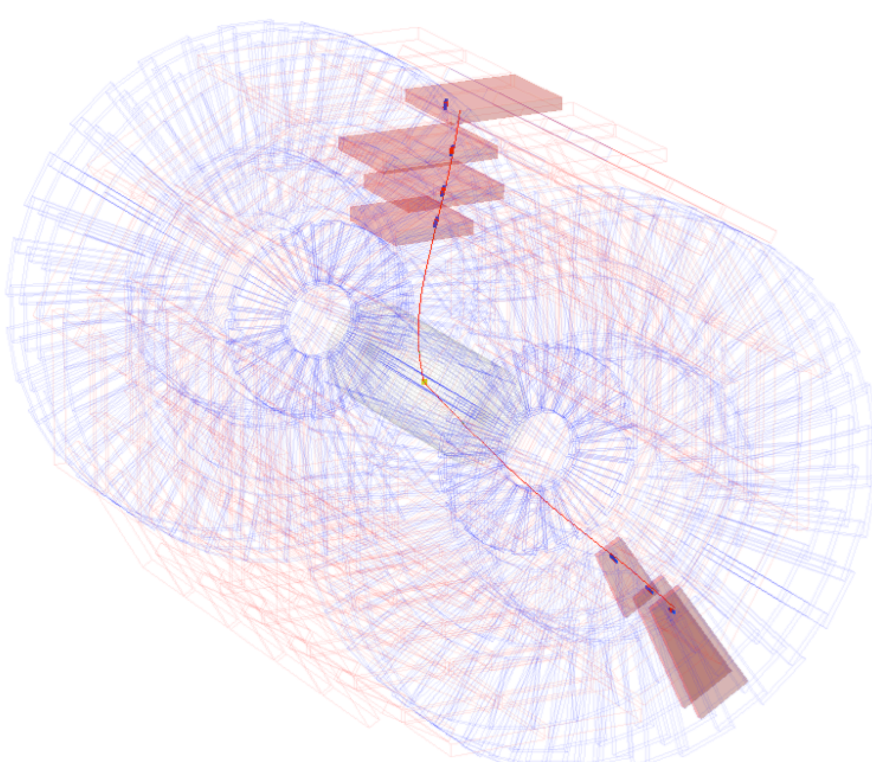


CMS Preliminary
√s=7TeV , L=40pb-1
data
Signal γγ→μ+μ-
Single dissociative γγ→μ+μ-
Double dissociative γγ→μ+μ-
Z/γ→μ+μ-
Events/0.2
η(μμ)

Exclusive γγ→μμ production







$$m = 20.51 \pm 0.2 \text{ GeV}$$
$$\frac{\Delta\phi}{\pi} = 0.98$$
$$\Delta p_T = 0.48$$

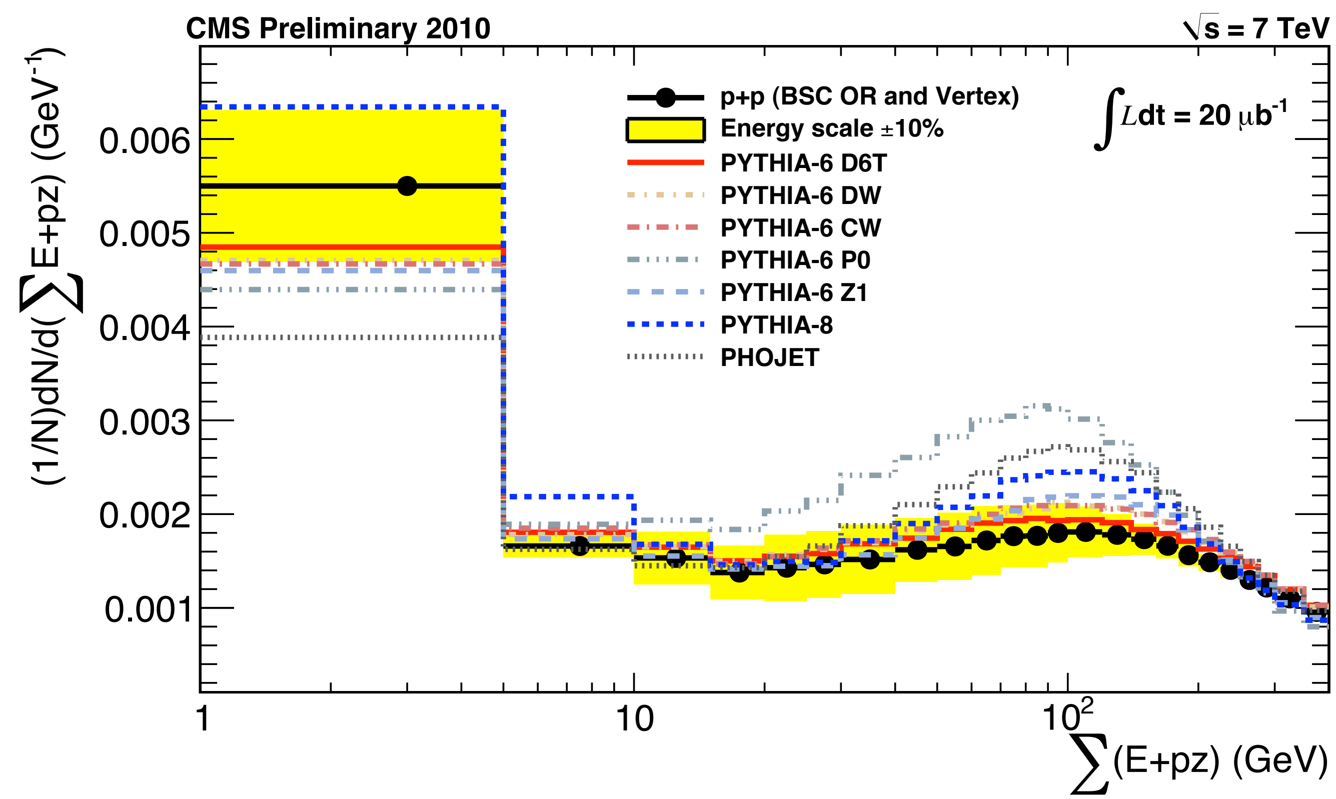
$$\text{track: } p_T > 0 \text{ GeV}$$
$$\text{HCAL: } E > 4 \text{ GeV}$$
$$\text{ECAL: } E > 2.5 \text{ GeV}$$

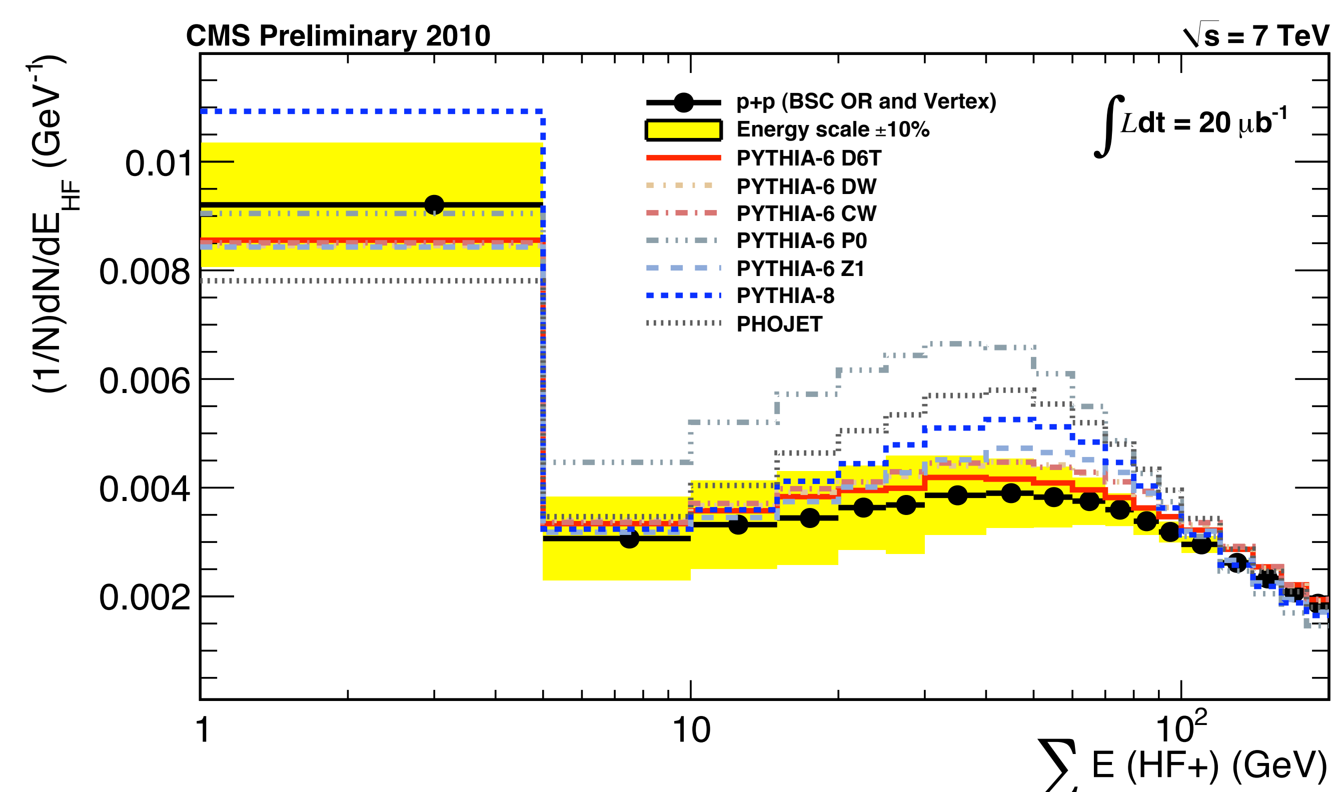
Data vs MC

Fair agreement with PYTHIA6 tunes D6T, DW, CW & Z1;

