Exclusive and Diffractive Physics with CMS

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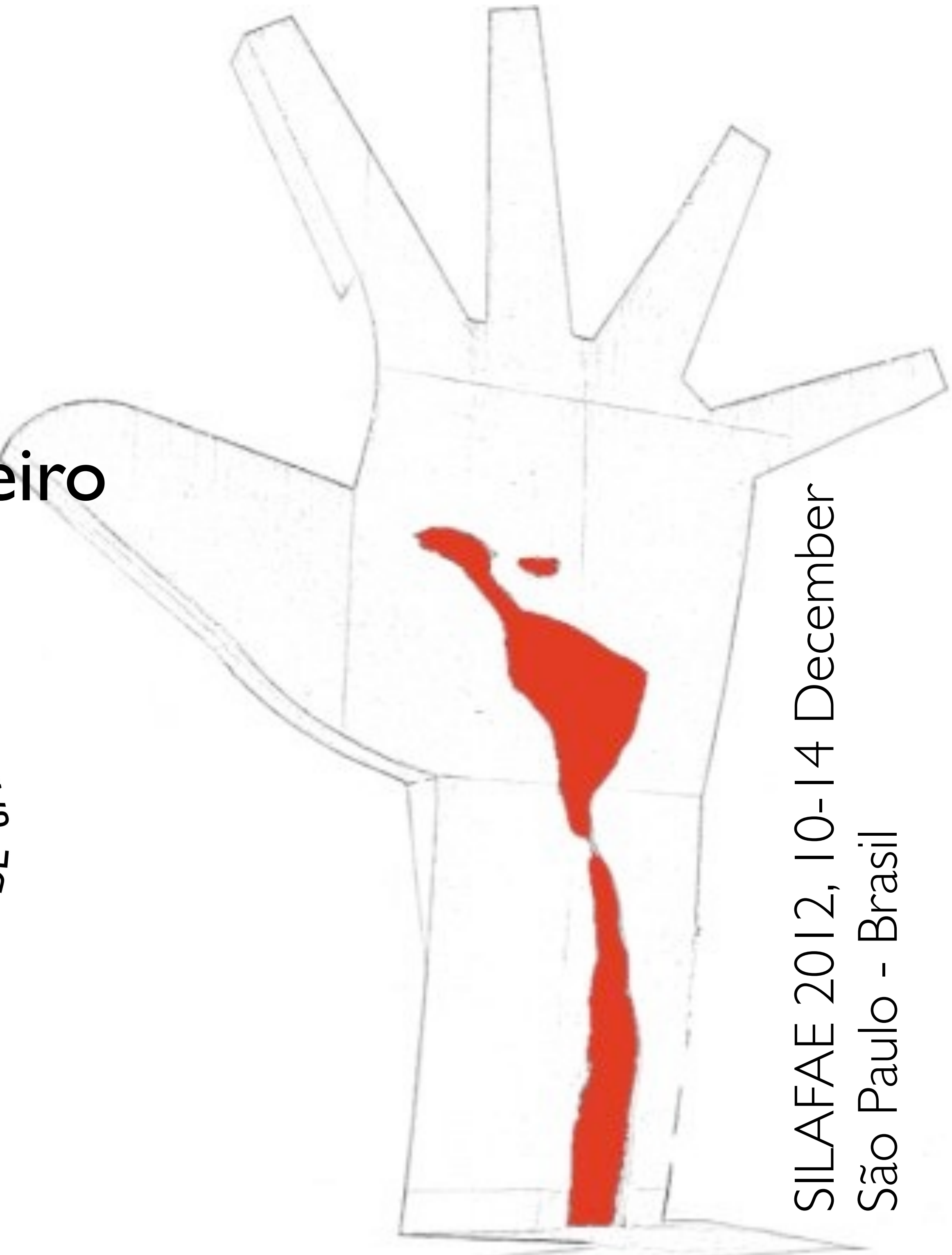
on behalf of the CMS collaboration
Universidade do Estado do Rio de Janeiro

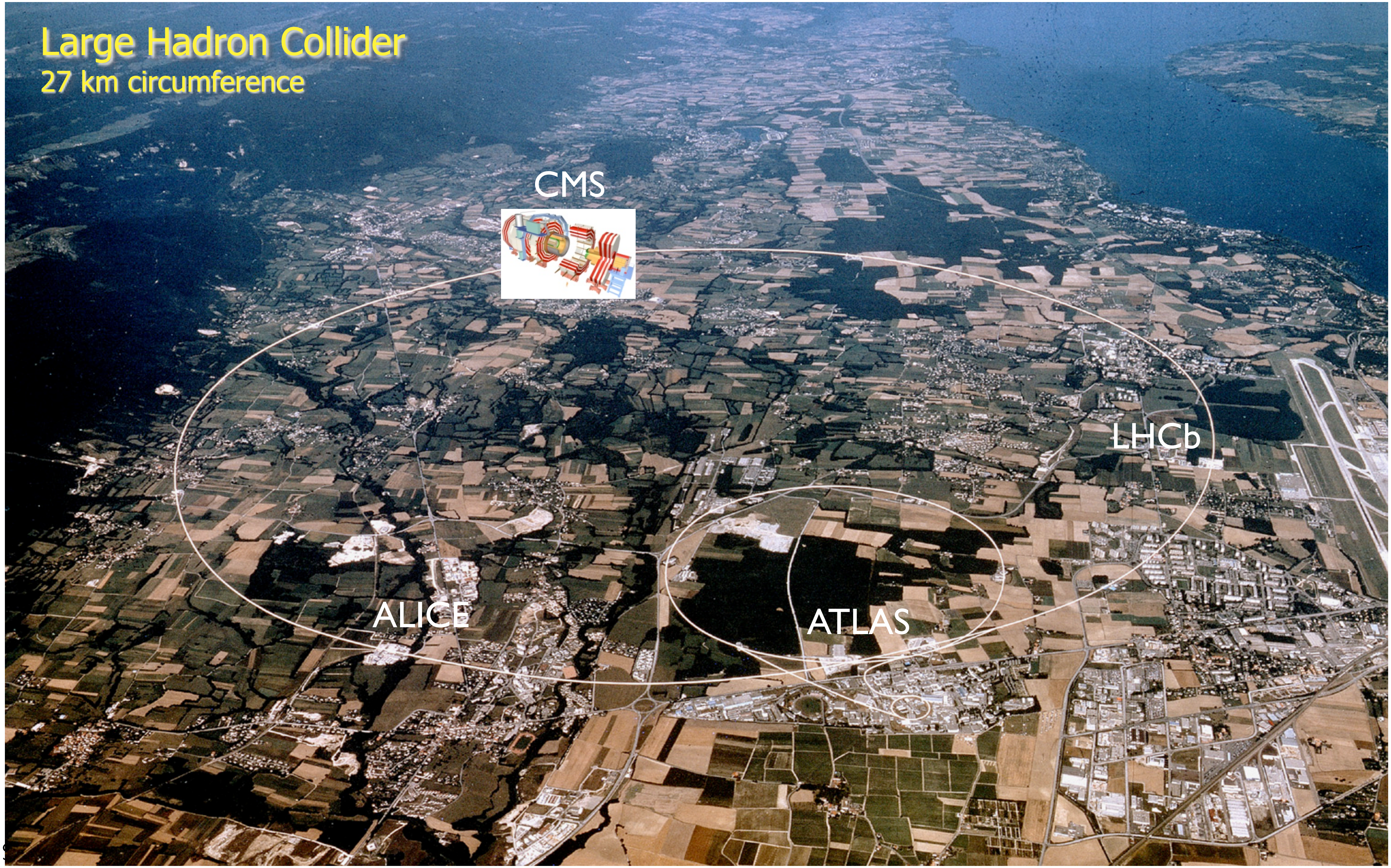


SILAFAE 2012, 10-14 December
São Paulo - Brasil

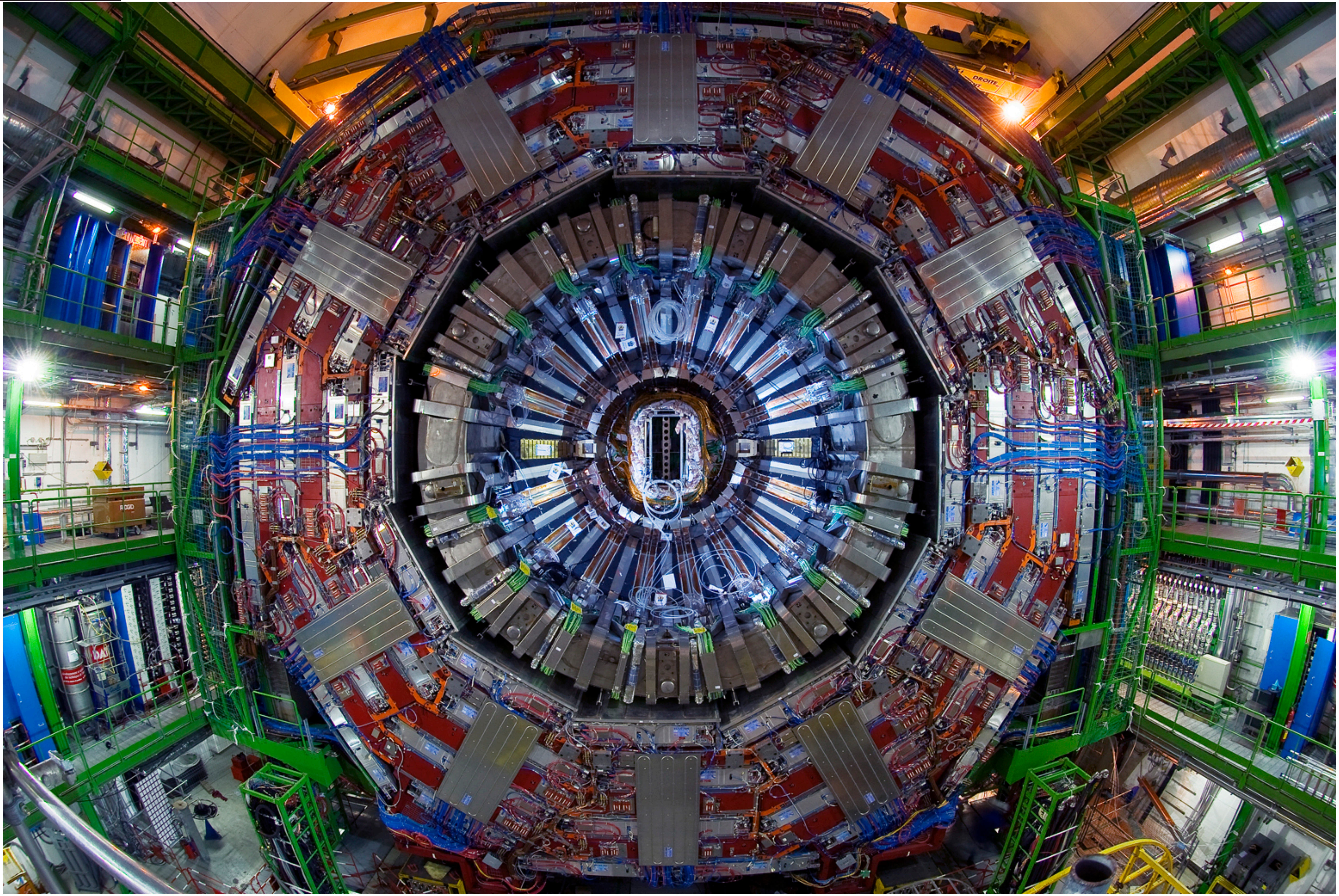
Outline

- CMS detector & forward instrumentation
- Probing hard diffraction
  - Diffractive dijet production
  - W/Z events with (pseudo-)rapidity gaps
- Exclusive processes
  - Exclusive $\gamma\gamma \rightarrow \mu\mu$ / $\gamma\gamma \rightarrow ee$
  - Central Exclusive Production

The CMS detector



The CMS detector



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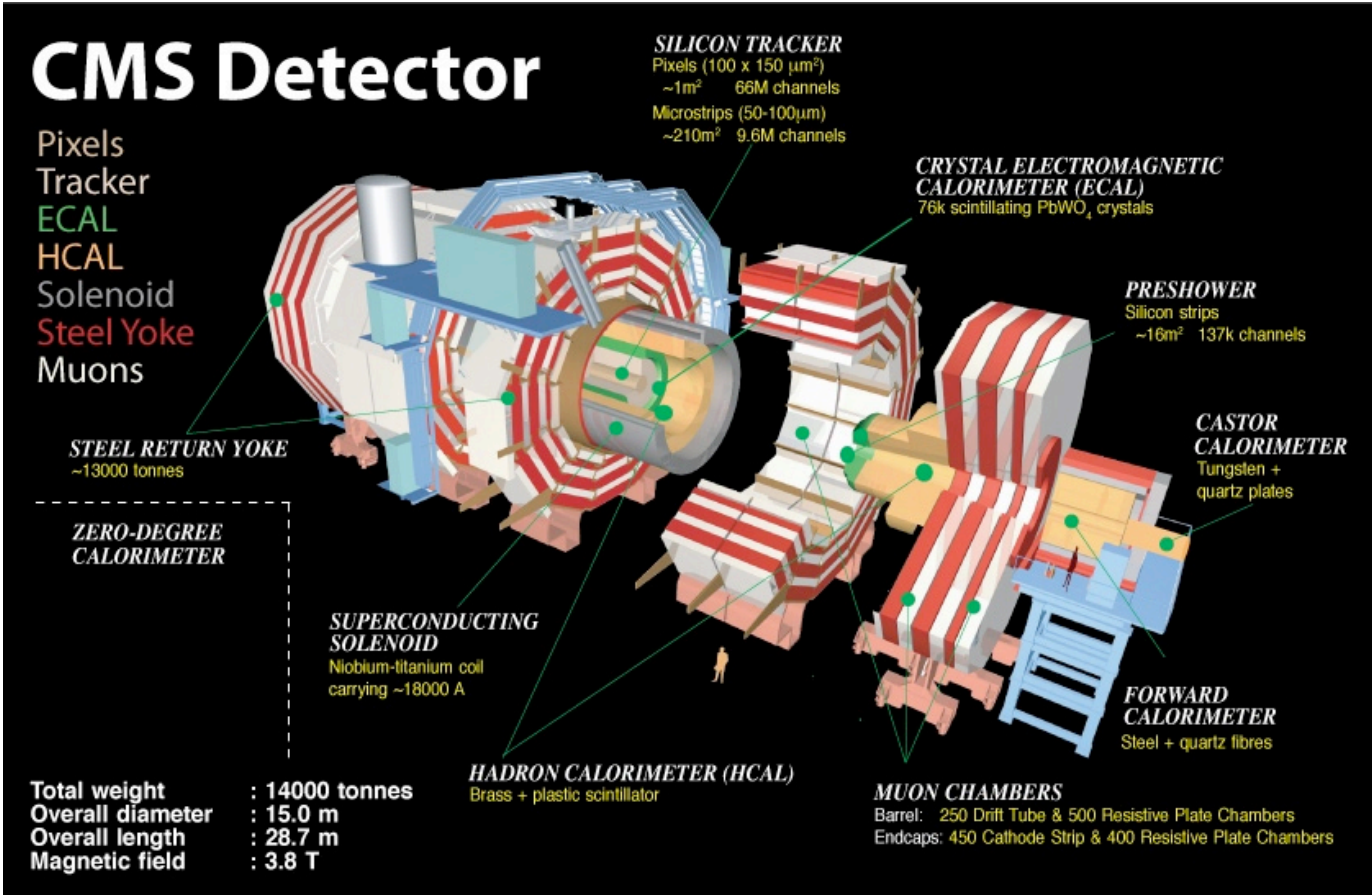


Forward detectors @ CMS

Detector configuration during 2010 - 2011

CMS

Hadronic Forward (HF)

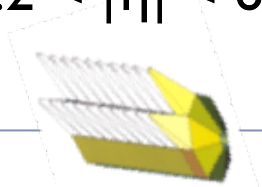
Hadronic Forward (HF)

($3.0 < |\eta| < 5.0$)

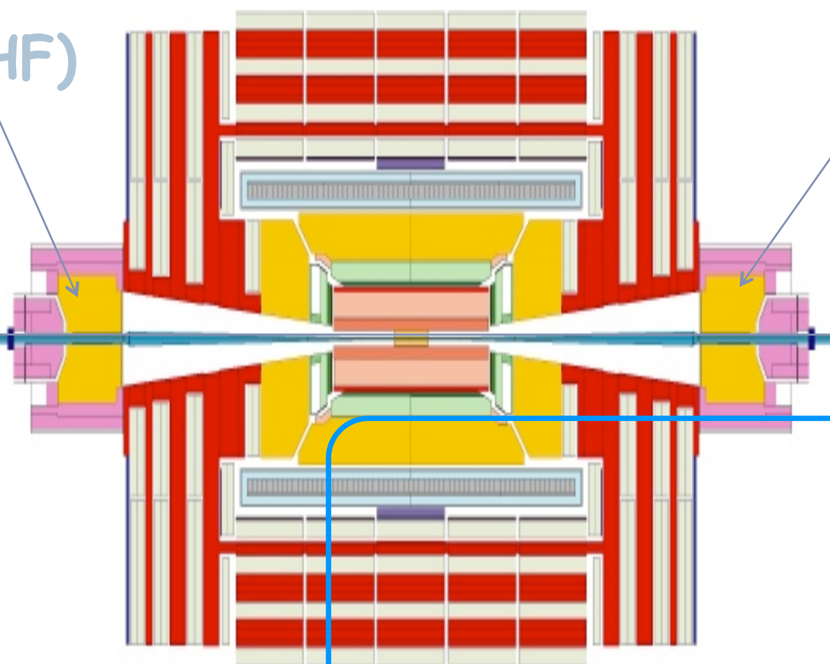
140m

140m

($5.2 < |\eta| < 6.6$)



CASTOR



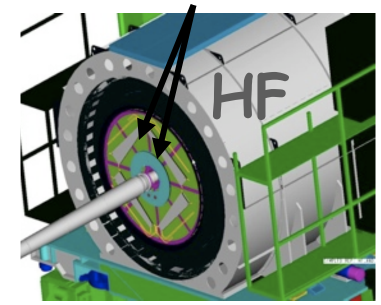
ZDC

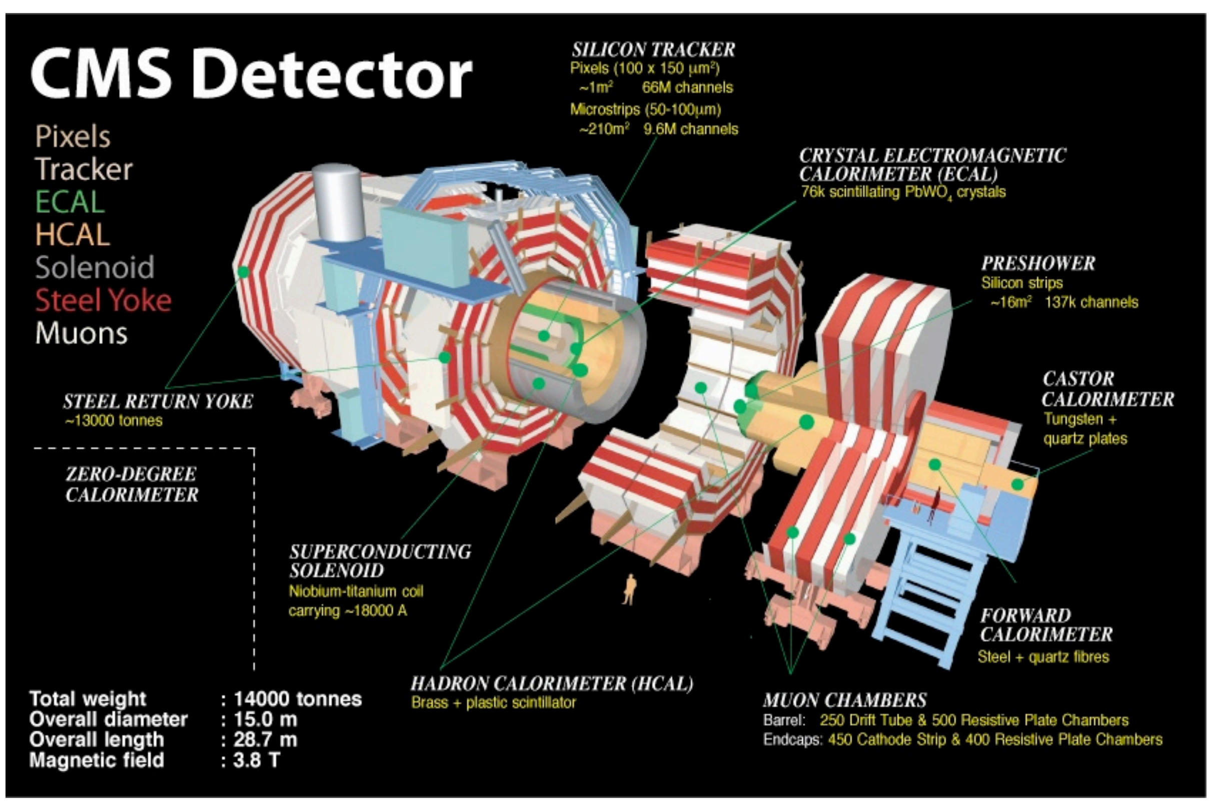
ZDC

($|\eta| > 8.1$)