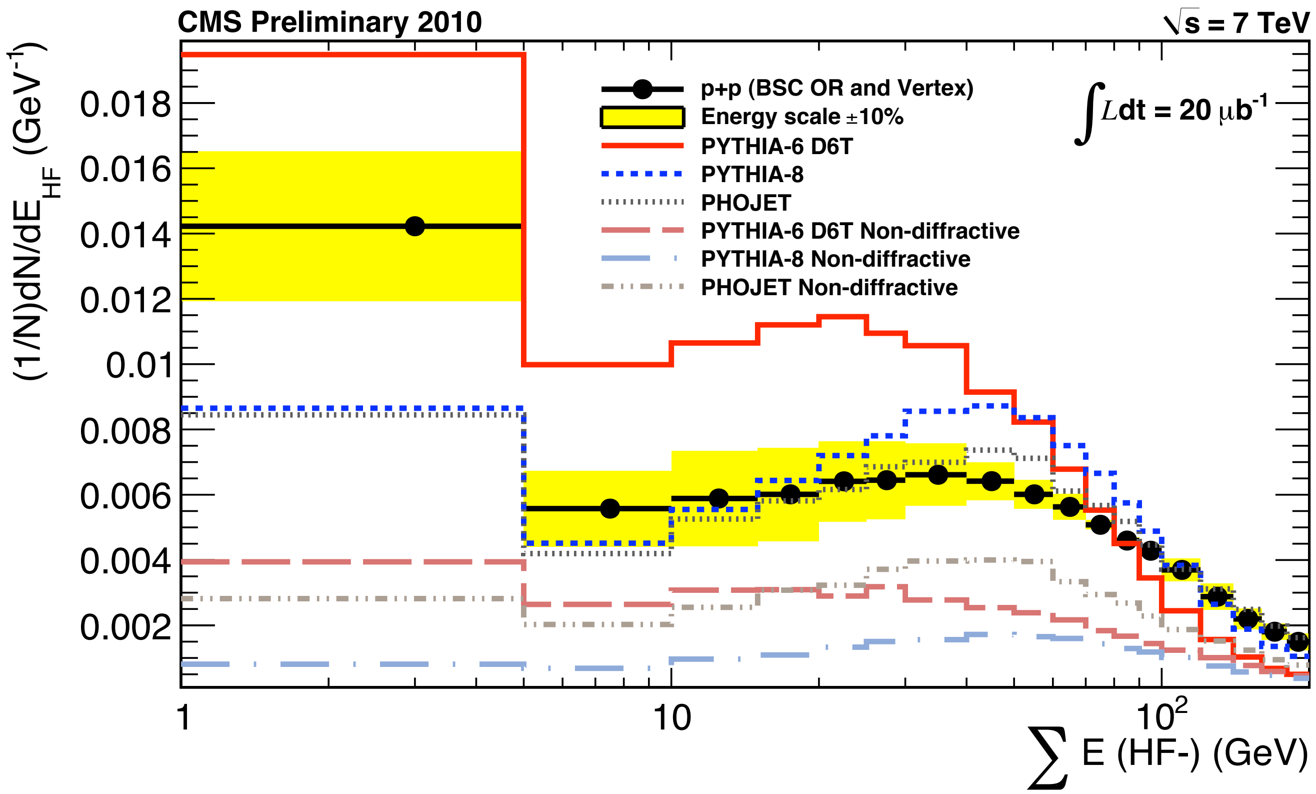
PYTHIA6 tune P0, as well as PHOJET considerably higher than data;

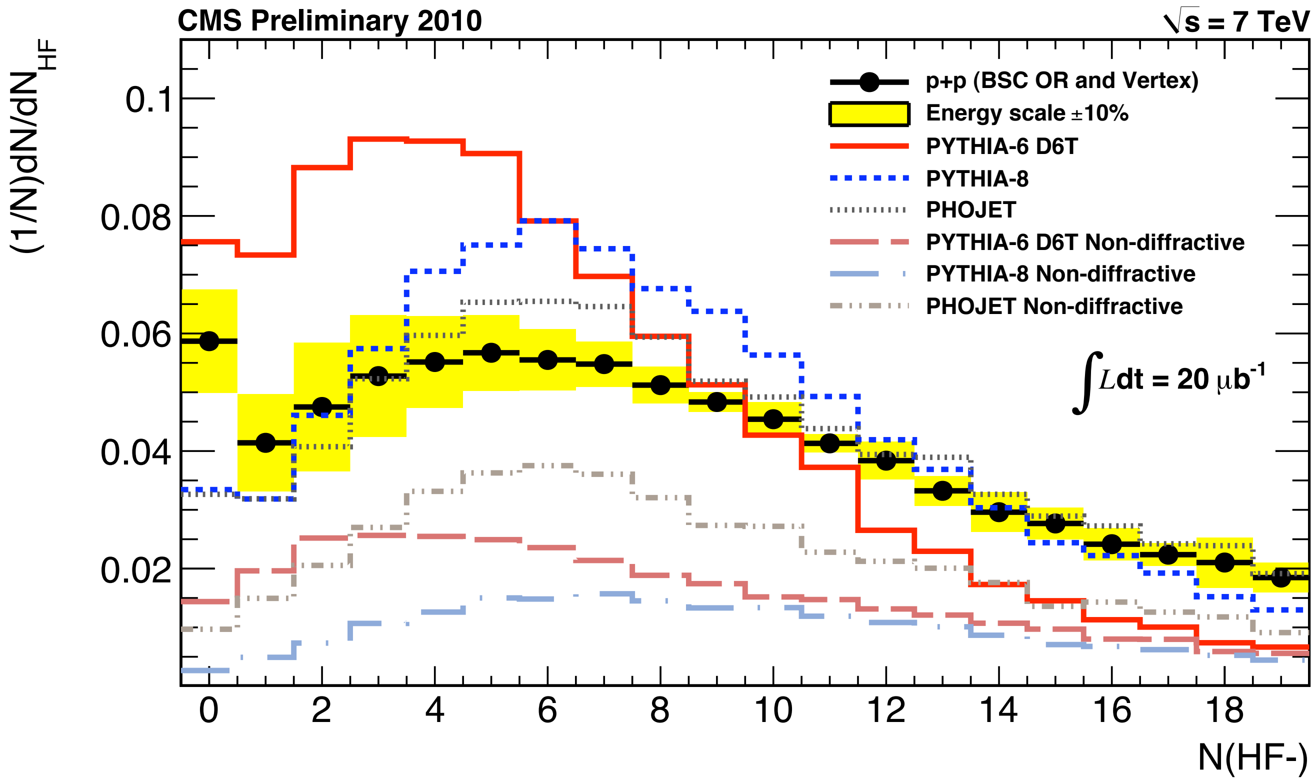
PYTHIA8 also does not agree well with the data.





Enhancing diffractive component





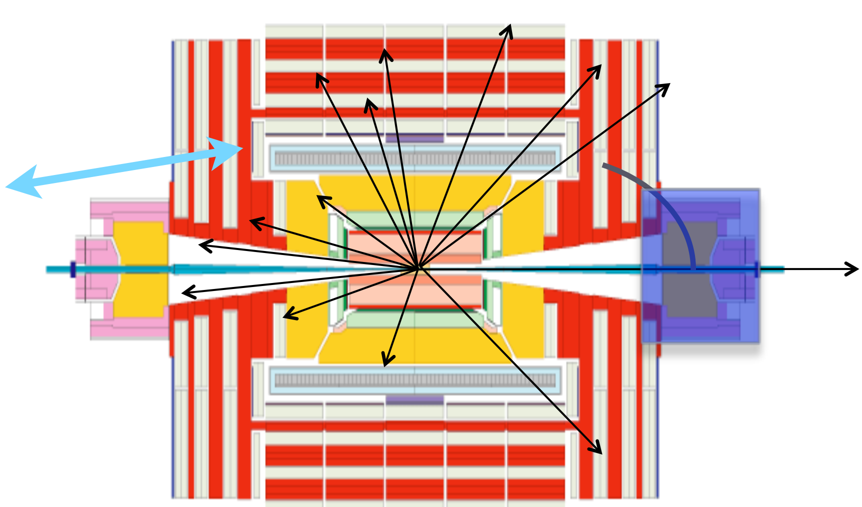
Look at events with no activity in one side: E(HF+) < 8 GeV.

Suppressed non-diffractive contribution.

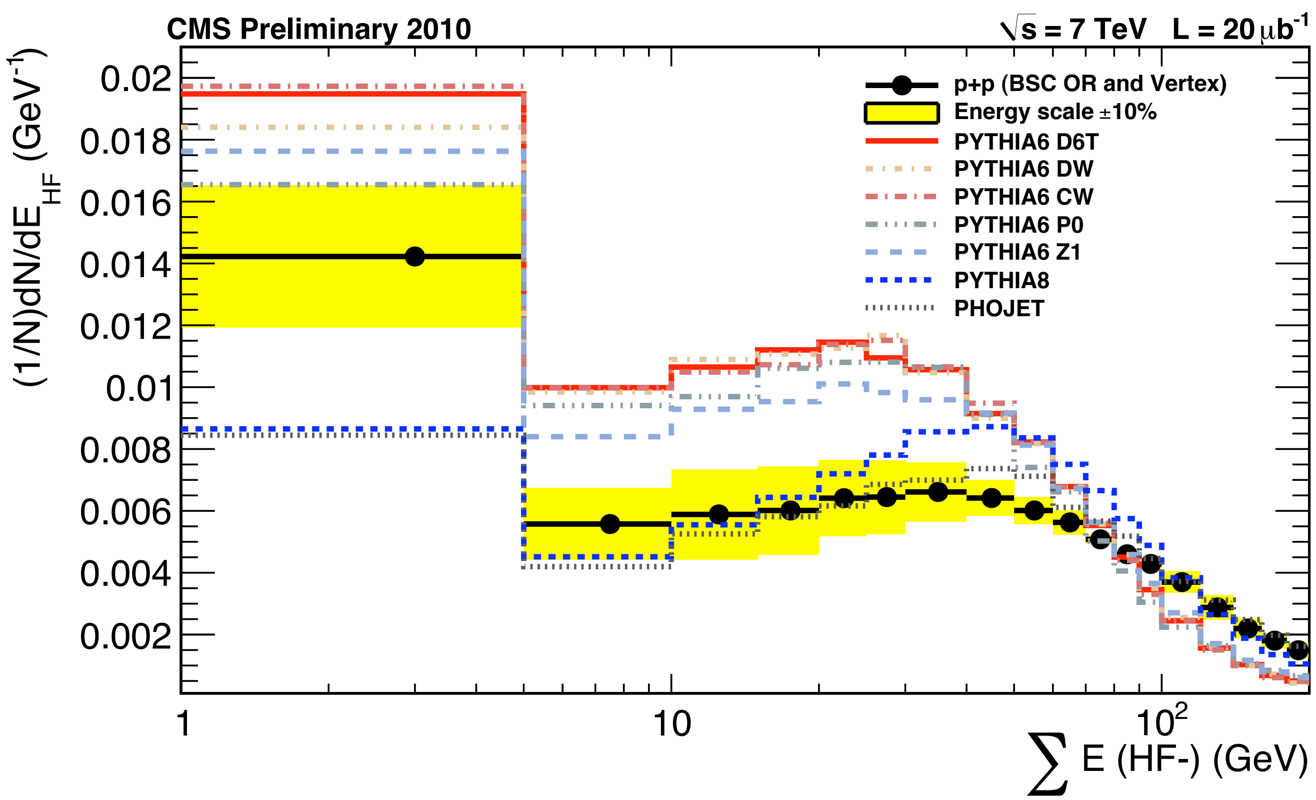
PYTHIA6 describes well inclusive spectrum shown before, but not diffractive enriched sample.

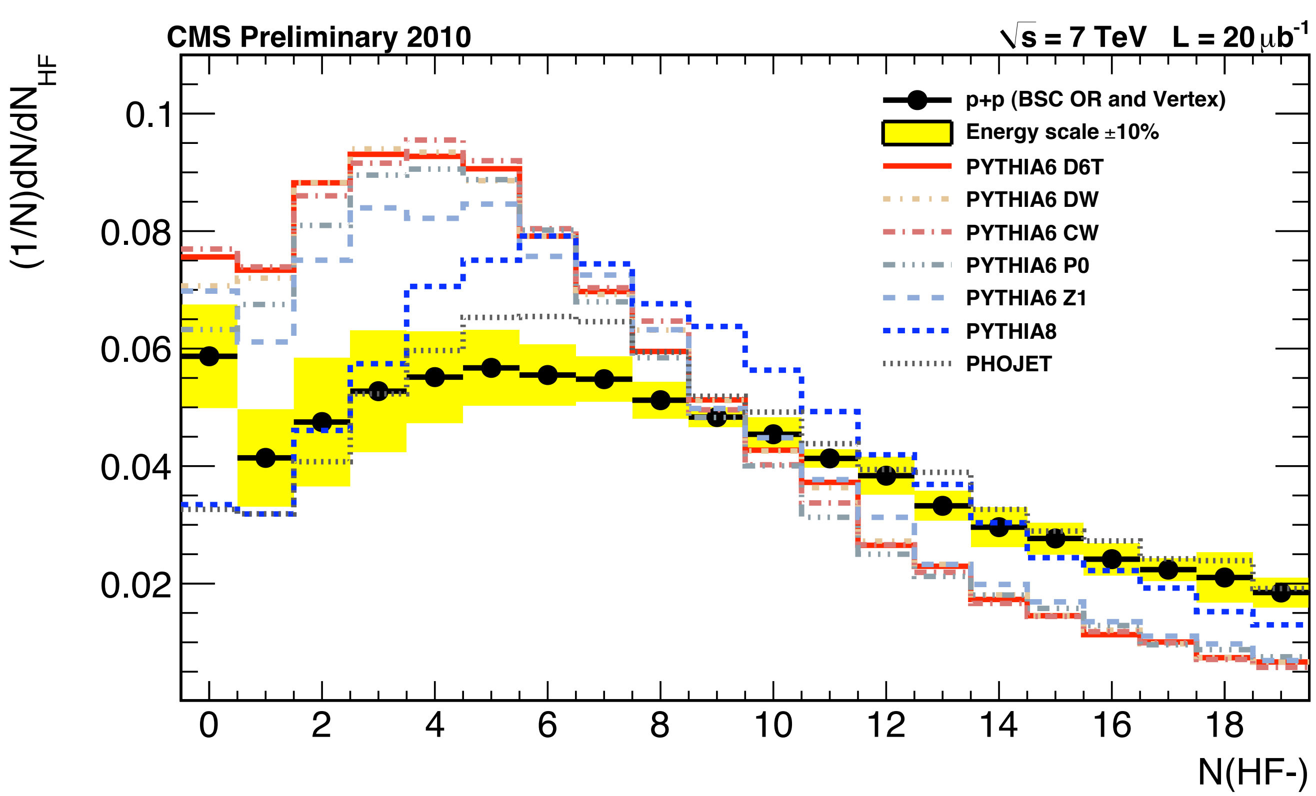
PYTHIA8 and PHOJET describe better tails of distributions, however not low energy region.

Test description of diffractive system (M_X)



Enhancing diffractive component





Look at events with no activity in one side: E(HF+) < 8 GeV.

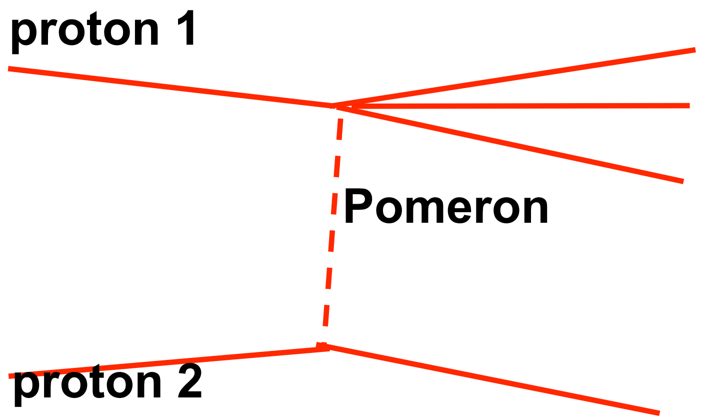
Suppressed non-diffractive contribution.

PYTHIA6 describes well inclusive spectrum shown before, but not diffractive enriched sample.

PYTHIA8 and PHOJET describe better tails of distributions, however not low energy region.

Different PYTHIA6 tunes show similar behavior (consistent since diffractive description does not change).

Meaning of E ± p_z



pp --> pX
pPomeron –-> X

- $\Sigma(E \pm p_z)$ runs over all calo towers
- Measure for the momentum of the Pomeron = momentum loss of the proton

Momentum and energy conservation:
E(Pomeron) + E(proton 1) = E(X)
p_z(Pomeron) + p_z(proton 1) = p_z(X)

Recall: in SD events proton loses almost none of its initial momentum.

If proton 1 moves in positive z direction: E(proton 1) - p_z(proton 1) ≈ 0 (and proton 2, and Pomeron, move in the negative z direction)

Hence:
E(Pomeron) - p_z(Pomeron) ≈ 2E(Pomeron) ≈ E(X) - p_z(X)