CASTOR & ZDC not used in results presented in this talk

BSC





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

Acceptance limited to $|\eta| < 4.9$ at analysis level

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  - W/Z events with (pseudo-)rapidity gaps
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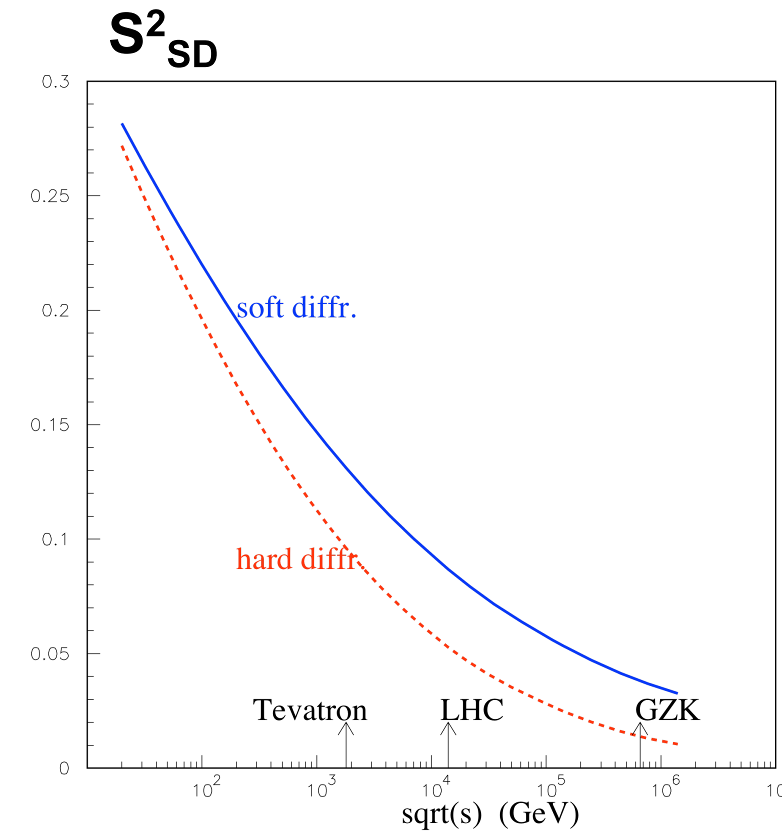
  - Exclusive $\gamma\gamma \to \mu\mu$ / $\gamma\gamma \to ee$
  - Central Exclusive Production

Probing hard diffraction

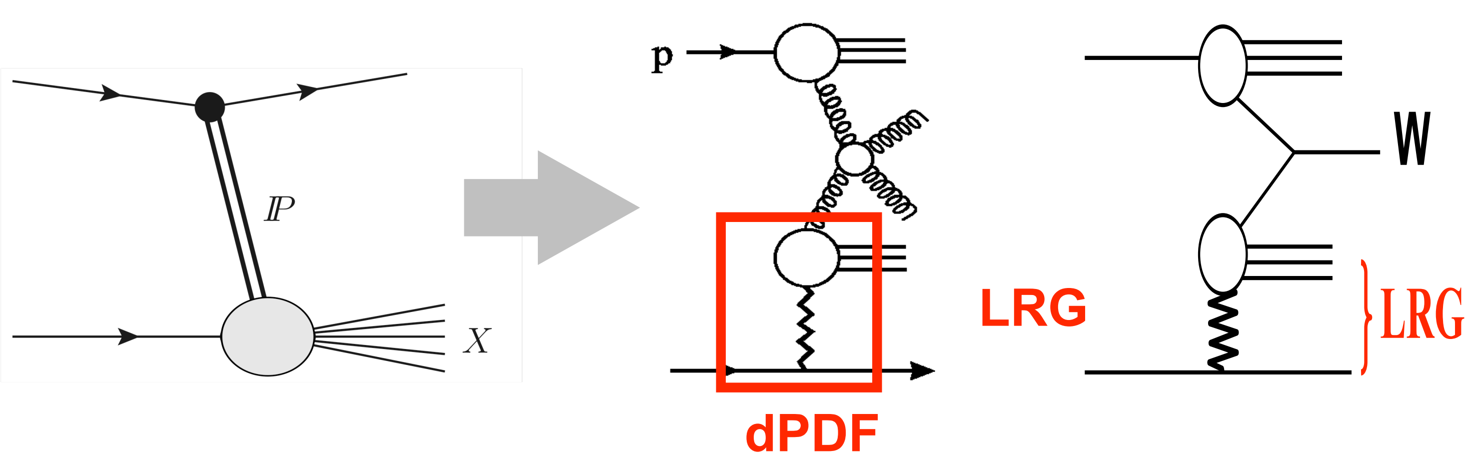
Diffractive events where a hard scale is present: high-p_T jets, W/Z's, ...

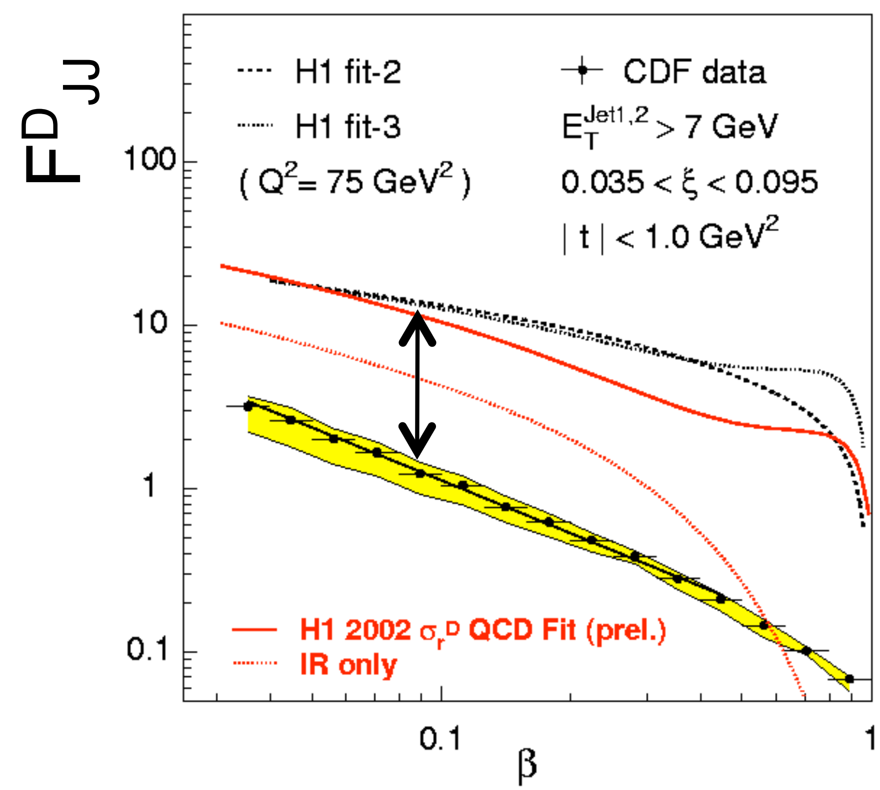
Extension of HERA/Tevatron studies on diffractive PDFs (dPDFs), rapidity gap survival probability ($\langle S^2 \rangle$) & exclusive processes

Set the framework for future searches with proton tagging at high luminosity



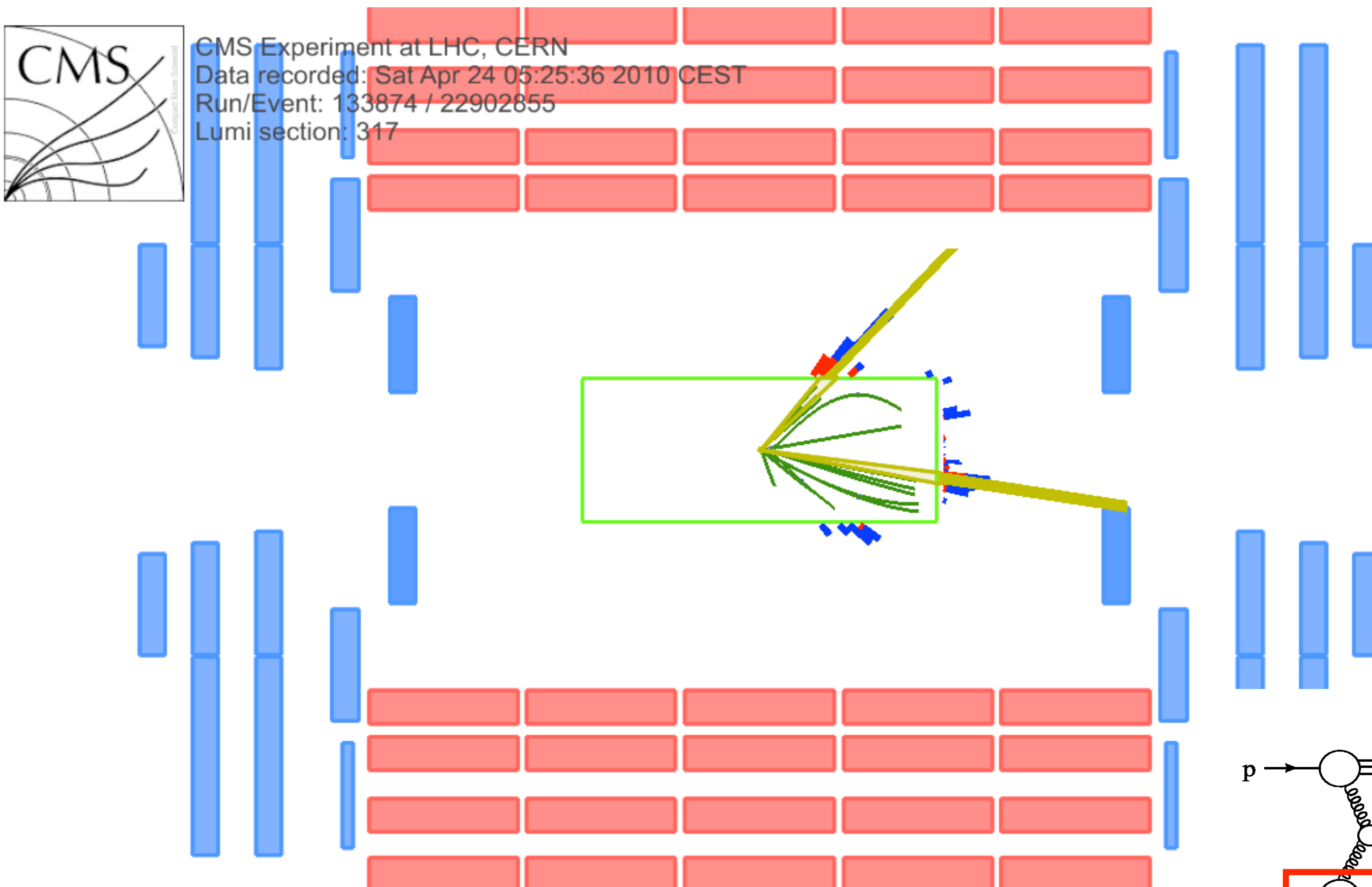
V.A.Khoze et al, Phys. Lett. B 643 (2006)

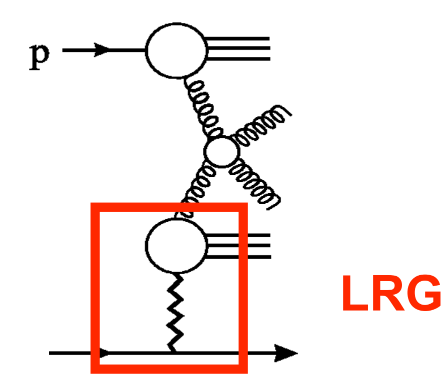




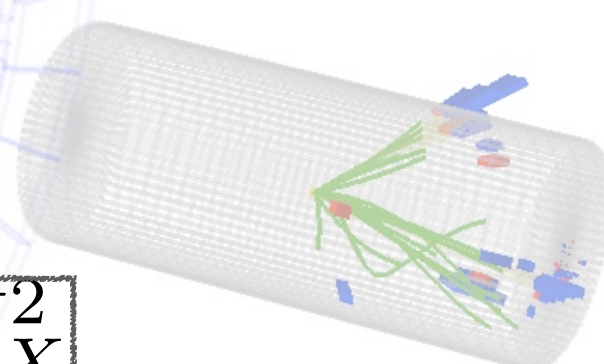
CDF Collaboration, Phys. Rev. Lett. 84, 5043 (2000)

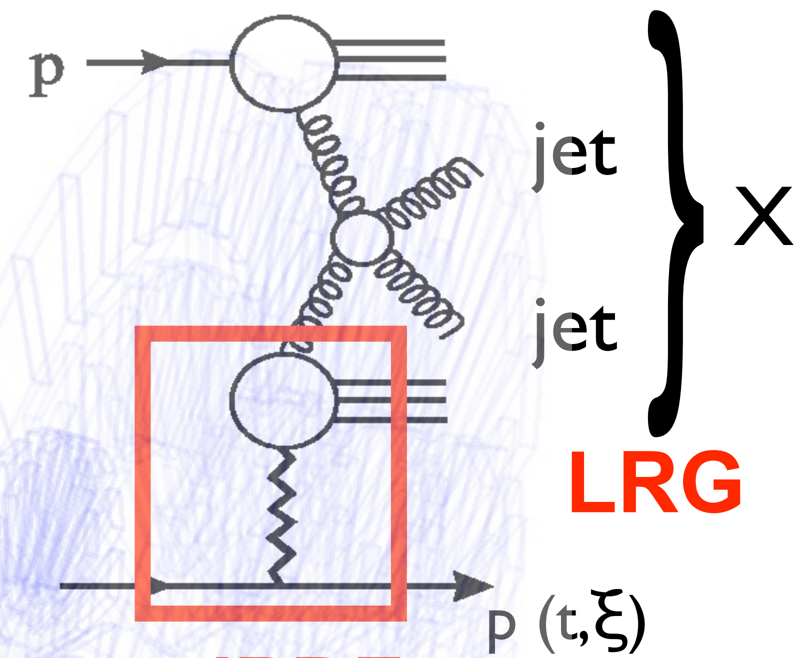
Diffractive dijet candidate





Kinematics & cross section





$$\boxed{\xi = \frac{M_X^2}{s}}$$

diffractive pdf:
"pomeron" flux ⊗ pdf

partonic cross section

$$\frac{d^2\sigma}{d\xi dt} = \sum \int dx_1 dx_2 \boxed{f(\xi,t)\, f_{I\!P}(x_1,\mu)}\, \boxed{f_p(x_2,\mu)}\, \boxed{\hat{\sigma}}$$

proton pdf

$$\boxed{f(\xi,t) = \frac{e^{Bt}}{\xi^{2\alpha_{I\!P}(t)-1}}}$$

Implemented in "hard-diffractive" MC's:
POMPYT, POMWIG, PYTHIA8, etc.

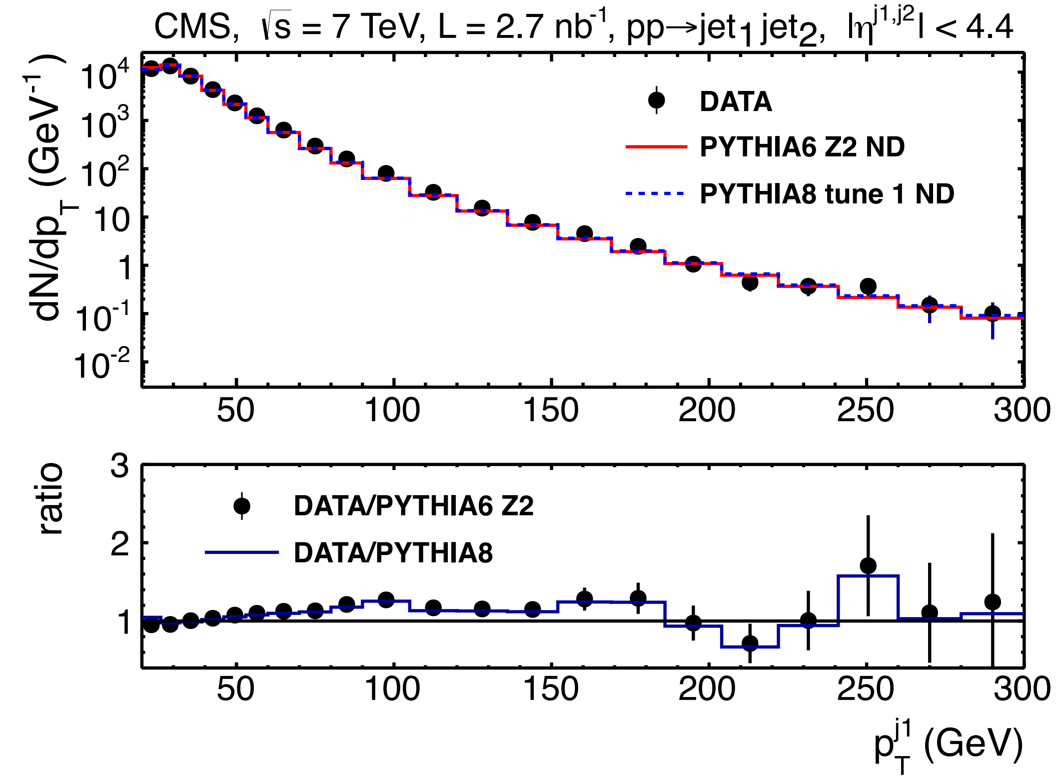
Event selection

Low-p_T trigger at 6 GeV (uncorrected)

High quality vertex + beam background and noise rejection

At least two jets with p_T > 20 GeV and within $-4.4 < \eta < 4.4$

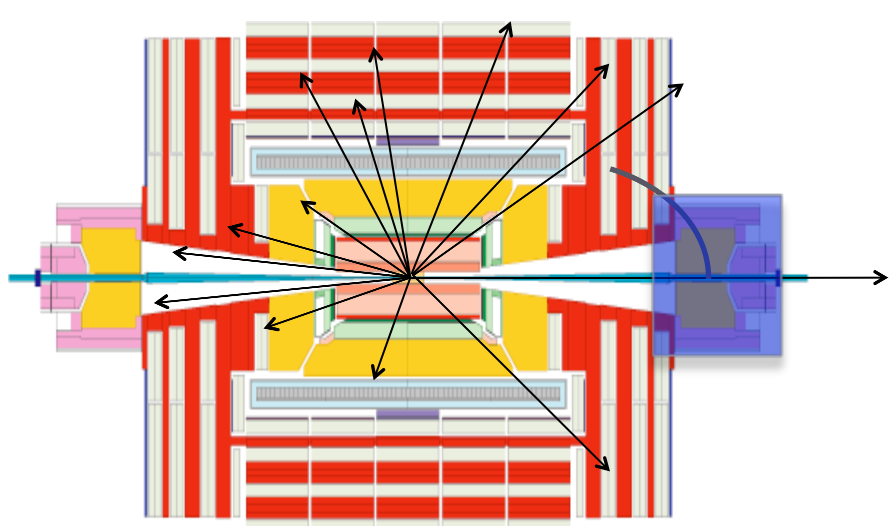
$\eta_{max(min)}$: most forward (backward) particle in the detector



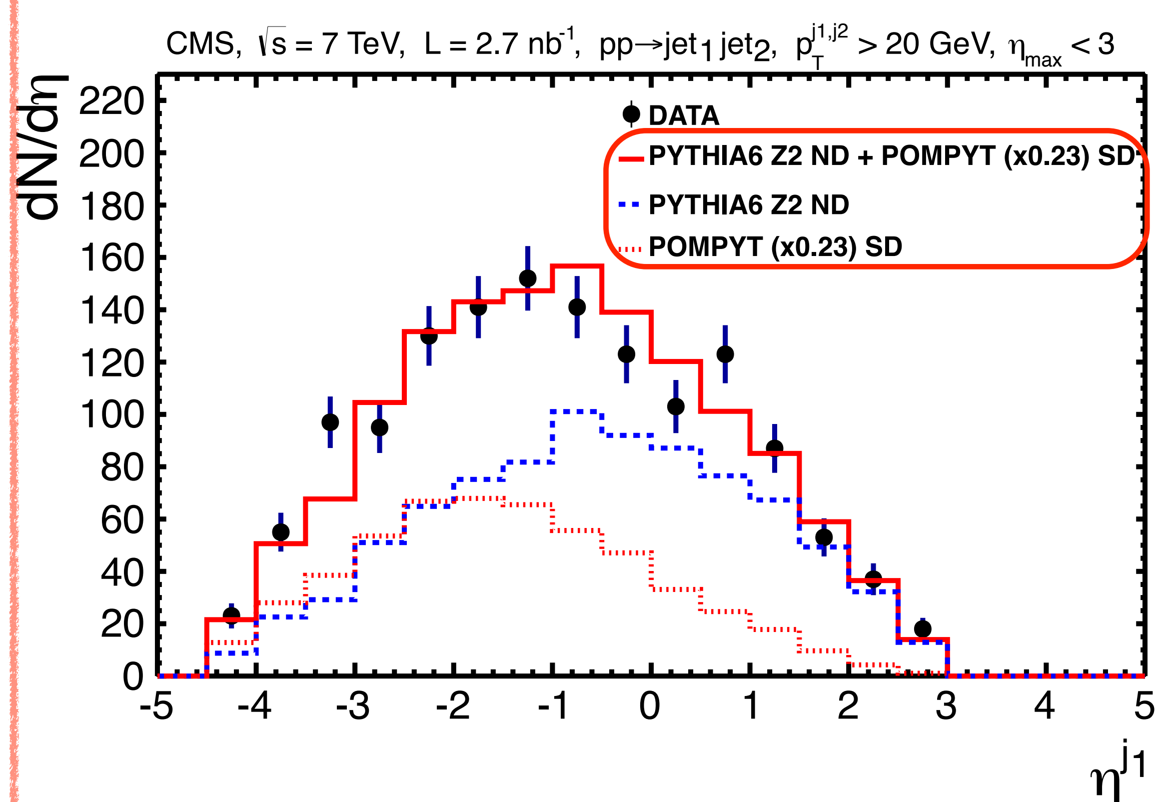
CMS FWD-10-004

arXiv:1209.1805

Forward η-gap selection



Selection comprising Δη ~ 1.9 in forward calorimeter (HF) acceptance



Normalised to fit of PYTHIA6 + POMPYT

Event distributions

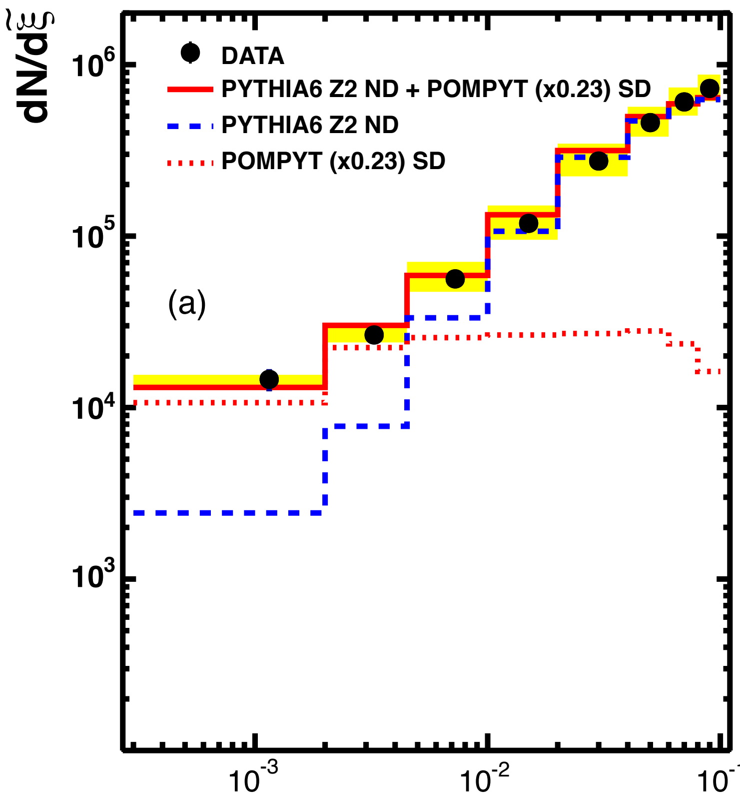
$$\tilde{\xi}^{\pm} = C \frac{\sum (E \pm p_z)}{\sqrt{s}}$$

(See Backup)

Distributions are obtained as a function of ξ^+ and ξ^-, and averaged

A combination of PYTHIA6 (Tune Z2) and POMPYT is used to describe the data, where their relative contributions are obtained from a fit to the ξ distribution

Note that different MC tunes would imply considerable variations in relative yields



CMS FWD-10-004

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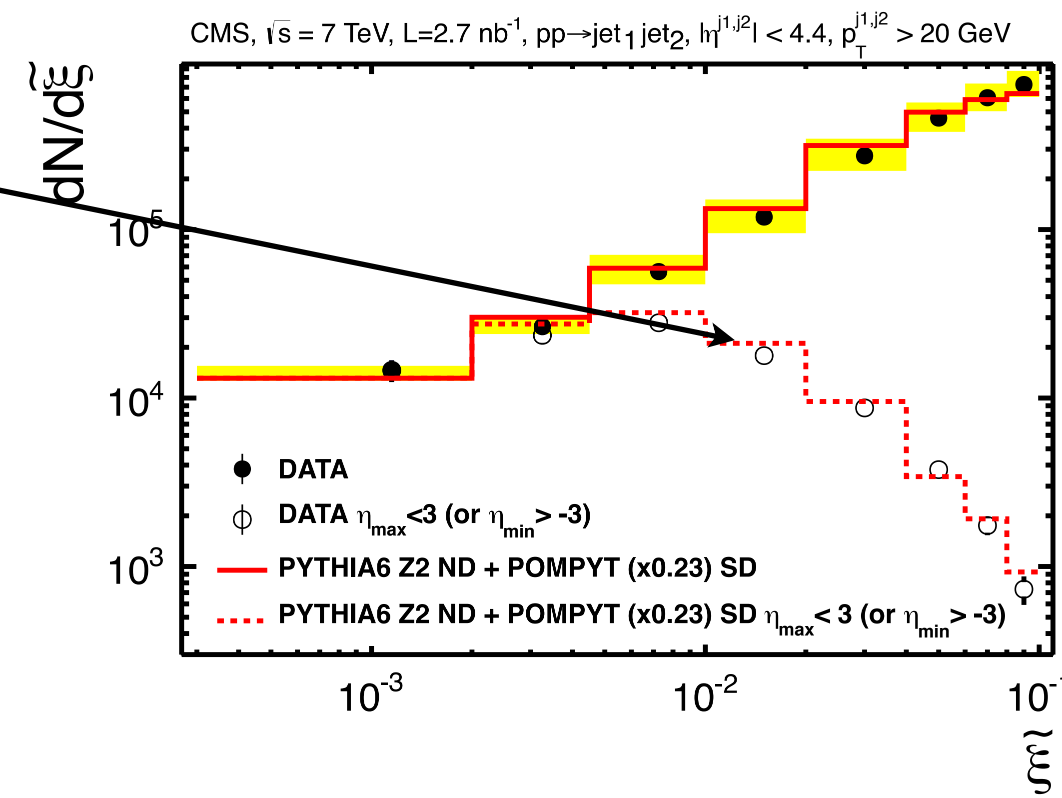
Suppression of events with high ξ values after $\eta_{max} < 3$ (or $\eta_{min} > -3$) selection, while low-ξ region is mostly unaffected

Results in three ξ bins: (0.0003,0.002); (0.002,0.0045); (0.0045,0.01)



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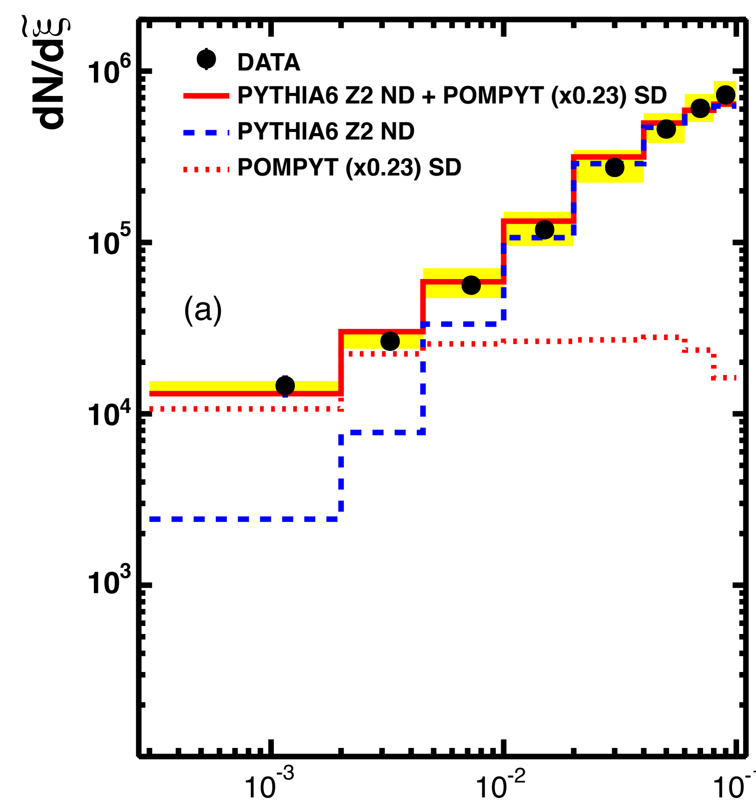
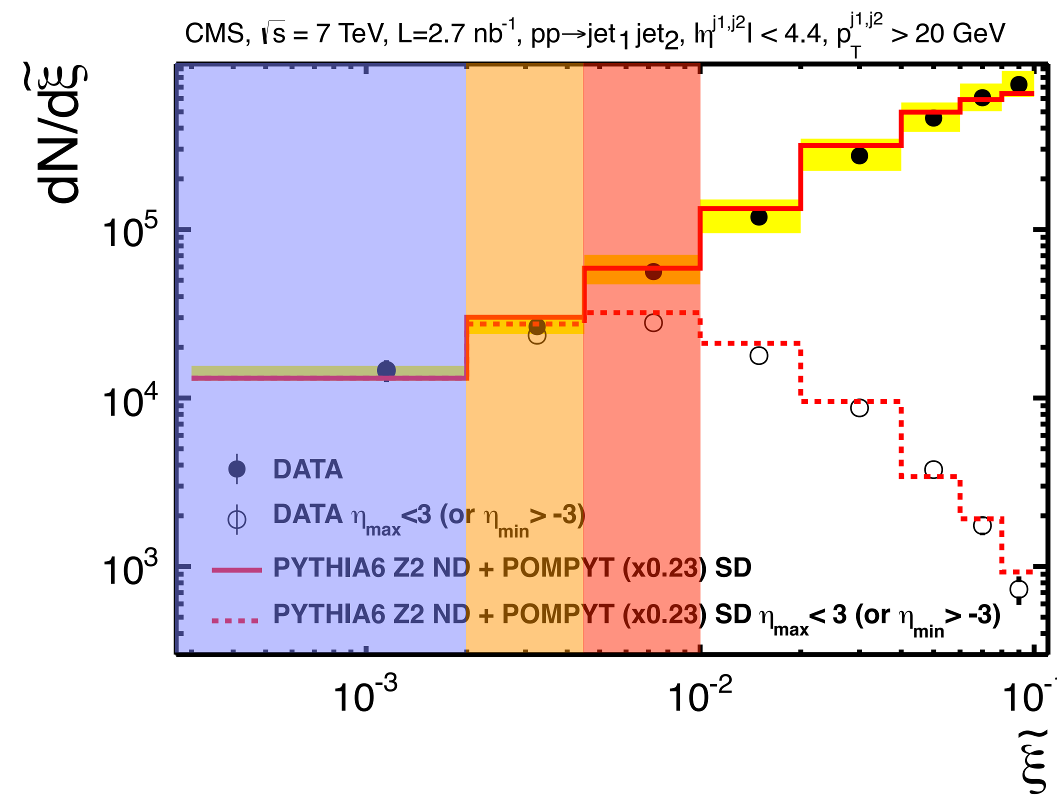


Energy scale uncertainties

CMS FWD-10-004

arXiv:1209.1805



Dijet cross sections

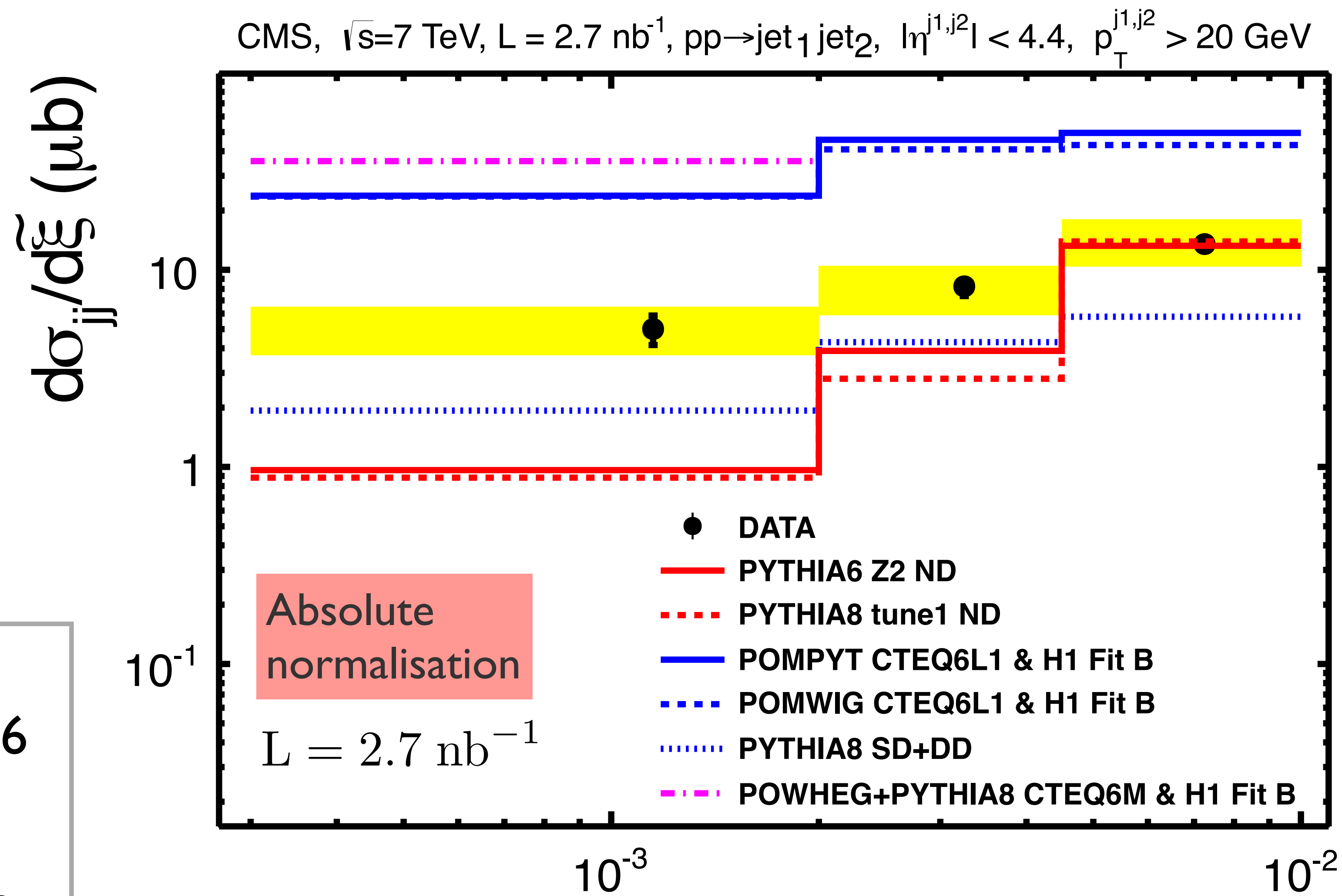
$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N^i_{jj}}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

$$A^i_{\mathrm{MC}} = \frac{N^i(\tilde{\xi}_{\mathrm{Rec}})}{N^i(\tilde{\xi}_{\mathrm{Gen}})}$$

Excess of events in low-ξ region with respect to non-diffractive MC's PYTHIA6 and PYTHIA8

POMPYT and POMWIG (LO) diffractive MC's as well as the NLO calculation from POWHEG, using diffractive PDFs, are a factor ~5 above the data in lowest ξ bin

PYTHIA8 diffractive cross sections are considerably lower due to different pomeron flux parametrisation

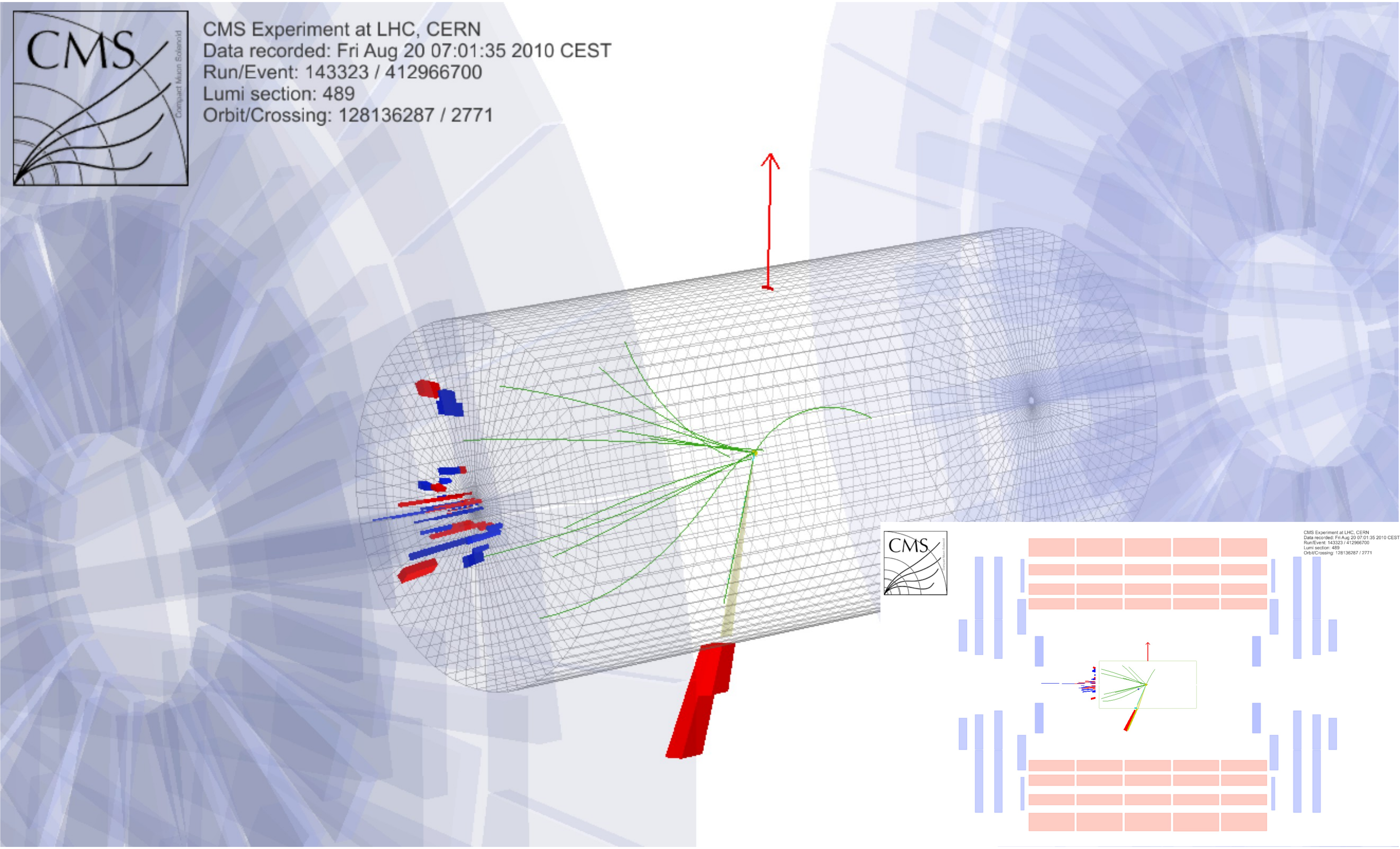


Normalisation discrepancies give upper limit predictions (including proton dissociation) to rapidity gap survival probability:

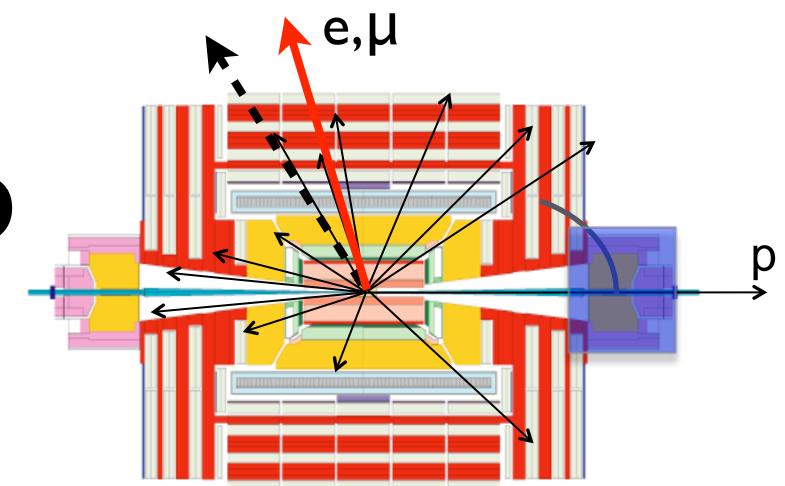
$$S^2_{\mathrm{data/MC}} = 0.21 \pm 0.07\ (\mathrm{LO\ MC})$$

$$S^2_{\mathrm{data/MC}} = 0.14 \pm 0.05\ (\mathrm{NLO\ MC})$$

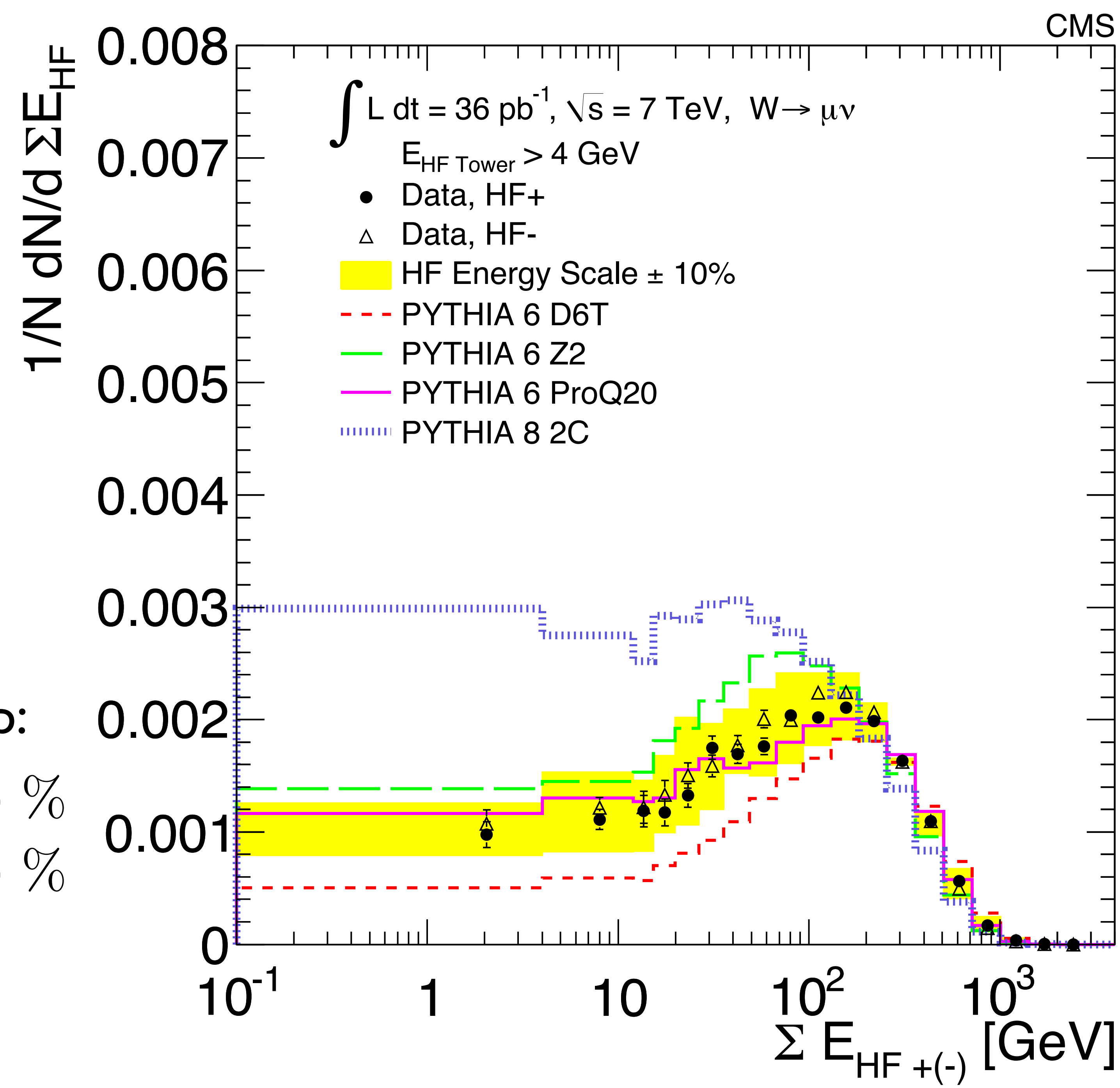
W/Z events with pseudorapidity gaps



W/Z events with an η-gap



- Diffractive component in W/Z data set
- Events with low energy deposits at the forward calorimeters
- Monte Carlo generators cannot describe the data (extensive studies on overall energy flow and correlations)



Fraction of W/Z events with a forward gap:

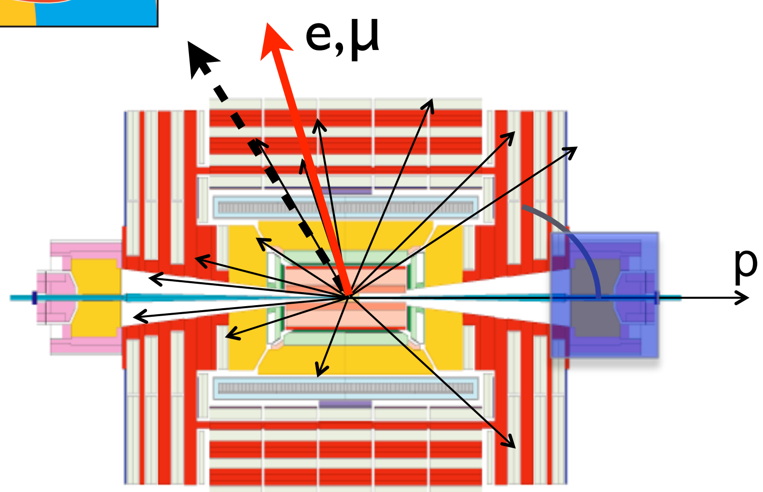
$W \to l\nu$: $1.46 \pm 0.09(\mathrm{stat.}) \pm 0.38(\mathrm{syst.})\ \%$

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

CMS FWD-10-008

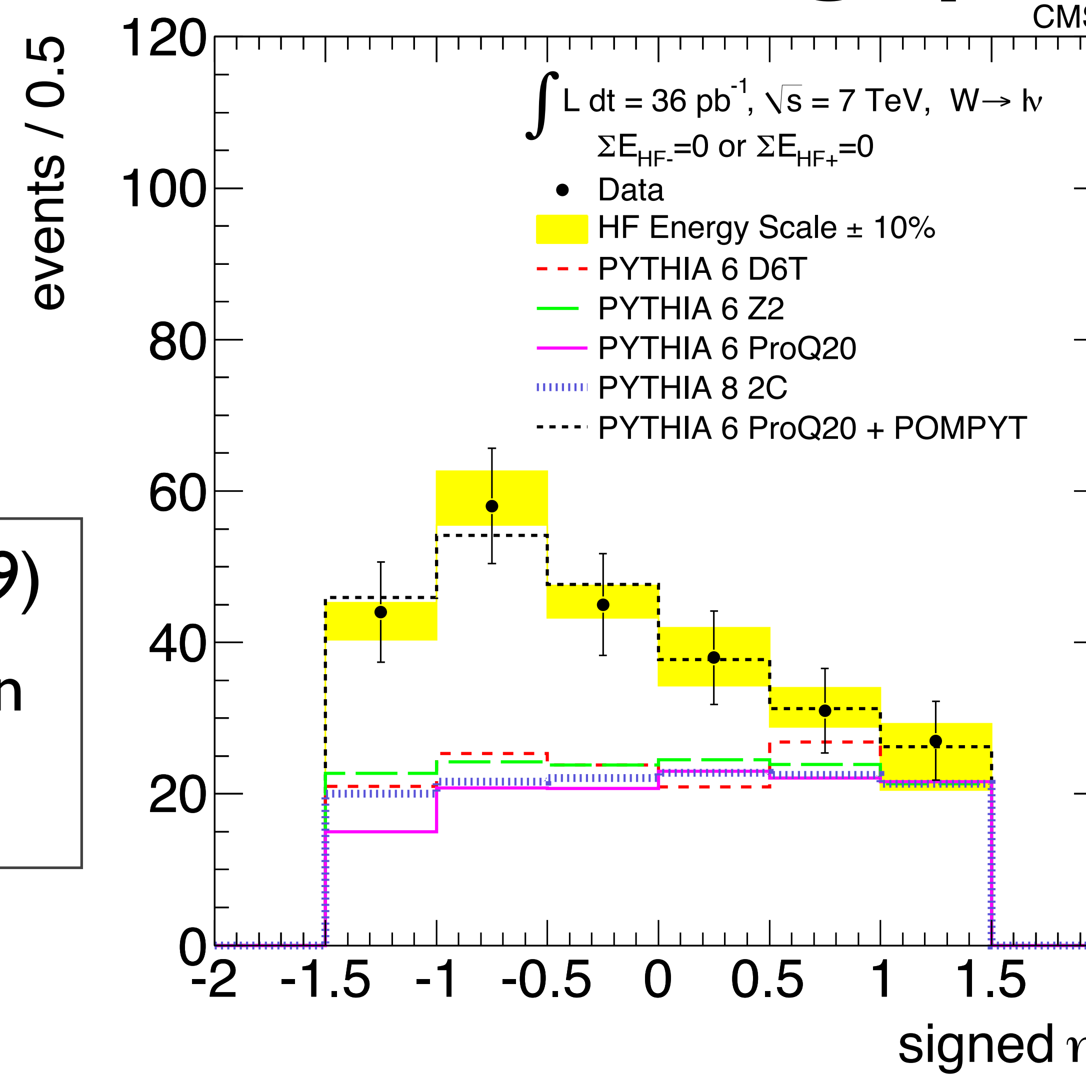
Eur. Phys. J. C (2012) 72:1839

W→eν(μν) events with a gap

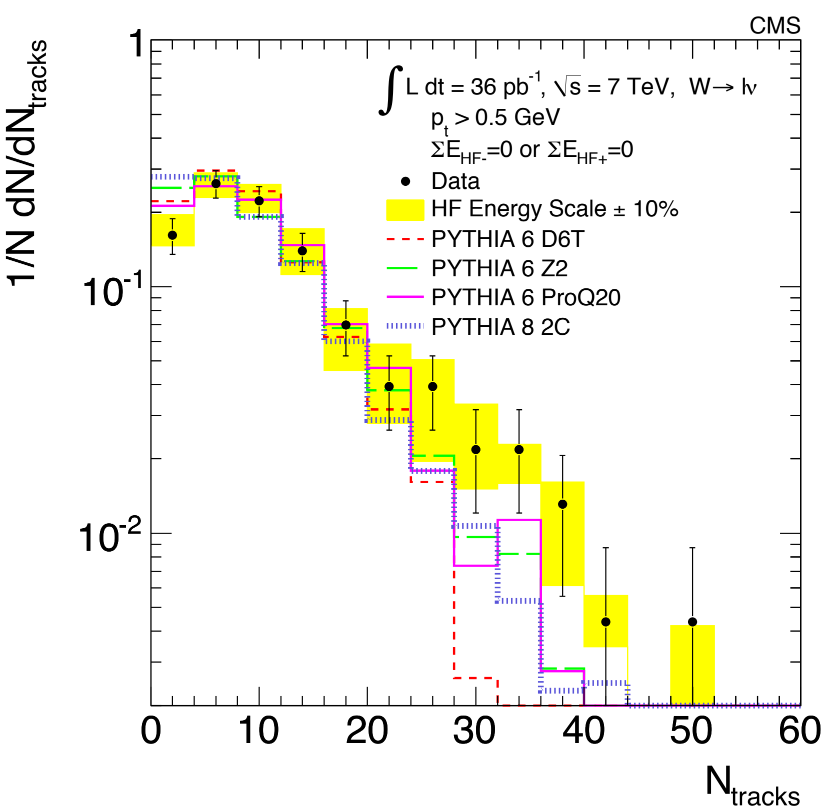


Forward gap selection in HF (3 < |η| < 4.9)

Signed η_{lepton} distribution (η_{lepton} < 0 when e,μ opposite to the pseudorapidity gap)



Normalised to fit of PYTHIA6 + POMPYT



Flat for non-diffractive, asymmetric for diffractive events

Evidence of diffractive W production in the data

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

$$f_{\rm SD} = 50.0 \pm 9.3({\rm stat.}) \pm 5.2({\rm syst.})\ \%$$

(η-gap sample)

CMS FWD-10-008
Eur. Phys. J. C (2012) 72:1839

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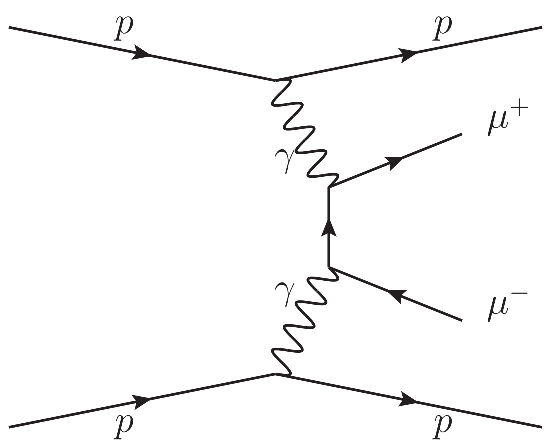
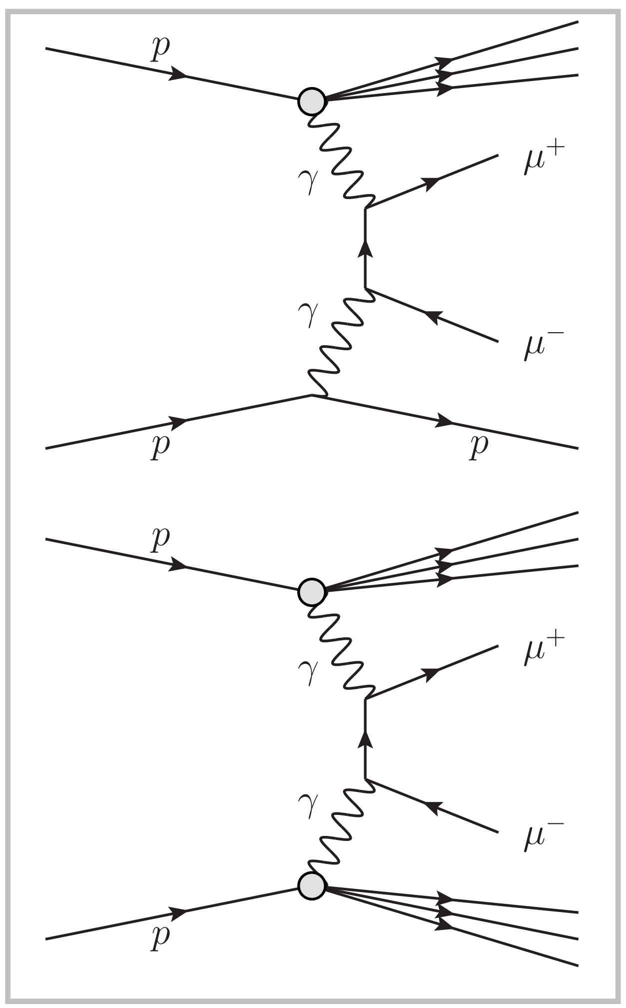
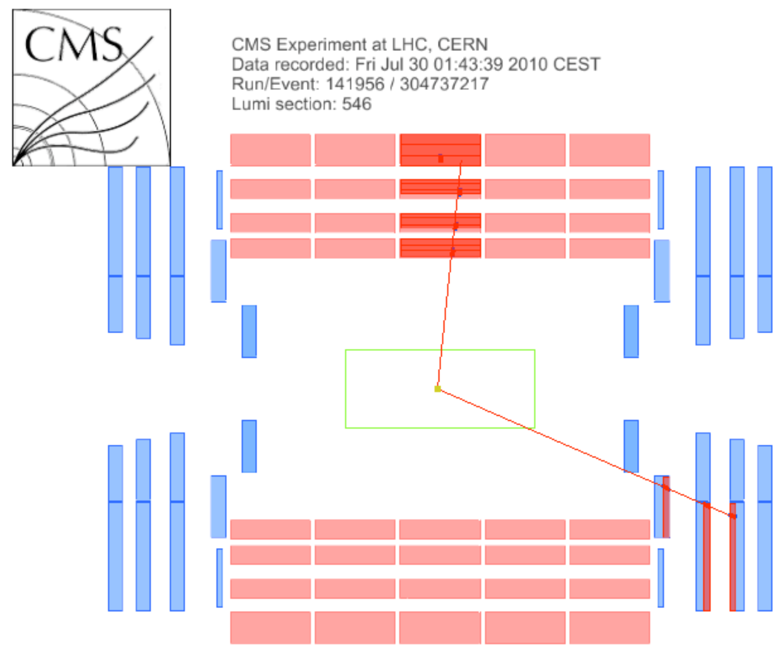
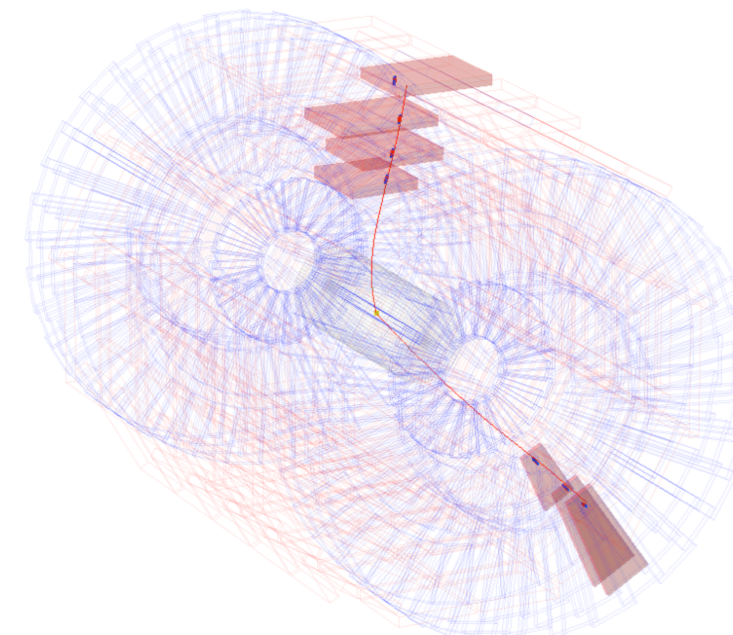
Exclusive $\gamma\gamma \rightarrow \mu\mu$ production

[CMS FWD-10-005](#)
[*J. High Energy Phys.* 01 (2012) 052](#)