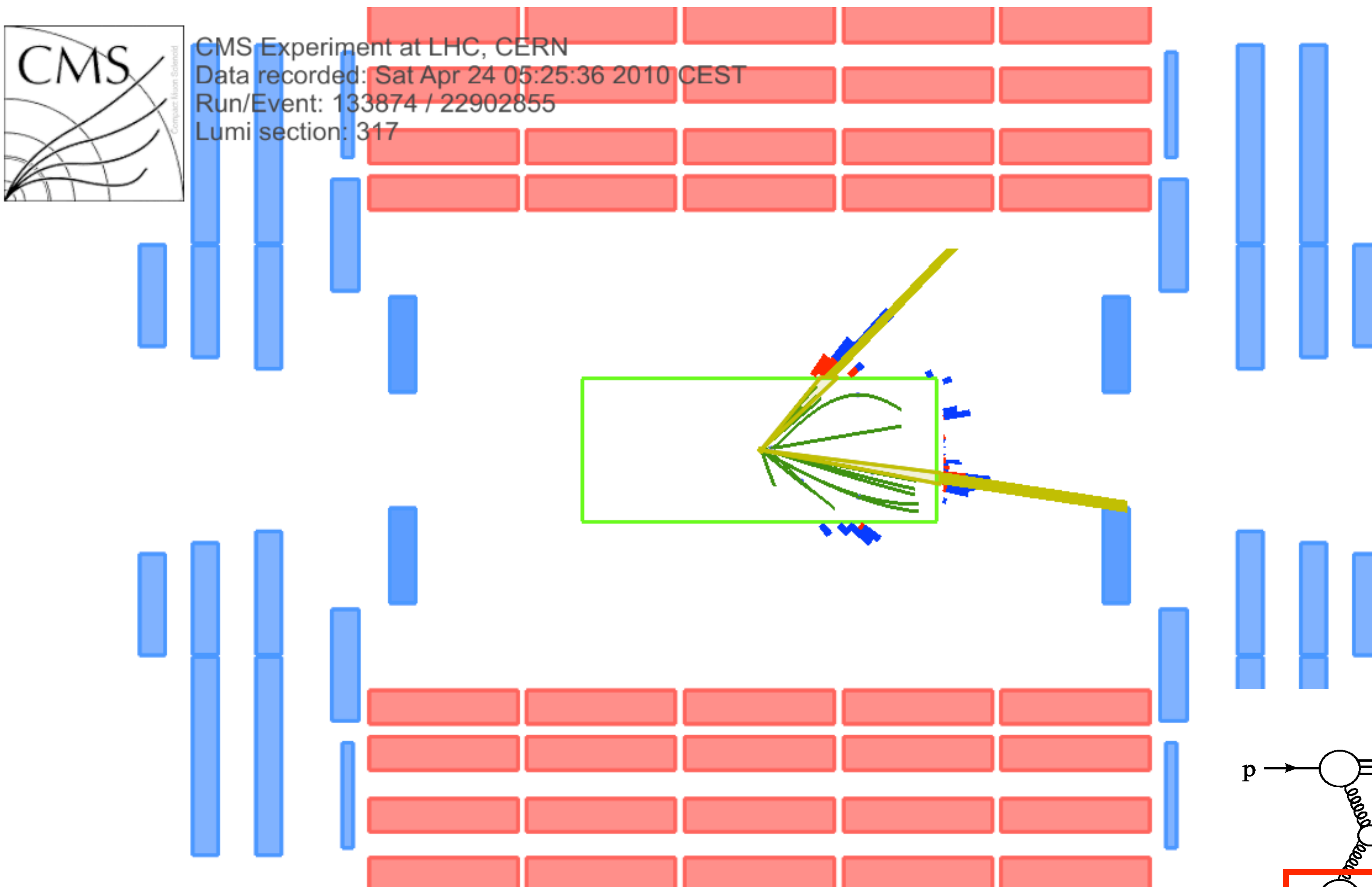
i.e. $\xi = 2E(\text{Pomeron})/\sqrt{s} \approx (E(X) - p_z(X))/\sqrt{s}$

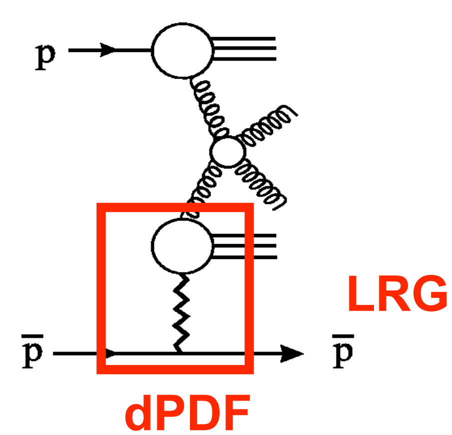
Conversely, if proton 1 moves in the negative z direction (and proton 2, and Pomeron, in the positive z direction), E(proton 1) + p_z(proton 1) ≈ 0, hence:

E(Pomeron) + p_z(Pomeron) ≈ 2E(Pomeron) ≈ E(X) + p_z(X)

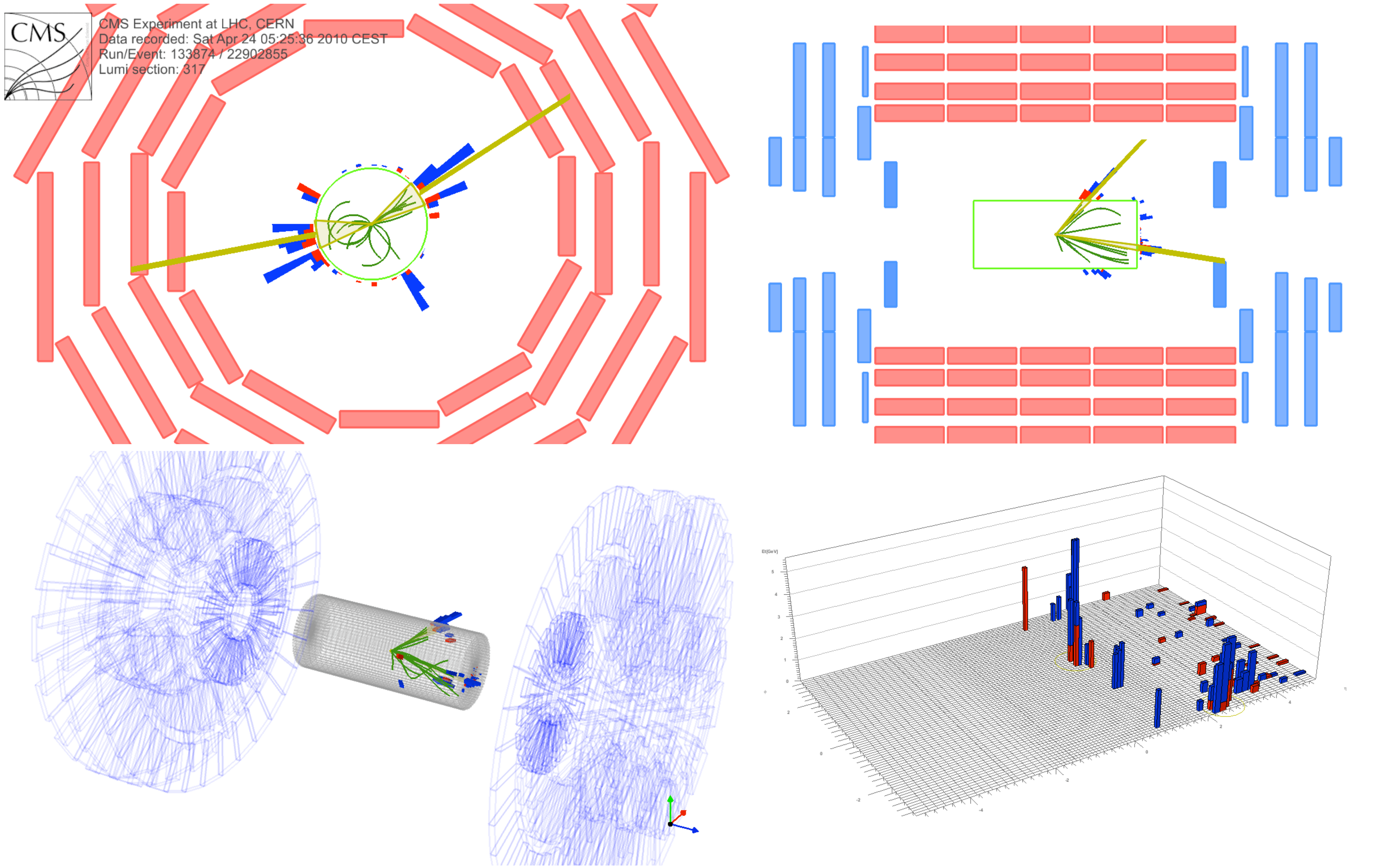
i.e. $\xi = 2E(\text{Pomeron})/\sqrt{s} \approx (E(X) + p_z(X))/\sqrt{s}$

Diffractive dijet candidate





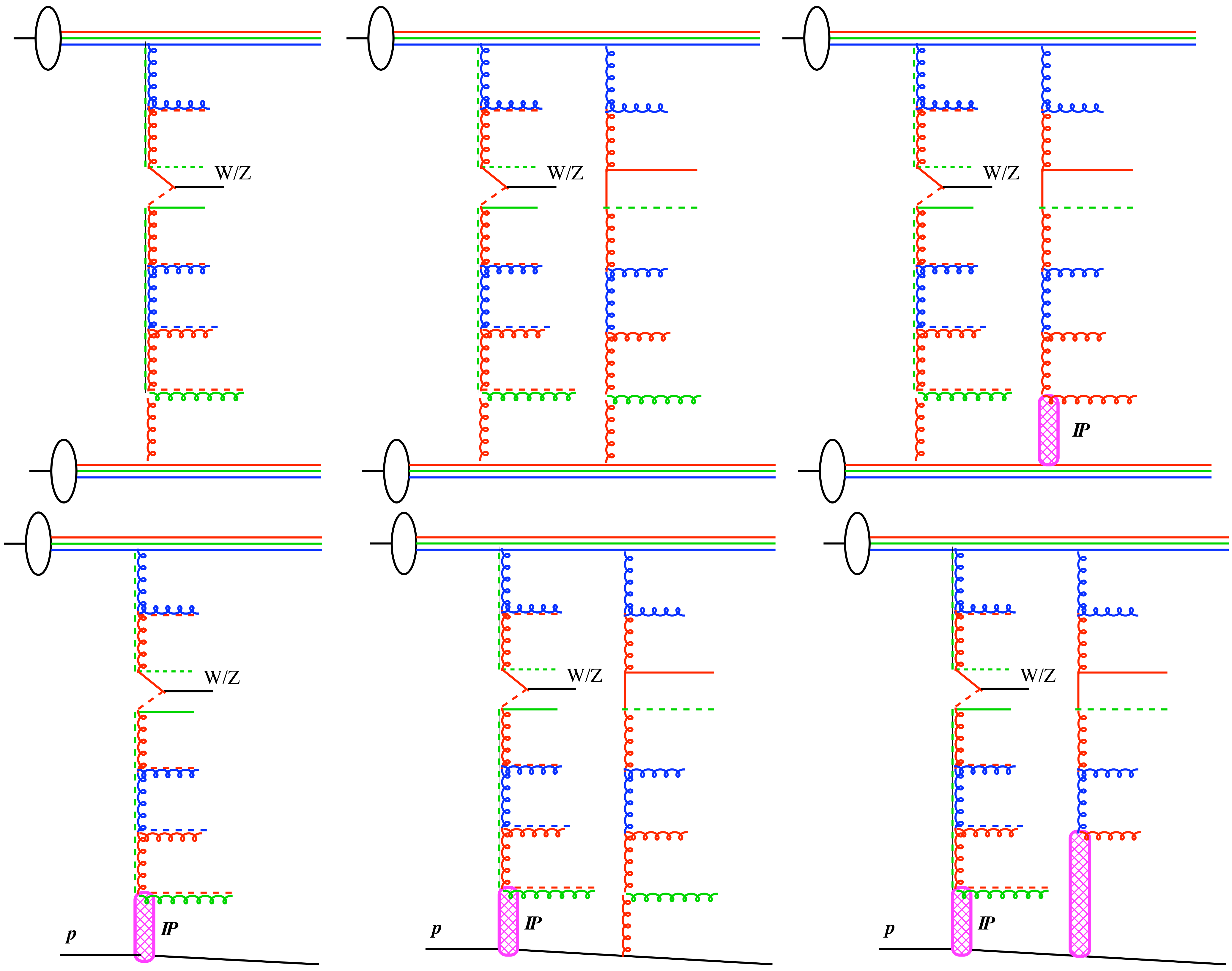
Diffractive dijet candidate

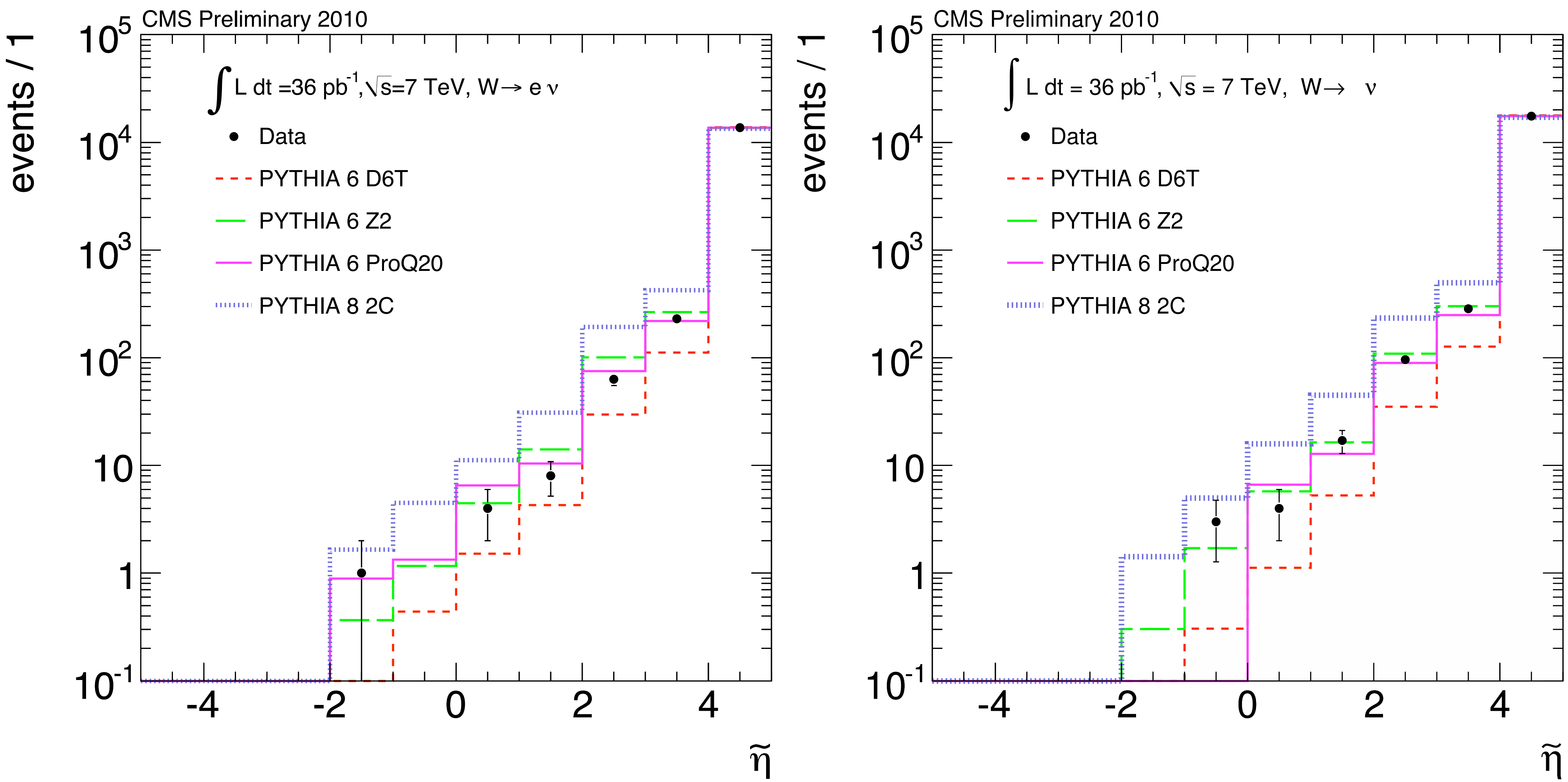


$E(\eta < 3.0) > 1.5$ GeV $\quad p_T(\text{track}) > 0.5$ GeV
$E(\eta \geq 3.0) > 2.0$ GeV