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

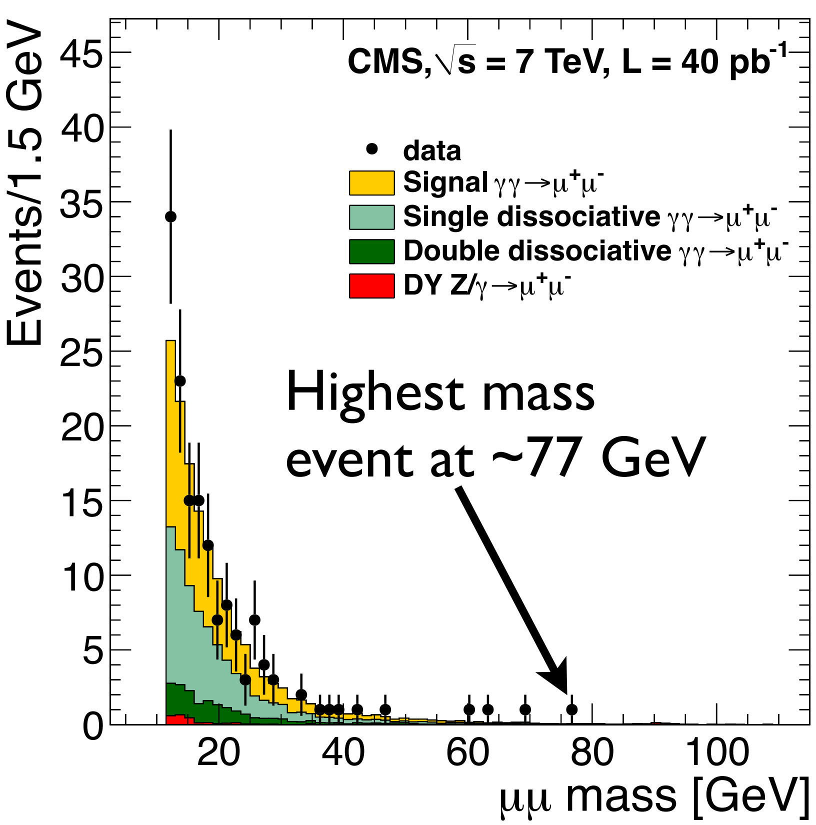
Standard candle for exclusive processes at the LHC and candidate for *absolute* luminosity measurement

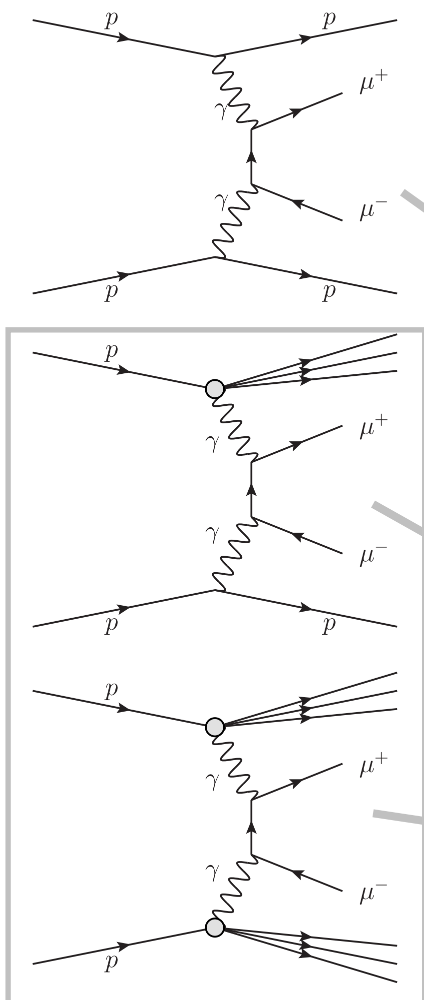
CMS FWD-10-005

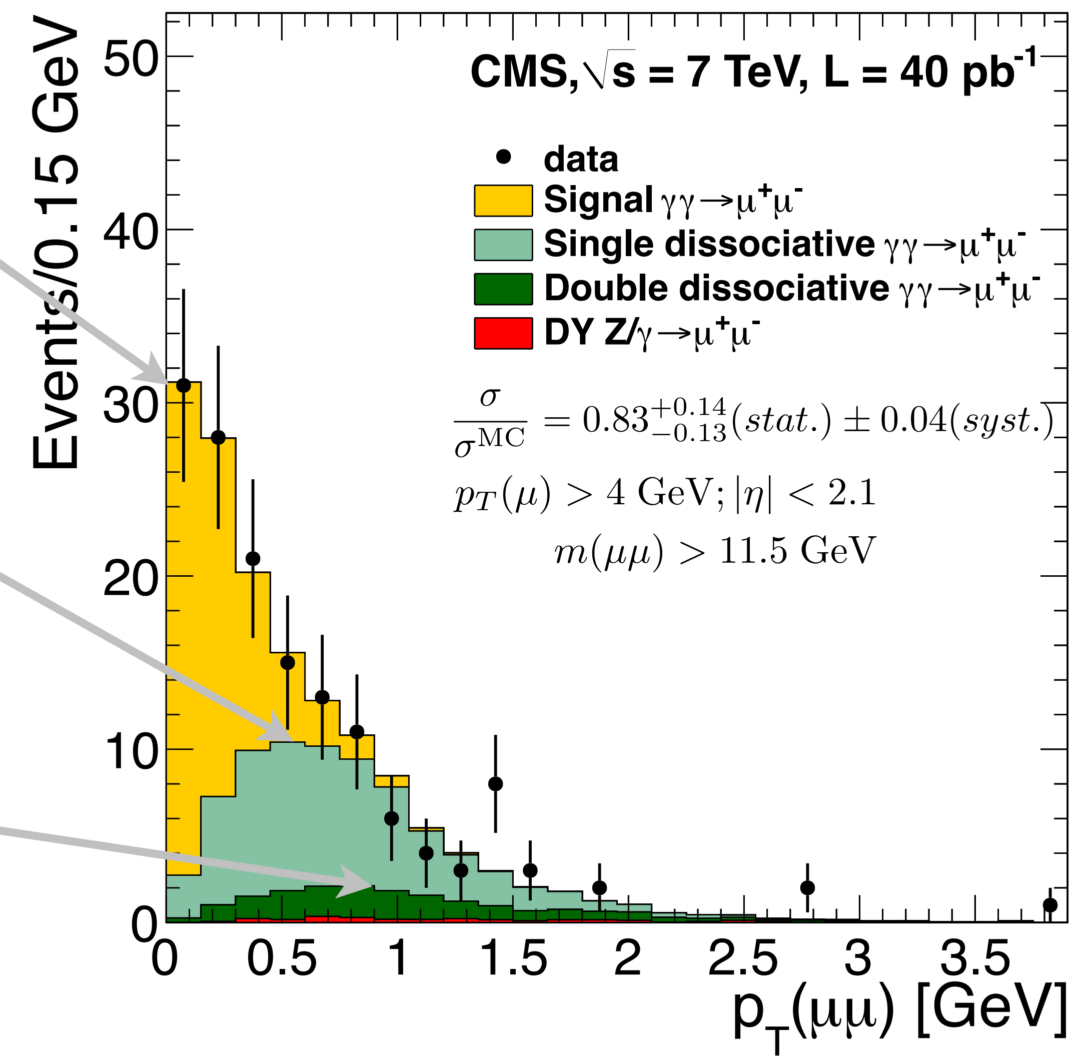
J. High Energy Phys. 01 (2012) 052

Exclusive γγ→μμ production

- 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



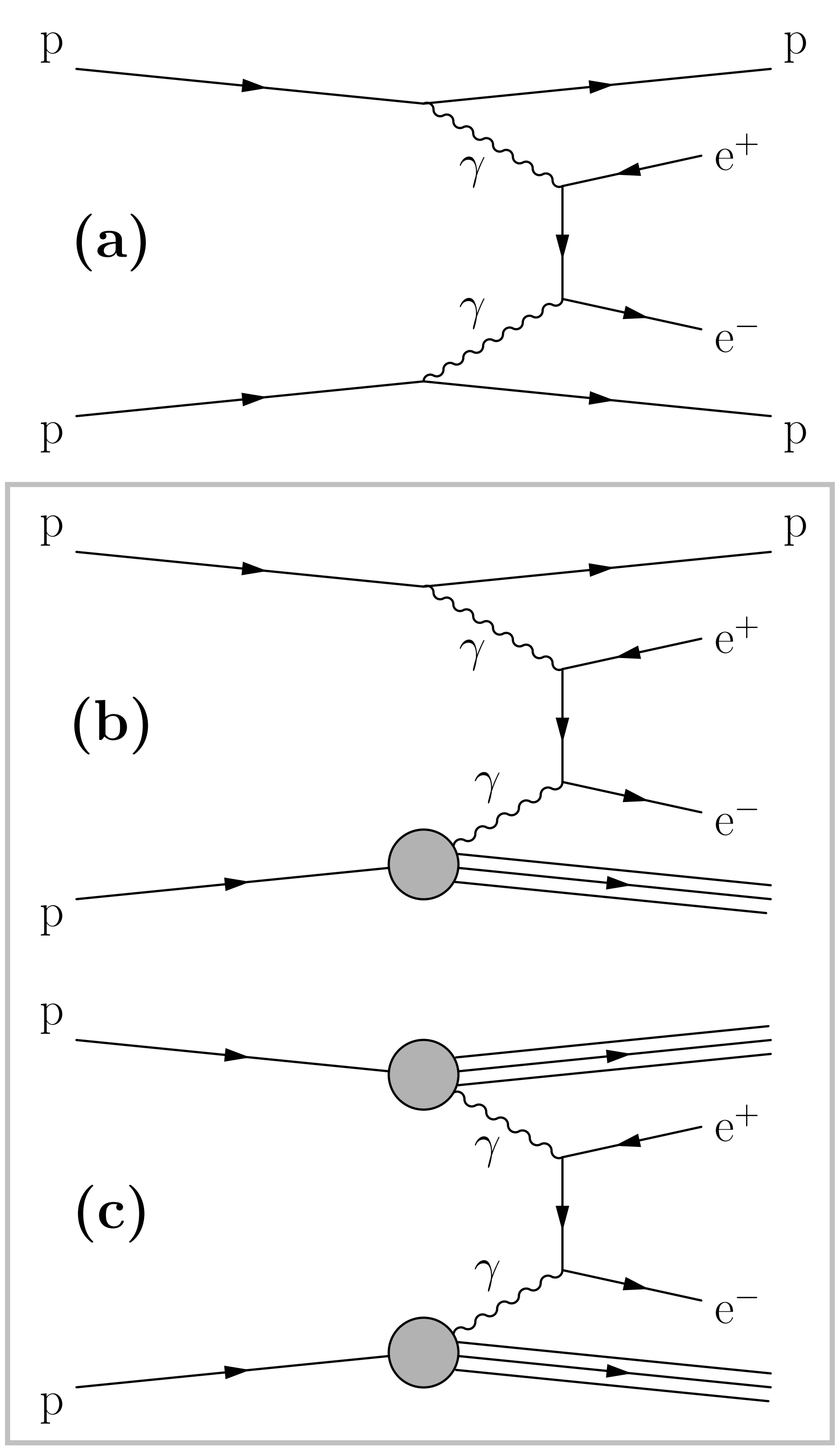


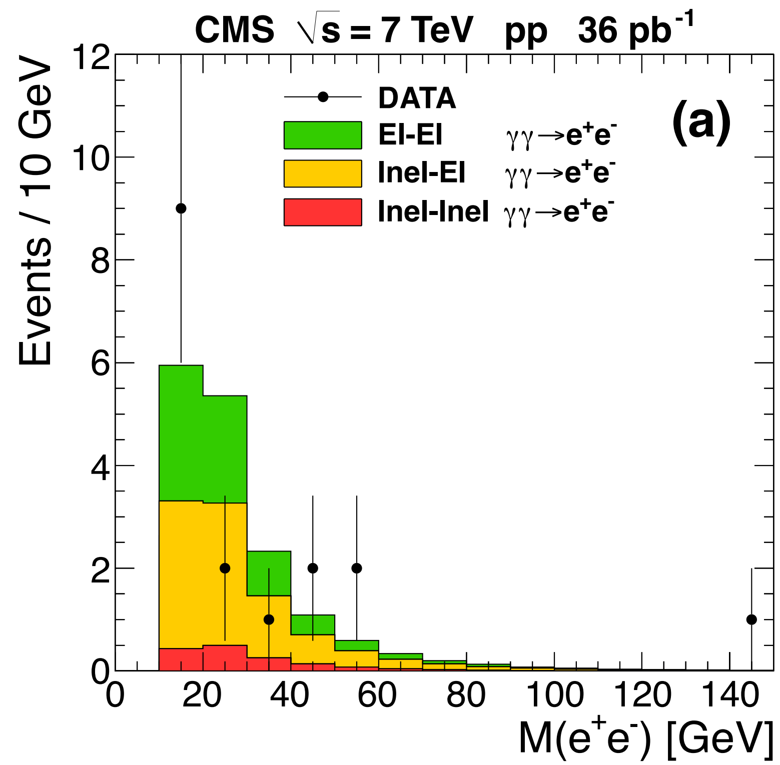


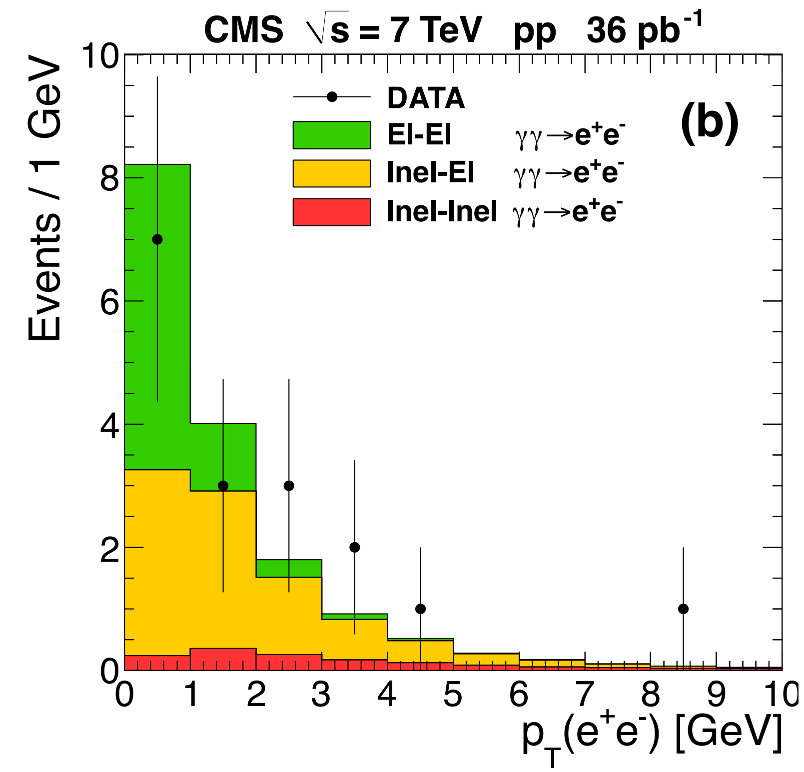
$$\boxed{\sigma(p + \mu\mu + p) = 3.38^{+0.58}_{-0.55}(stat.) \pm 0.16(syst.) \pm 0.14(lum.)\text{pb}}$$

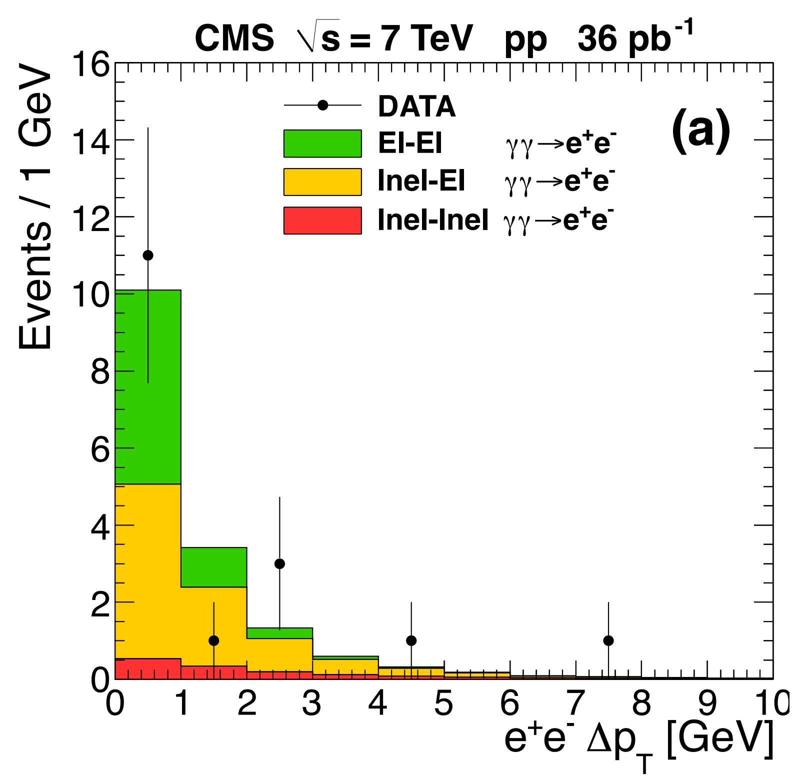
- Largest systematics from track veto efficiency (data driven - pile-up sensitive)
- Good agreement between data and LPAIR MC (signal and proton dissociation)
- Potential to become competitive luminosity monitor at the LHC

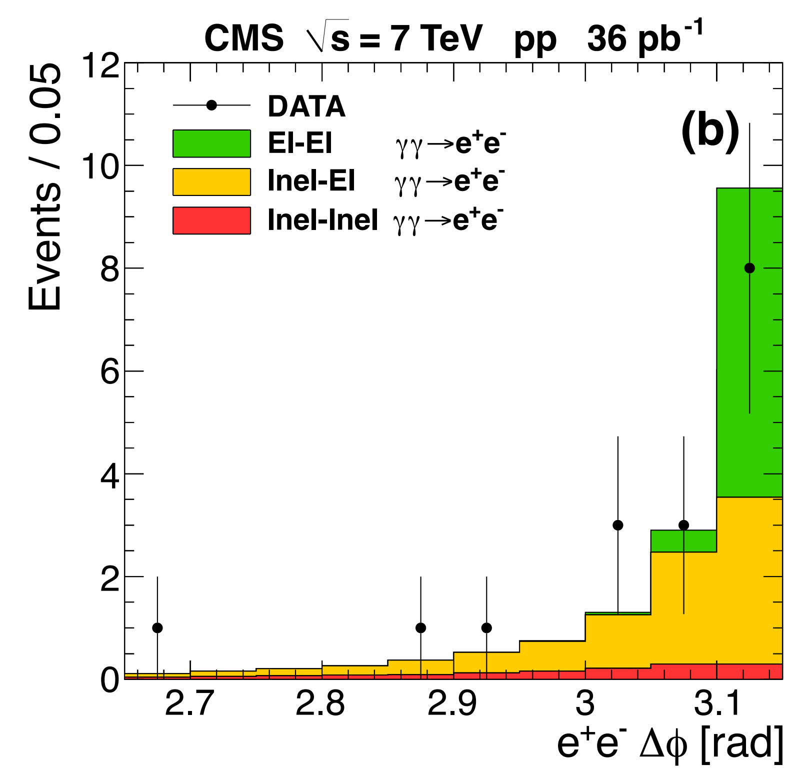
Exclusive $\gamma\gamma \to e^+e^-$ production





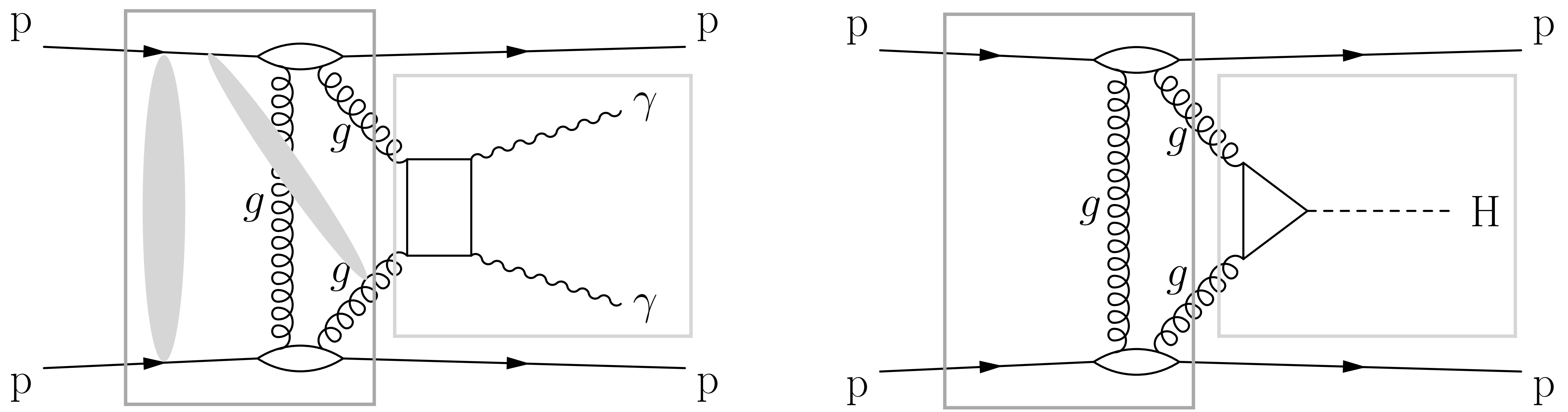






Good agreement between data and LPAIR MC (signal + proton dissociation)

“Central Exclusive” production

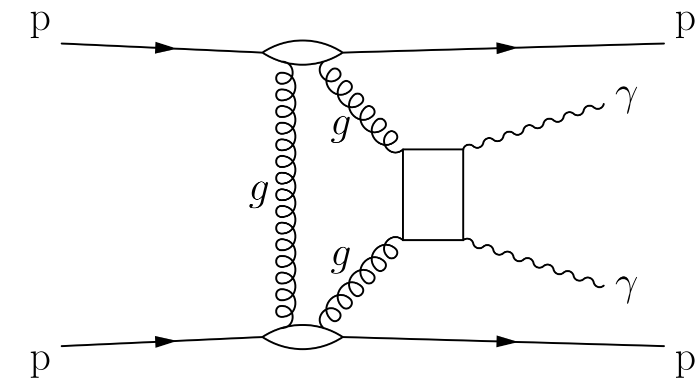


Exclusive channel through exchange of color singlet, lowest order given by gluon-gluon fusion, plus *screening* low-Q^2 gluon

Protons remain intact as in QED process, or dissociate in a low mass system, and are separated from the central system (γγ, H, etc.) by rapidity gaps

Main theoretical uncertainties common among different final states. Higher cross section channels, such as γγ or dijets, can test predictions for central exclusive production of a Higgs boson, and other states.