p_T (jet1) = 43.5 GeV, p_T (jet2) = 36.9 GeV
η (jet1) = 0.83, η (jet2) = 2.55

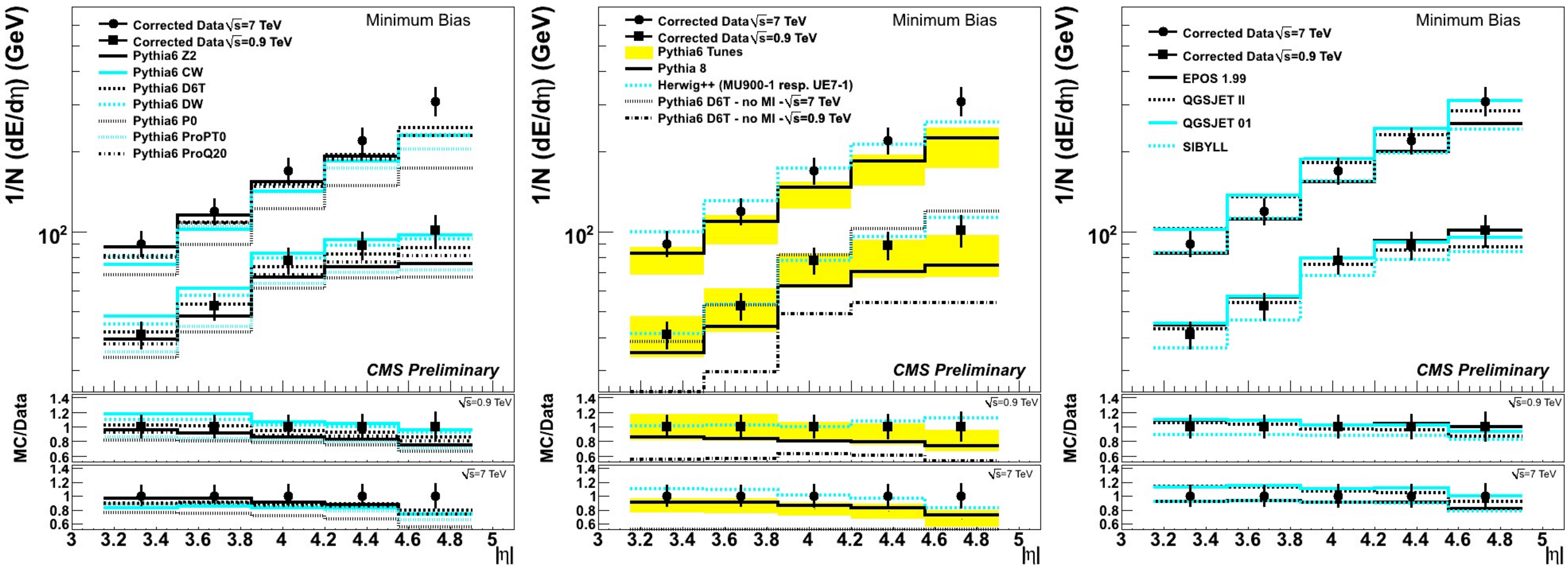
Underlying event in hard interactions





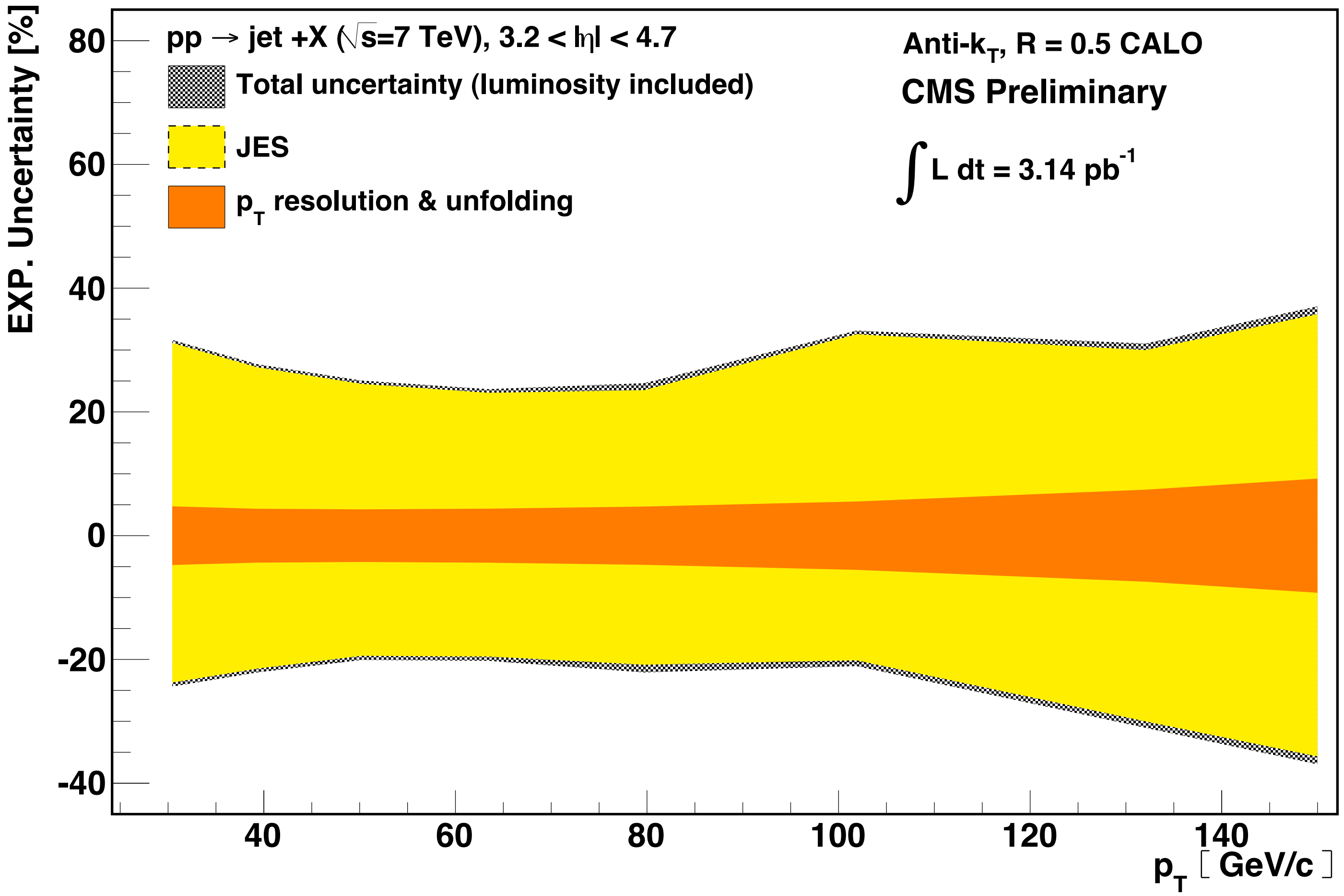
CMS PAS FWD-10-008

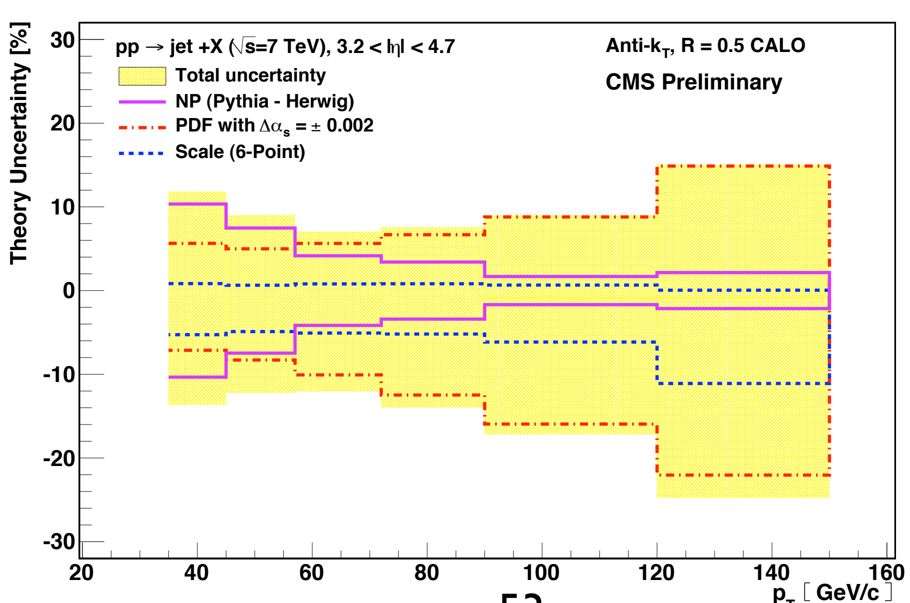
dE/dη

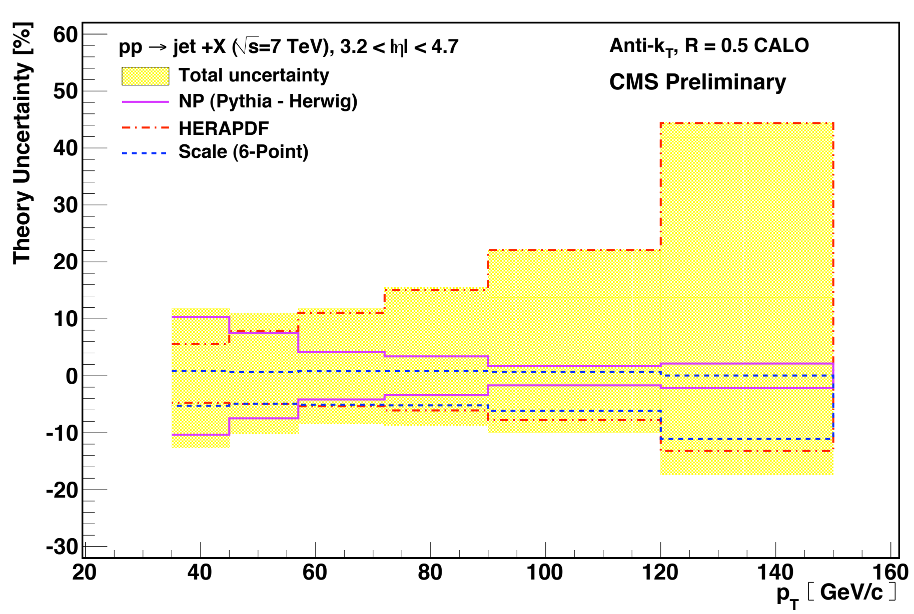


CMS PAS FWD-10-011

Forward jets







P. Skands
MB & UE Working Group
March 2010

PYTHIA 6

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi} \beta_{A\mathbb{P}}^2 \beta_{B\mathbb{P}} \frac{1}{M^2} \exp(B_{sd(AX)}t) F_{sd} ,$$

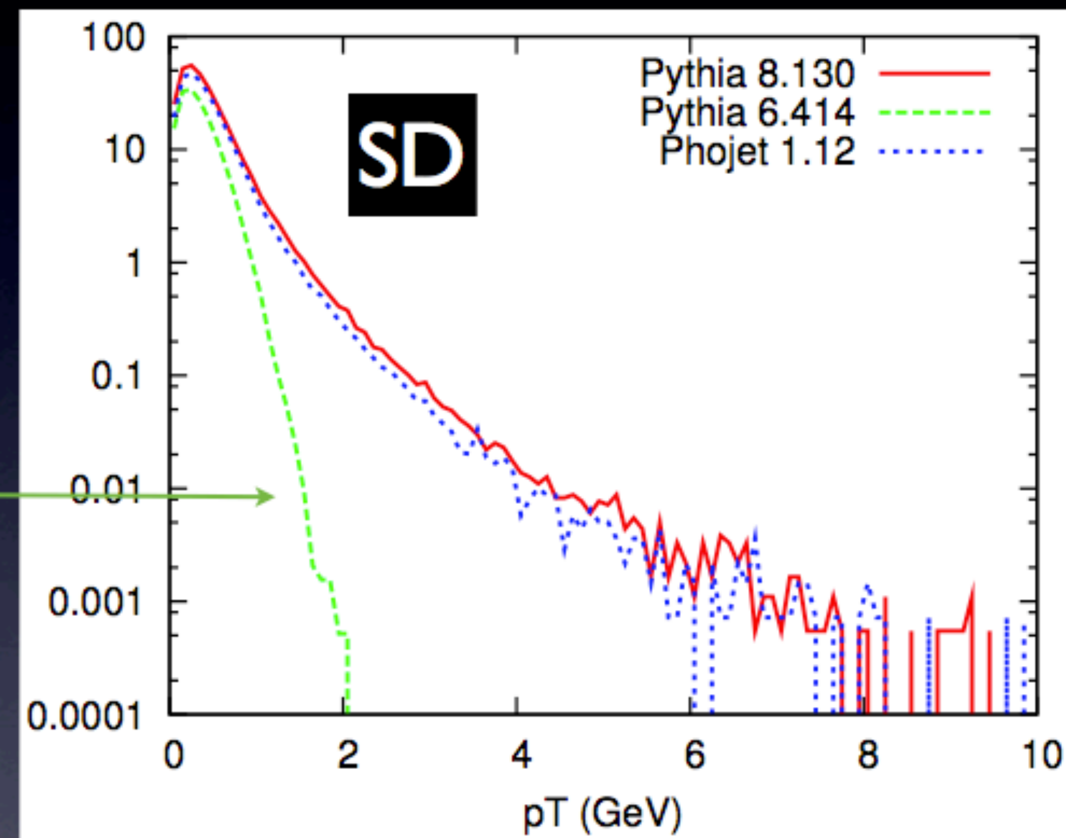
$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi} \beta_{A\mathbb{P}} \beta_{B\mathbb{P}} \frac{1}{M_1^2} \frac{1}{M_2^2} \exp(B_{dd}t) F_{dd} .$$

Spectra:

2 $m_{pi} < M_D <$ 1 GeV: 2-body decay
$M_D >$ 1 GeV : string fragmentation

Partonic Substructure in Pomeron:

Only in POMPYT addon (P. Bruni, A. Edin, G. Ingelman) ► high-p_T "jetty" diffraction absent



Very soft spectra without POMPYT

Status: Supported, but not actively developed

P. Skands
MB & UE Working Group
March 2010

PYTHIA 8

S. Navin (MCnet) + T. Sjöstrand

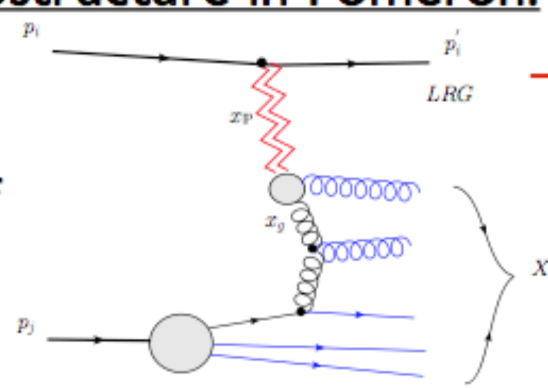
Diffractive Cross Section Formulæ:

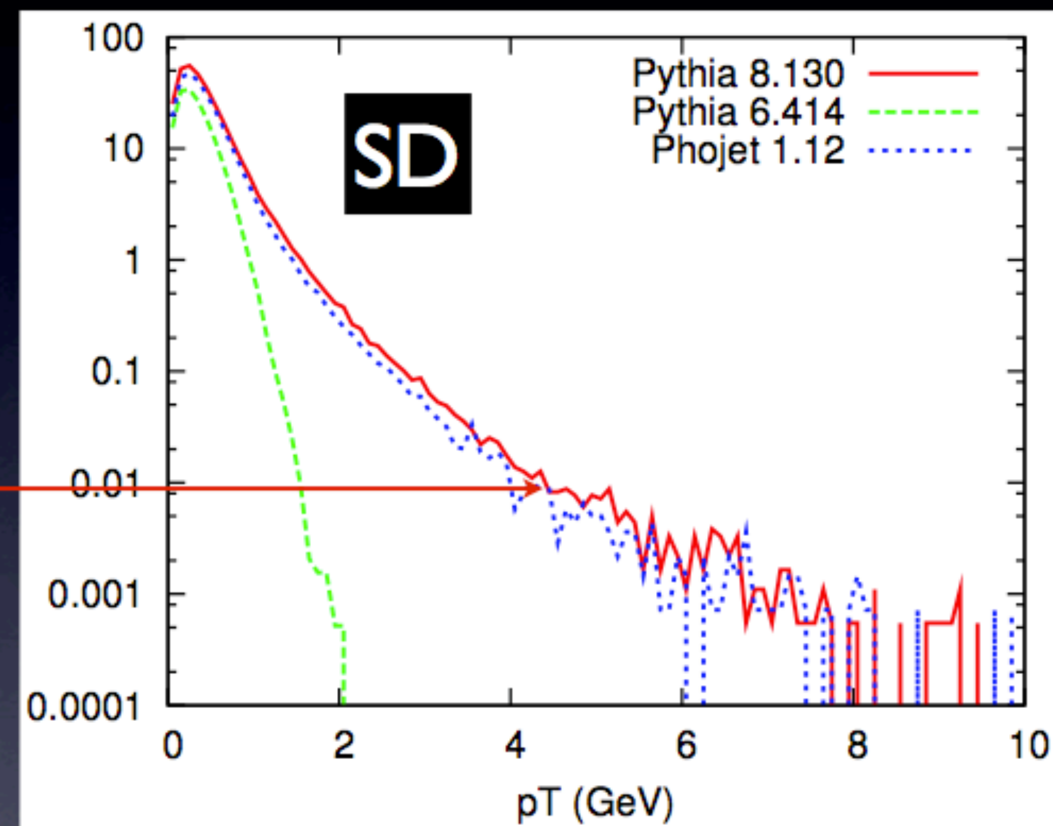
$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta^2_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\,,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g^2_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\,.$$

Partonic Substructure in Pomeron:

Follows the approach of Pompyt





- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: new perturbative description used

Status: Supported and actively developed

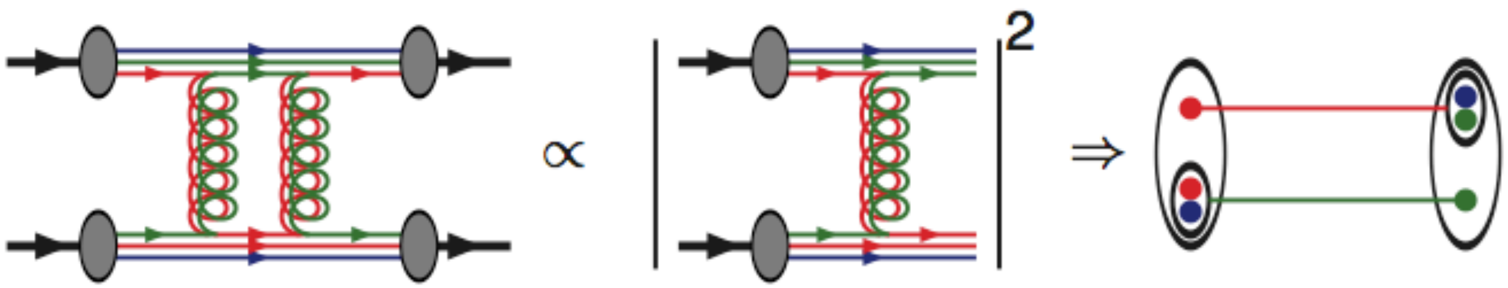
P. Skands
MB & UE Working Group
March 2010

PHOJET (& Relatives)

Slide from T. Sjostrand

(1) Cut Pomeron (1982)

- Pomeron predates QCD; nowadays $\sim$ glueball tower
- Optical theorem relates σ_{total} and σ_{elastic}

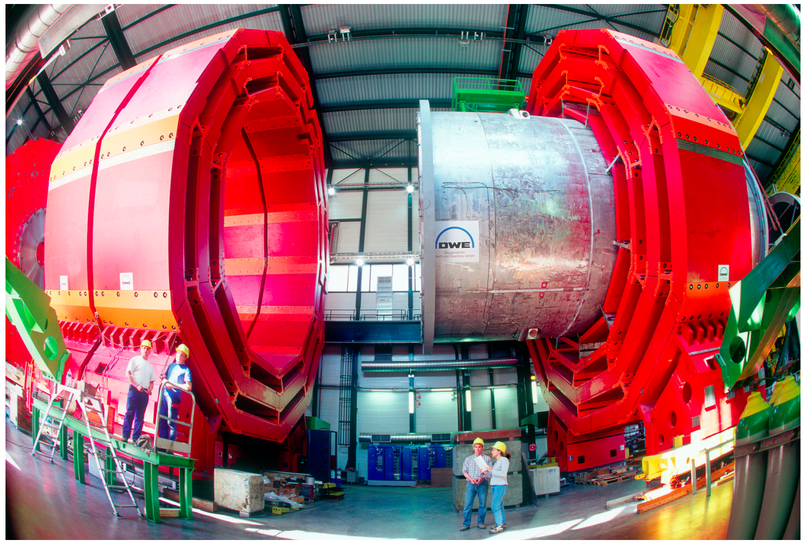


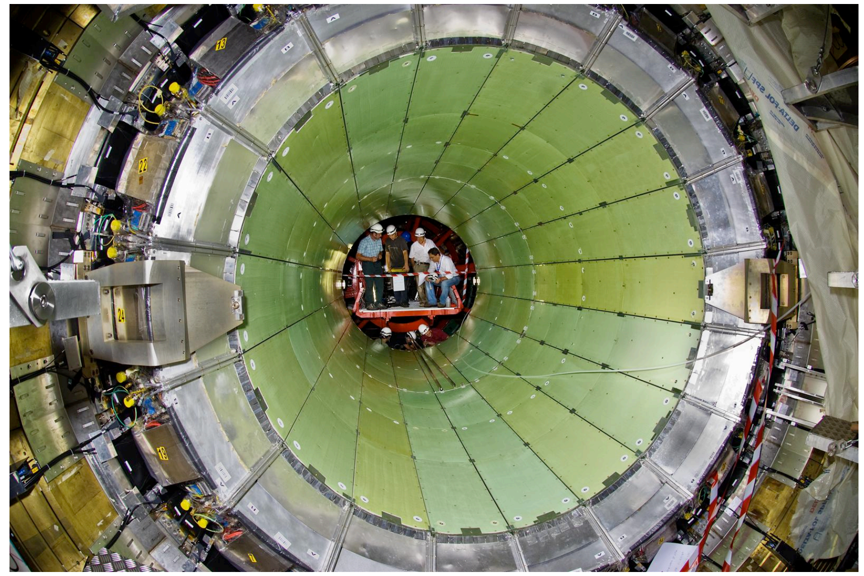
- Unified framework of nondiffractive and diffractive interactions
- Purely low-$p_\perp$: only primordial $k_\perp$ fluctuations
- Usually simple Gaussian matter distribution