Exclusive γγ production



No candidate events observed with an expected background of 1.79 ± 0.40 events

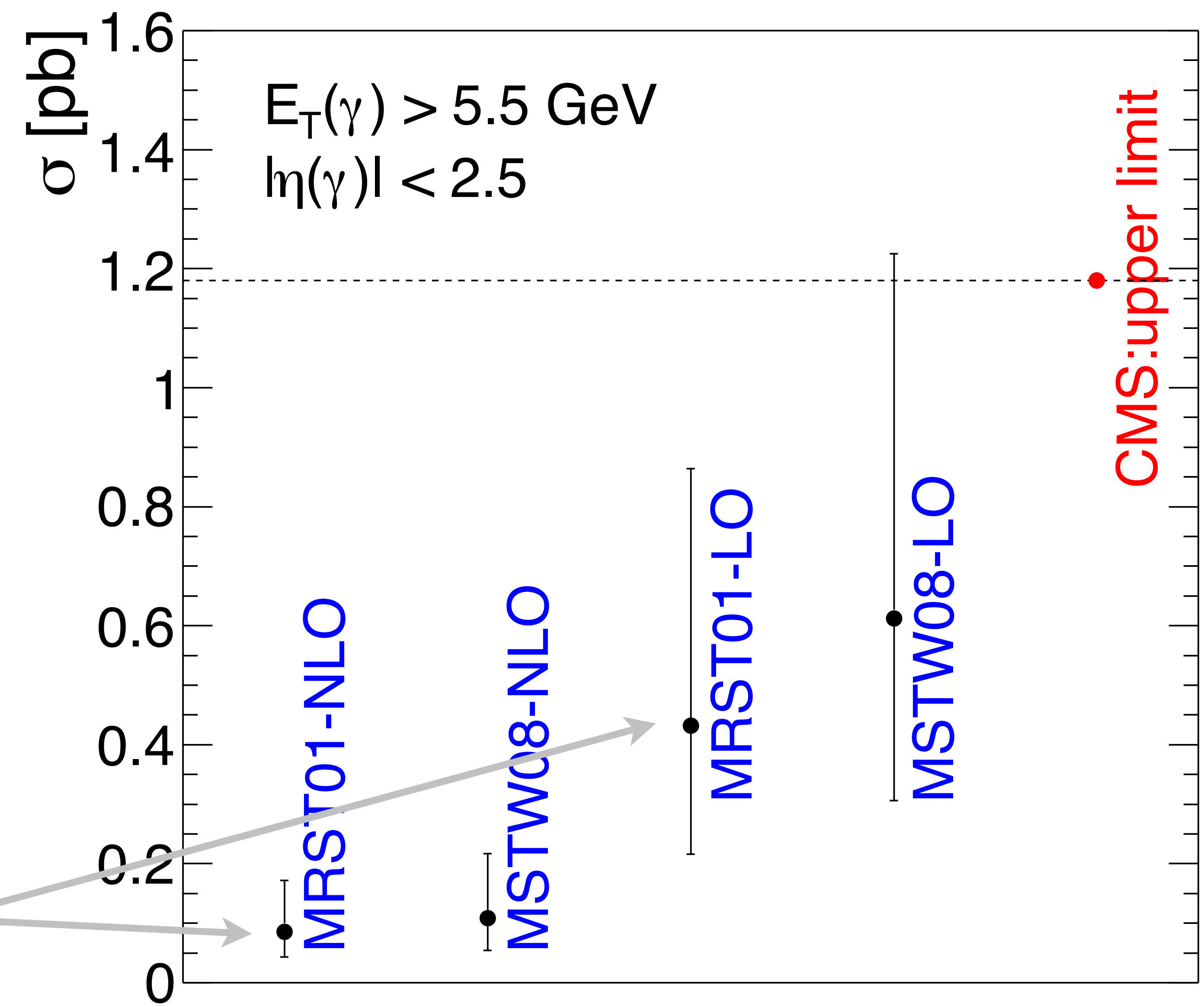
95% confidence level upper limit:

$$\sigma\left(E_T(\gamma) > 5.5GeV, |\eta(\gamma)| < 2.5\right) < 1.18\ \text{pb}$$

Upper limit on the sum of exclusive (el-el) and semi-exclusive (inel-el + inel-inel) where the proton dissociation leaves no signal in the detector acceptance

Theoretical predictions for exclusive (el-el) cross section

Difference from LO and NLO cross sections mostly from low-x gluon density



CMS FWD-11-004

arXiv:1209.1666

Summary

First measurements of hard diffraction at the LHC, associated with high-pT jets and W/Z bosons

The differential dijet cross section has been measured, as a function of a variable (ξ) that approximates the momentum loss of protons in diffractive events

Diffractive dijet events dominate the low-ξ region. Comparing the measured cross section to diffractive MC predictions based on dPDFs from HERA, an estimate of the survival probability was obtained

A large asymmetry is observed with the charged lepton in the opposite or same hemisphere as the pseudorapidity gap signature, in a W/Z data set, consistent with diffractive W/Z production

These measurements give constraints on hard-diffractive processes at the LHC, diffractive PDFs, and especially estimates of the survival probability.

Summary

Exclusive events induced by photon-photon interactions have been observed. The exclusive dimuon cross section has been measured. The exclusive dimuon and dielectron yields are in agreement with the predictions from the LPAIR generator

An upper limit on the central exclusive diphoton production has been given. It is the first search for such events at center of mass energy of 7 TeV, at the LHC

Result gives already some constraint on the theoretical predictions of central exclusive production cross sections

Future measurements will give further information on the predictions of central exclusive processes associated with a Higgs boson, and other states

The current measurements form a benchmark for future searches in exclusive & diffractive channels with near beam proton detectors at the LHC

Extra slides

Forward physics results at CMS

Low-x QCD & PDFs

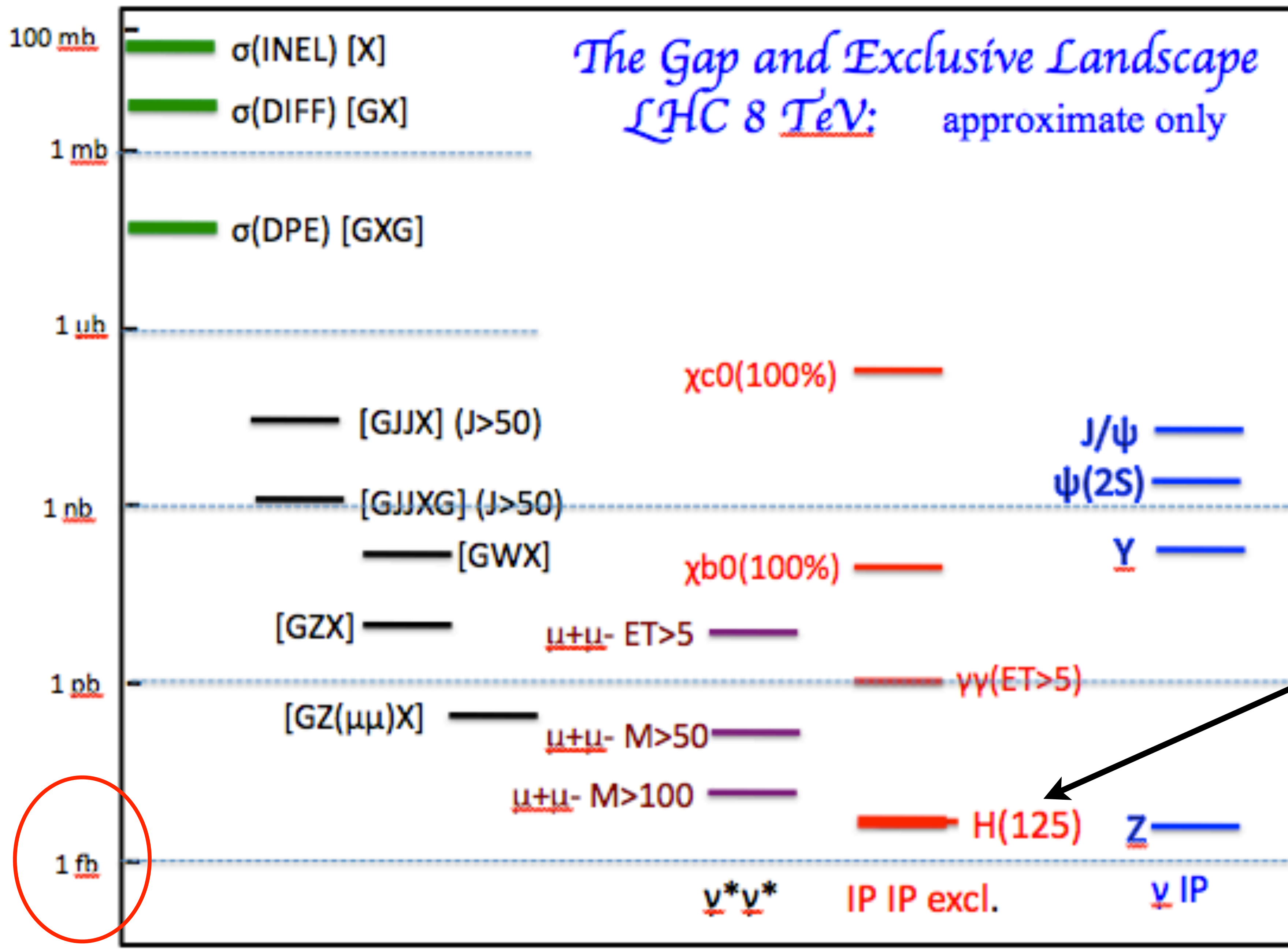
Soft and hard diffraction

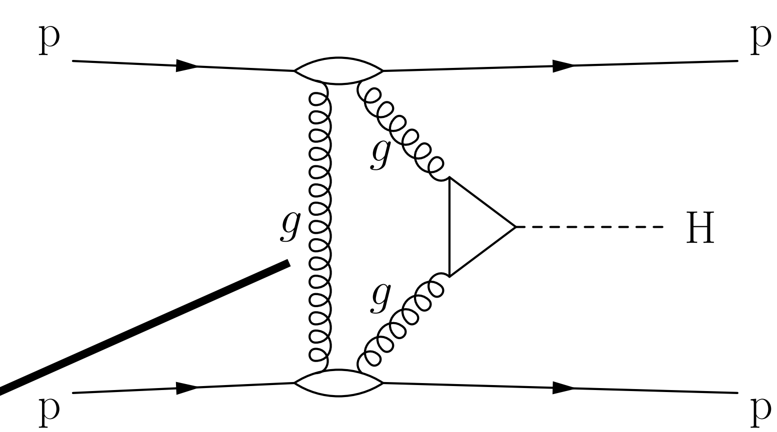
Exclusive processes, γγ interactions

Underlying event & MPI, etc.

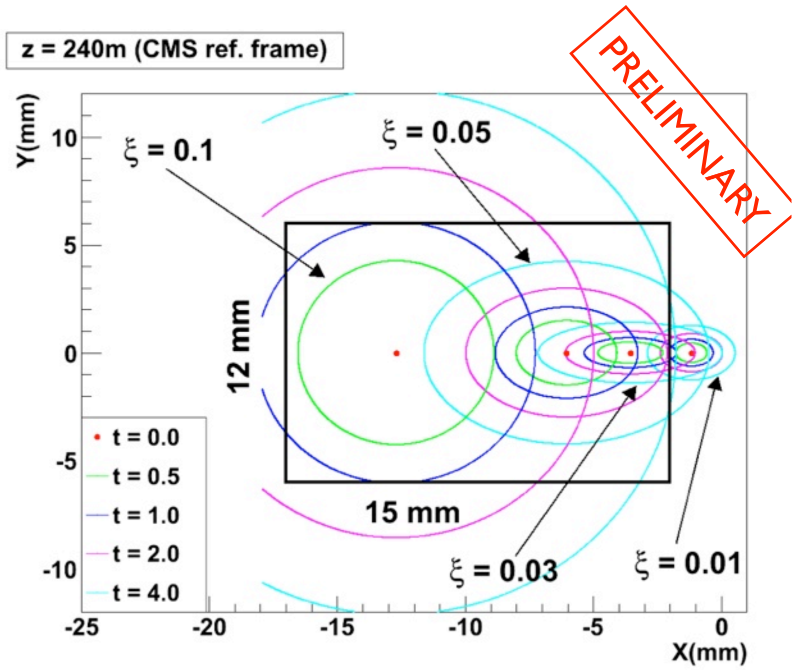
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

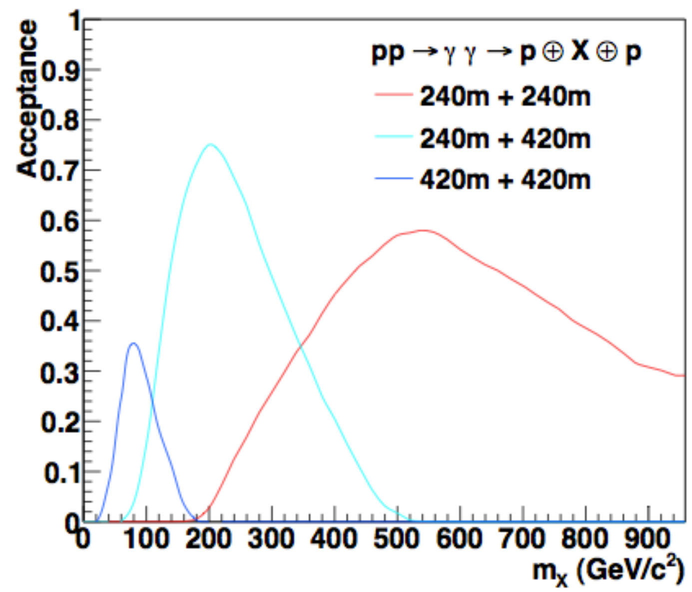
Exclusive/diffractive cross sections

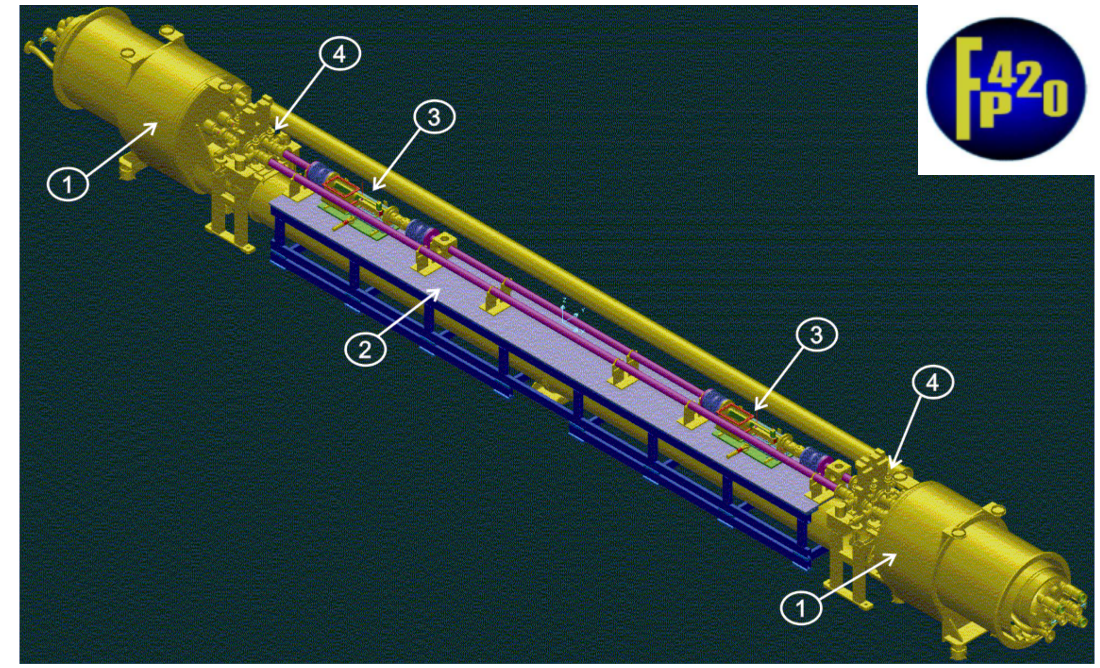


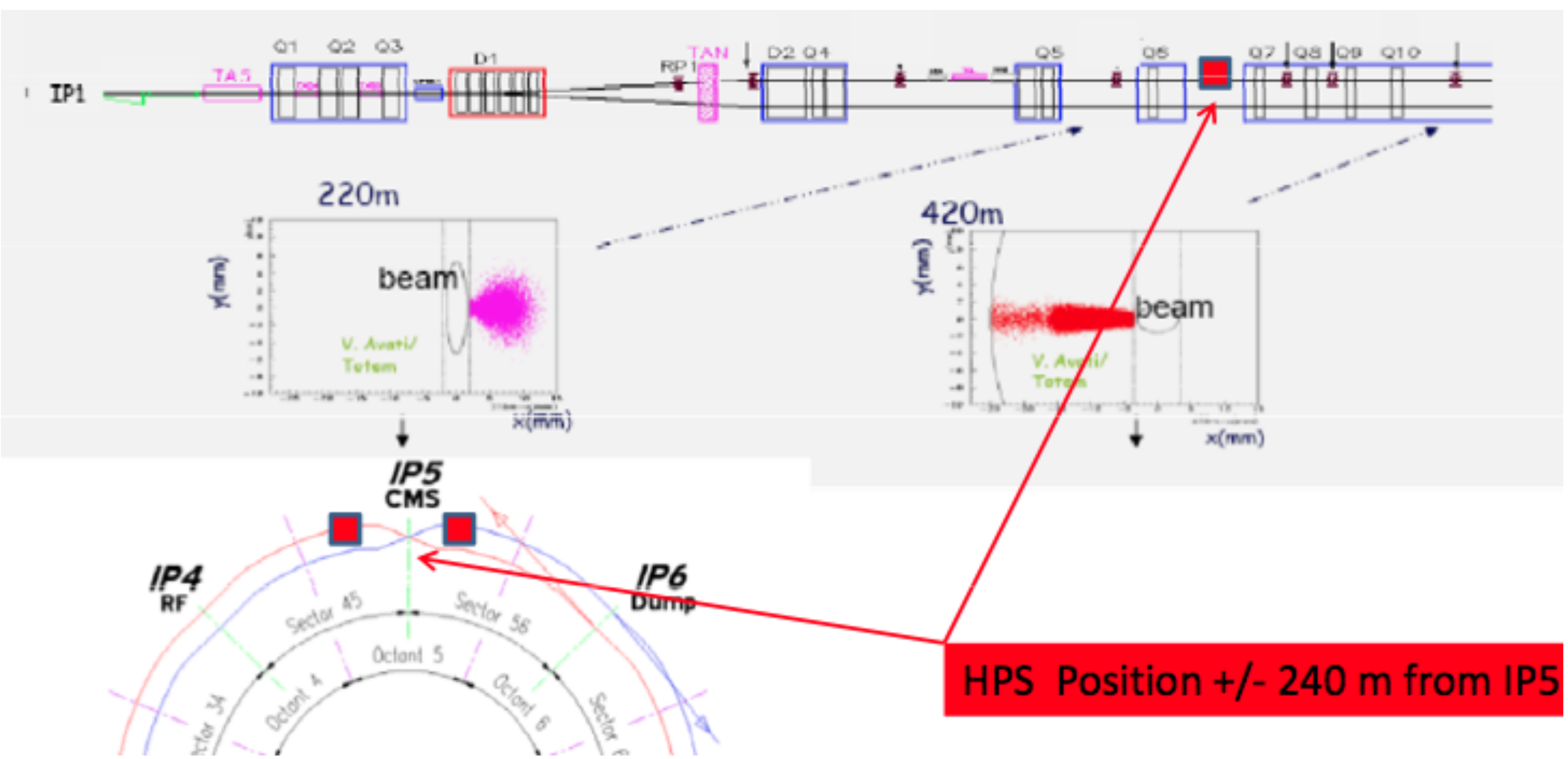


HPS and protons at high luminosity





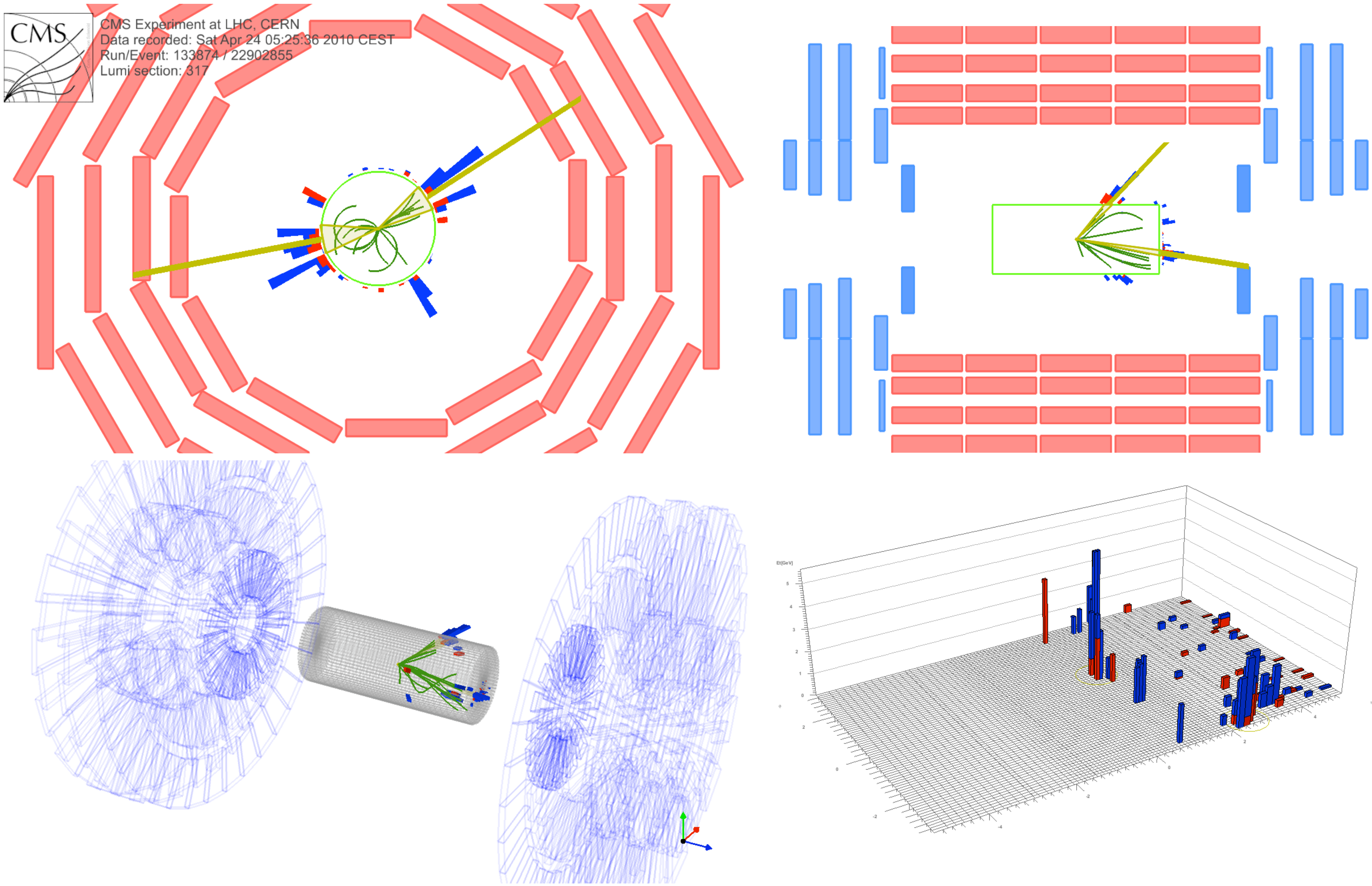




Outline

- CMS detector & forward instrumentation
- Probing hard diffraction
  - Diffractive dijet production
  - W/Z events with (pseudo-)rapidity gaps
- Exclusive processes
  - Exclusive $\gamma\gamma \rightarrow \mu\mu$ / $\gamma\gamma \rightarrow ee$
  - Central Exclusive Production

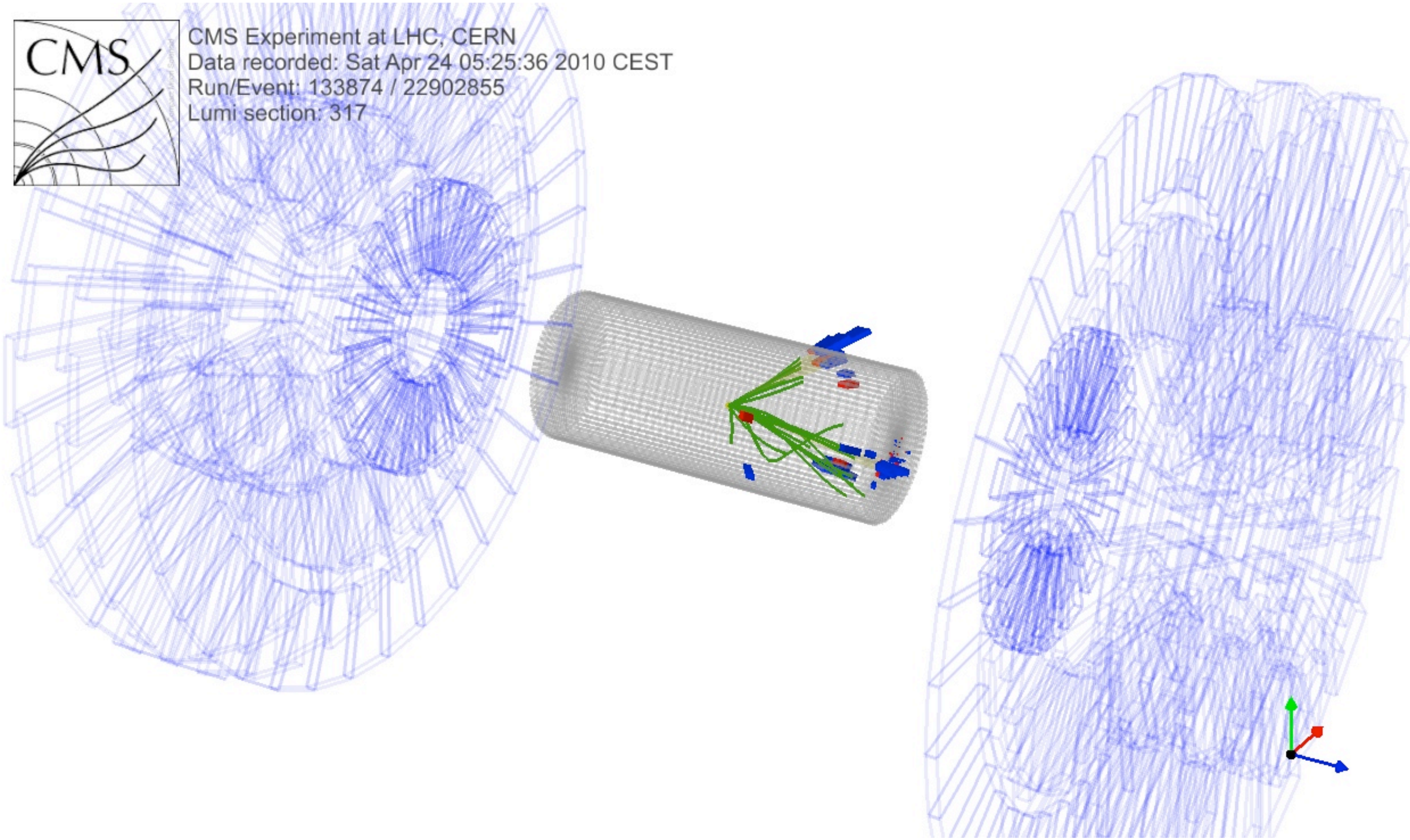
Diffractive dijet candidate



E(η < 3.0) > 1.5 GeV p_T(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

Diffractive dijet candidate



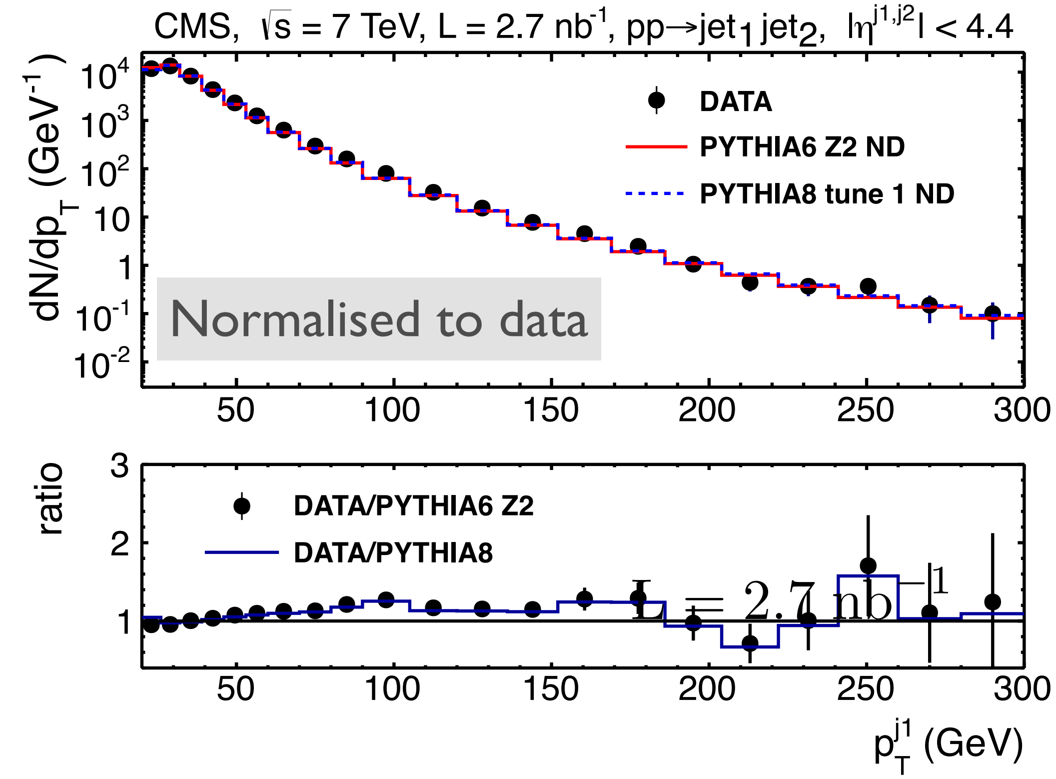
Event selection

Low-p_T trigger at 6 GeV (uncorrected)

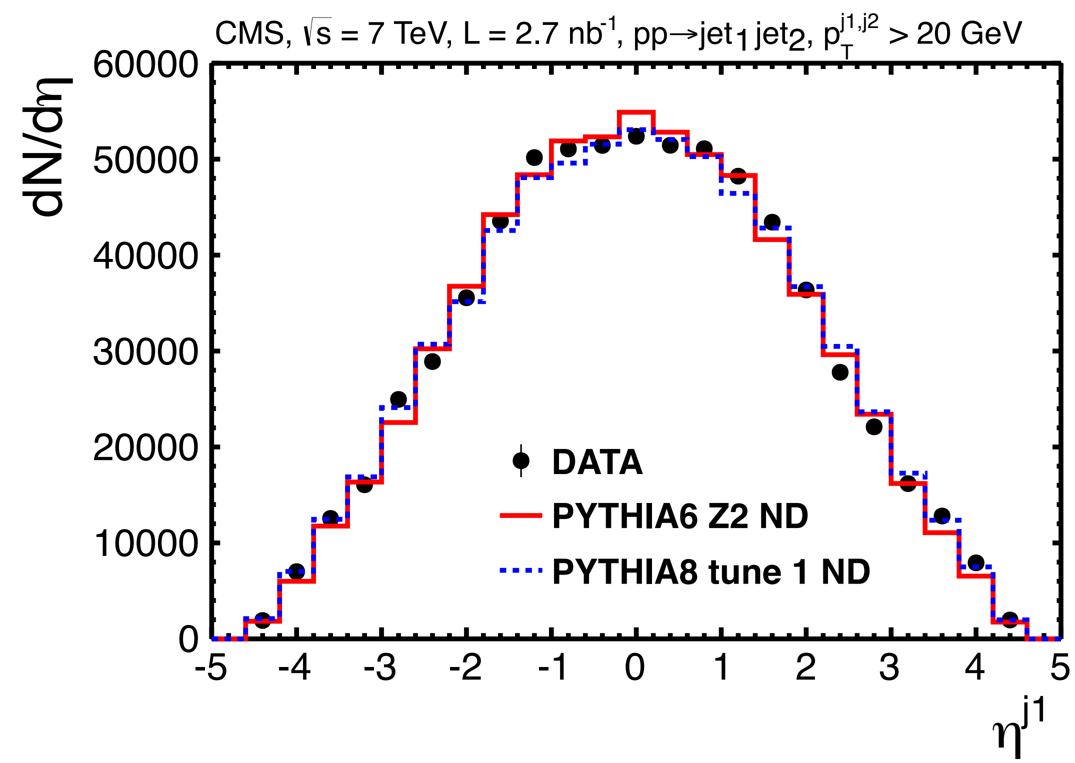
High quality vertex + beam background and noise rejection

At least two jets with p_T > 20 GeV and within $-4.4 < \eta < 4.4$

$\eta_{max(min)}$: most forward (backward) particle in the detector



CMS PAS FWD-10-004
arXiv:1209.1805



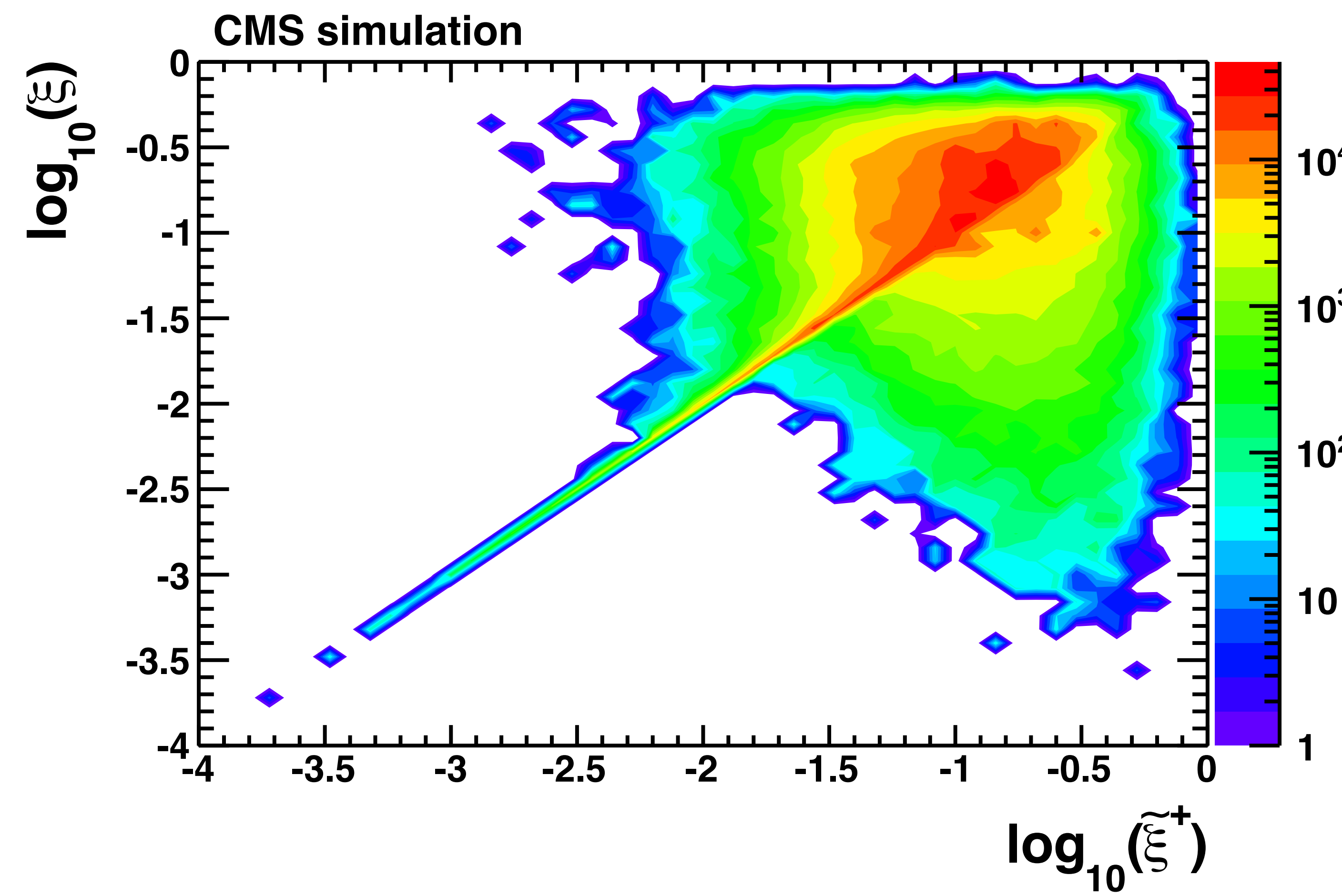
ξ definition

Sum over all final state particles with $\eta < 4.9$ (ξ^+) or $\eta > -4.9$ (ξ^-):

$$\tilde{\xi}^+ = \frac{\sum(E+p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

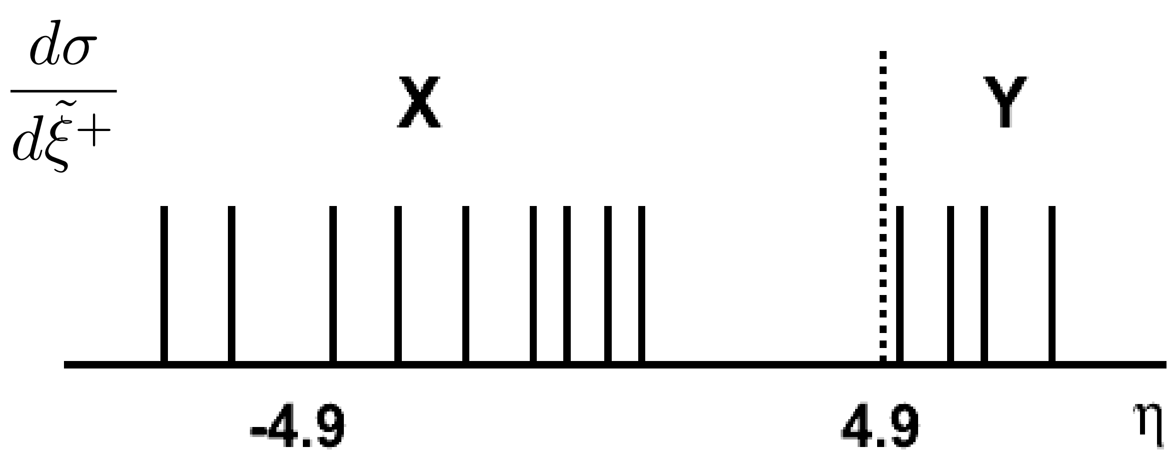
$$\tilde{\xi}^- = \frac{\sum(E-p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