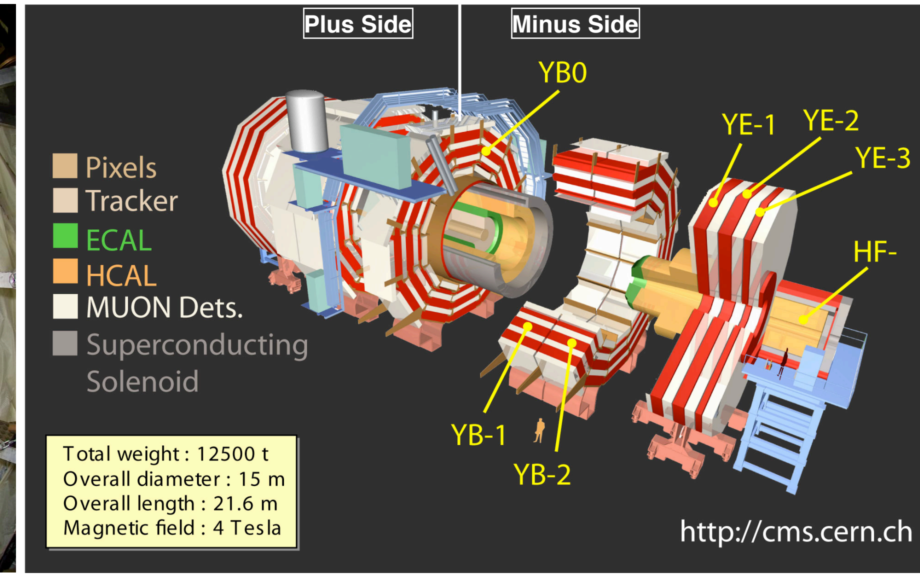
(2) Extension to large $p_\perp$ (1990)

- distinguish soft and hard Pomerons (cf. Ivan):
  soft = nonperturbative, low-$p_\perp$, as above
  hard = perturbative, "high"-$p_\perp$
- hard based on PYTHIA code, with lower cutoff in $p_\perp$

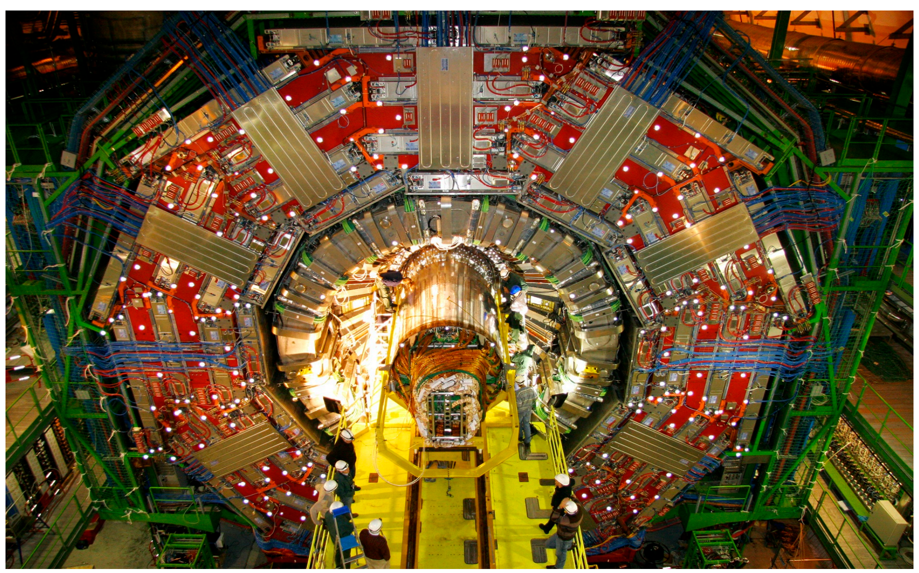
Status: PHOJET web site to be resurrected soon

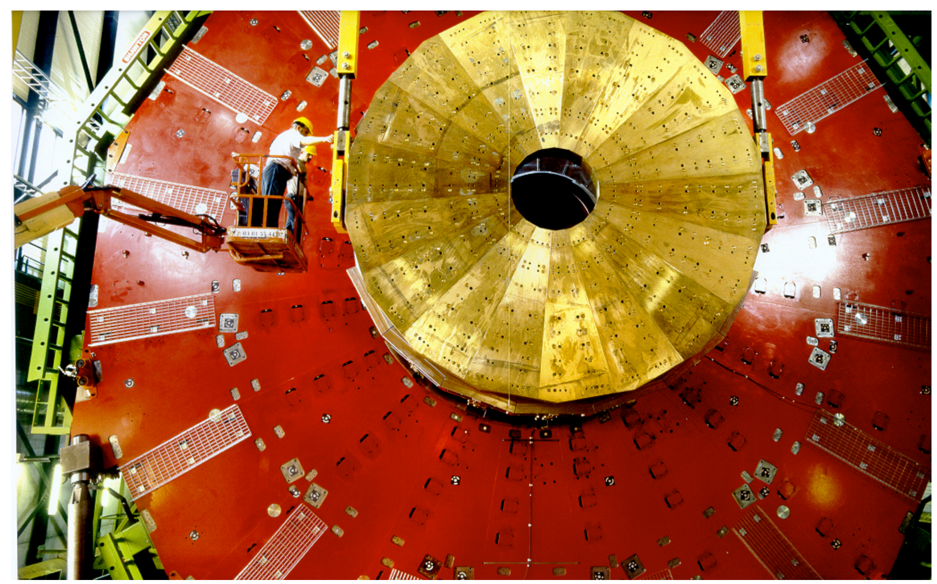


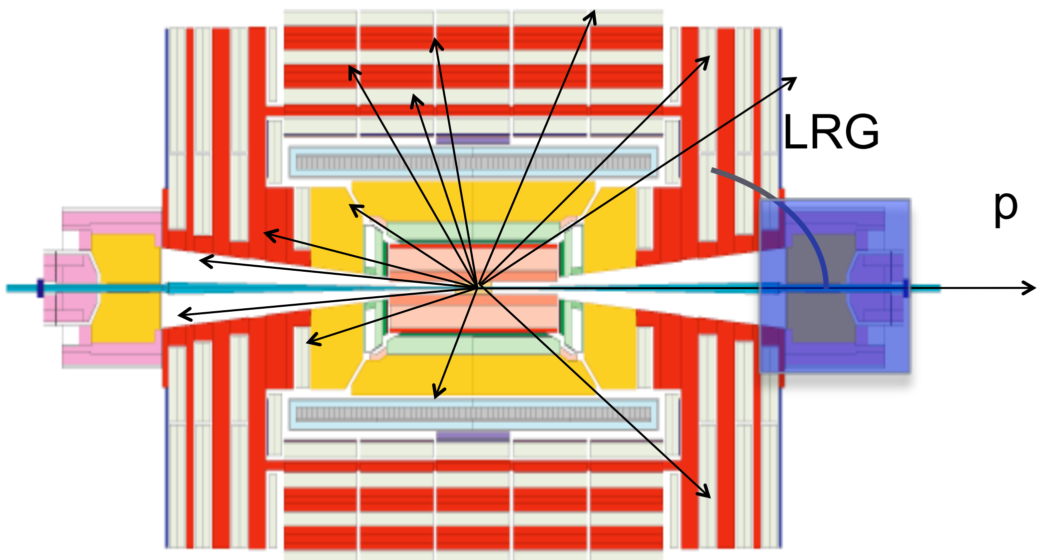


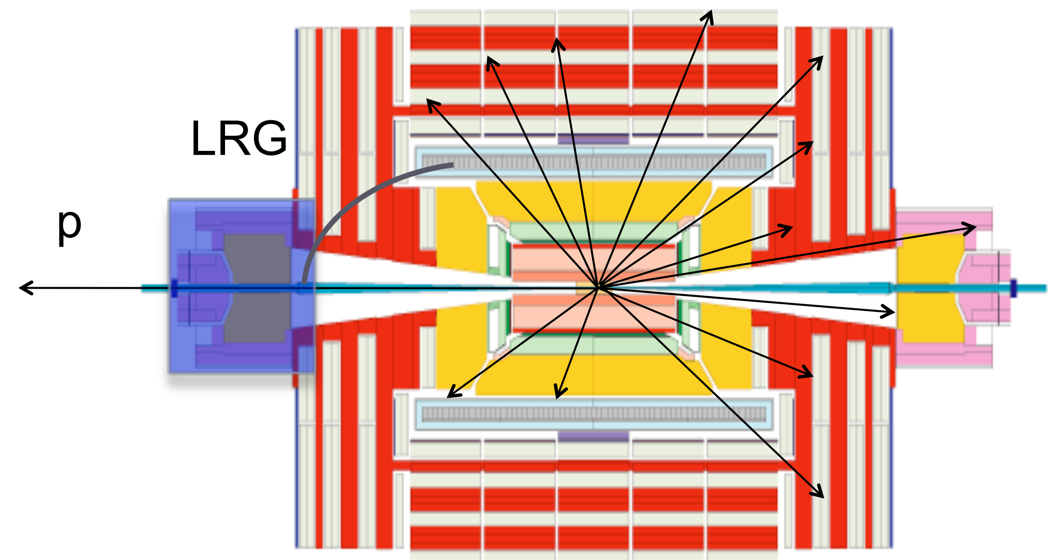


Plus Side
Minus Side
YB0
YE-1
YE-2
YE-3
HF-
YB-1
YB-2
Pixels
Tracker
ECAL
HCAL
MUON Dets.
Superconducting
Solenoid
Total weight : 12500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
http://cms.cern.ch






LRG
p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