Defnition converges to "true" ξ (M_X^2/s) for SD events in low-ξ region



System X defined in acceptance region of CMS

System Y is undetected (M_Y mostly below ~ 12 GeV)



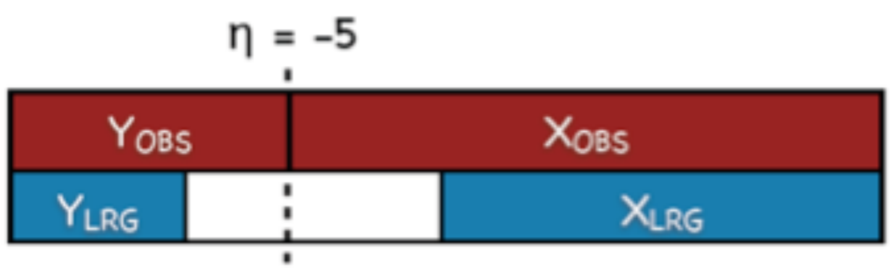
At reconstruction level, ξ is defined from all particles (using a particle-flow algorithm) above threshold, and a scale correction factor (resolution ~25%):

$$\tilde{\xi}^\pm = C\,\frac{\sum(E \pm p_z)}{\sqrt{s}}$$

ξ definition

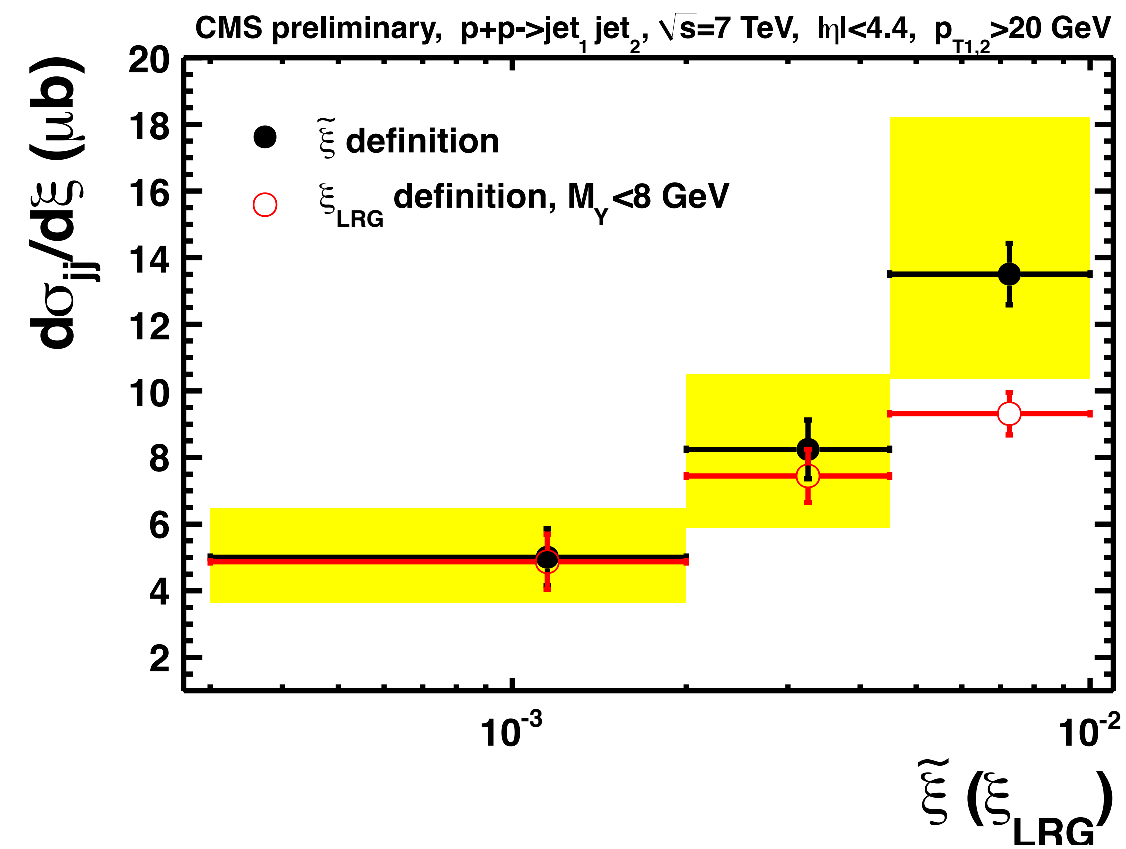
$$\tilde{\xi}^{\pm} = \frac{\sum (E \pm p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

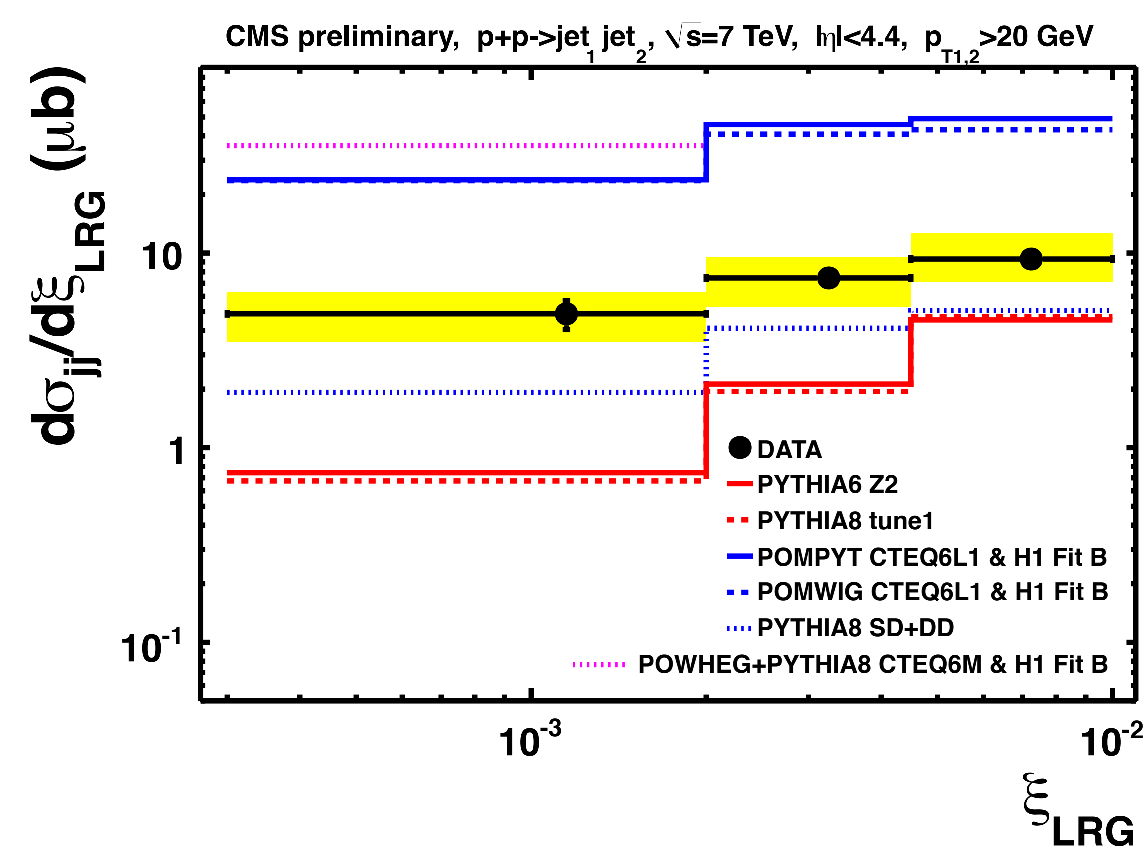
- ideal topology
  $M_{X,OBS} = M_{X,LRG}$



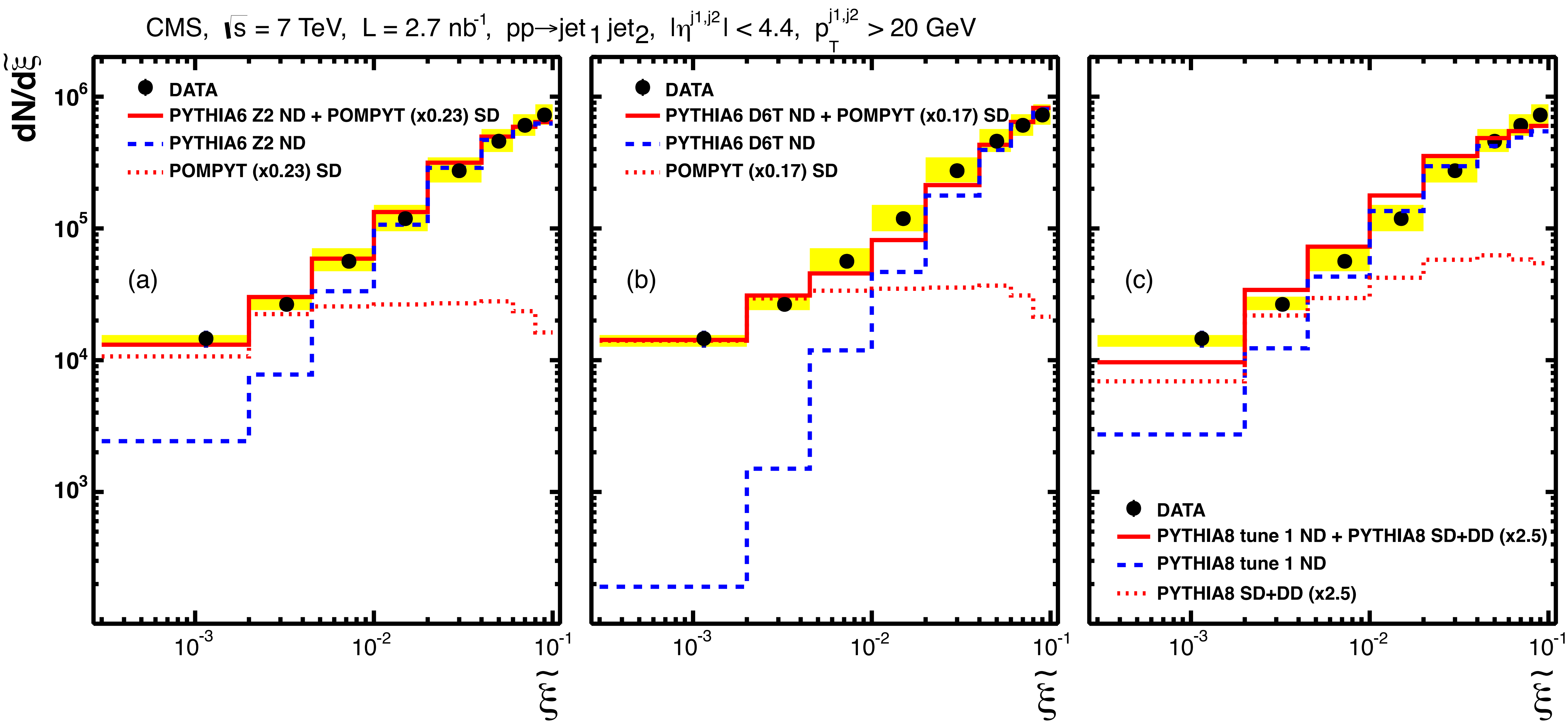
- X_{LRG} extends beyond detector acceptance
  $M_{X,OBS} \neq M_{X,LRG}$

- Y_{LRG} penetrates detector acceptance
  $M_{X,OBS} \neq M_{X,LRG}$





Event distributions



Systematic uncertainties

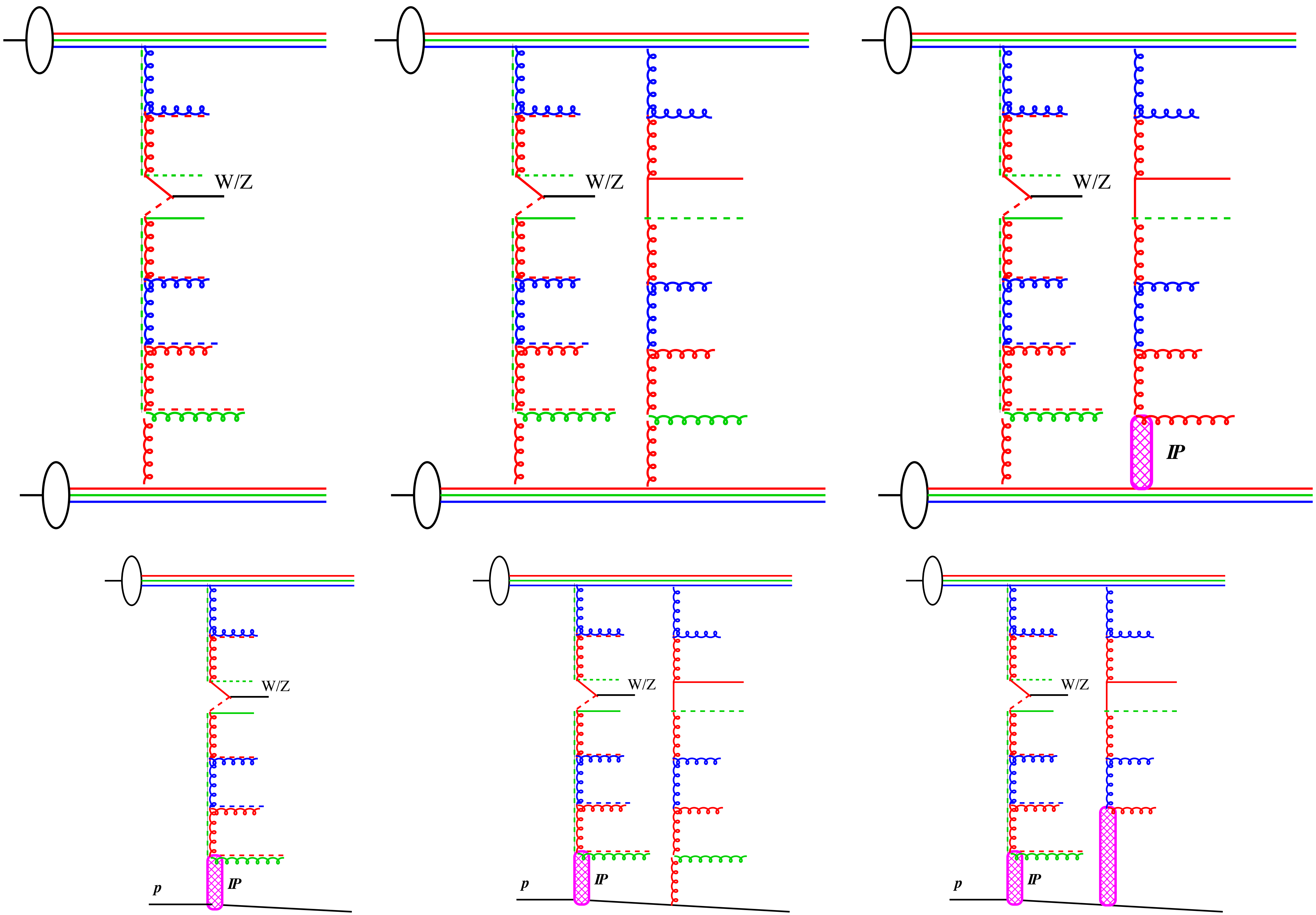
Largest contribution from Jet Energy Scale uncertainty

Average systematic error around 30%

$\tilde{\xi}$ bin	$\Delta\sigma_{jj}/\Delta\tilde{\xi}$ (μb)
$0.0003 < \tilde{\xi} < 0.002$	$5.0 \pm 0.9(\mathrm{stat.})^{+1.5}_{-1.4}(\mathrm{syst.})$
$0.002 < \tilde{\xi} < 0.0045$	$8.2 \pm 0.9(\mathrm{stat.})^{+2.3}_{-2.3}(\mathrm{syst.})$
$0.0045 < \tilde{\xi} < 0.01$	$13.5 \pm 0.9(\mathrm{stat.})^{+4.7}_{-3.1}(\mathrm{syst.})$

Uncertainty source	$0.0003 < \tilde{\xi} < 0.002$	$0.002 < \tilde{\xi} < 0.004$	$0.0045 < \tilde{\xi} < 0.01$
1. Jet energy scale	$(+26/-19)\%$	$(+21/-20)\%$	$(+28/-16)\%$
2. Jet energy resolution	$(+5/-3)\%$	$(+2/-1)\%$	$(+3/-1)\%$
3. Calorimeter energy scale	$(+7/-14)\%$	$(+14/-8)\%$	$(+12/-10)\%$
4. MC uncertainty	$(+5/-6)\%$	$(+3/-14)\%$	$(+3/-3)\%$
5. HF threshold	$(+0/-6)\%$	$(+2/-0)\%$	$(+2/-0)\%$
6. Tracks p_T threshold	$(+0/-1)\%$	$(+1/-0)\%$	$(+0/-2)\%$
7. One vertex selection	$(+6/-0)\%$	$(+0/-1)\%$	$(+1/-0)\%$
8. Calorimeter jets	$(+0/-4)\%$	$(+0/-4)\%$	$(+2/-4)\%$
9. $\tilde{\xi}^+$, $\tilde{\xi}^-$ difference	$\pm 8\%$	$\pm 8\%$	$\pm 11\%$
10. η_{max} (η_{min}) cut	$(+0/-0)\%$	$(+3/-0)\%$	$(+9/-0)\%$
11. Trigger efficiency	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
12. Luminosity	$\pm 4\%$	$\pm 4\%$	$\pm 4\%$

Underlying event in hard interactions

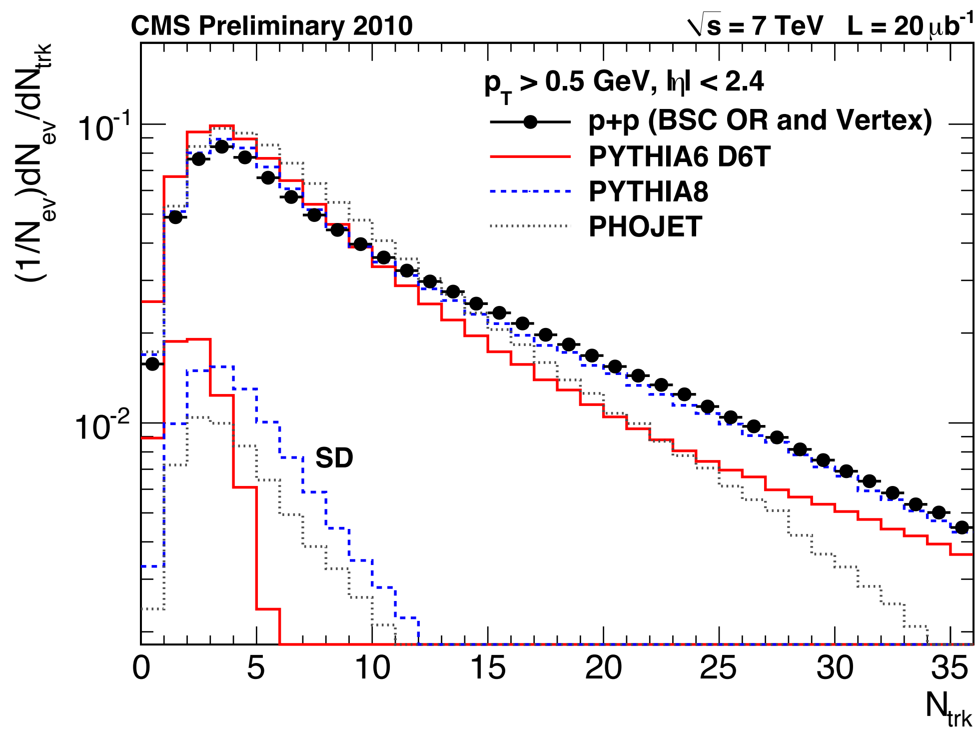


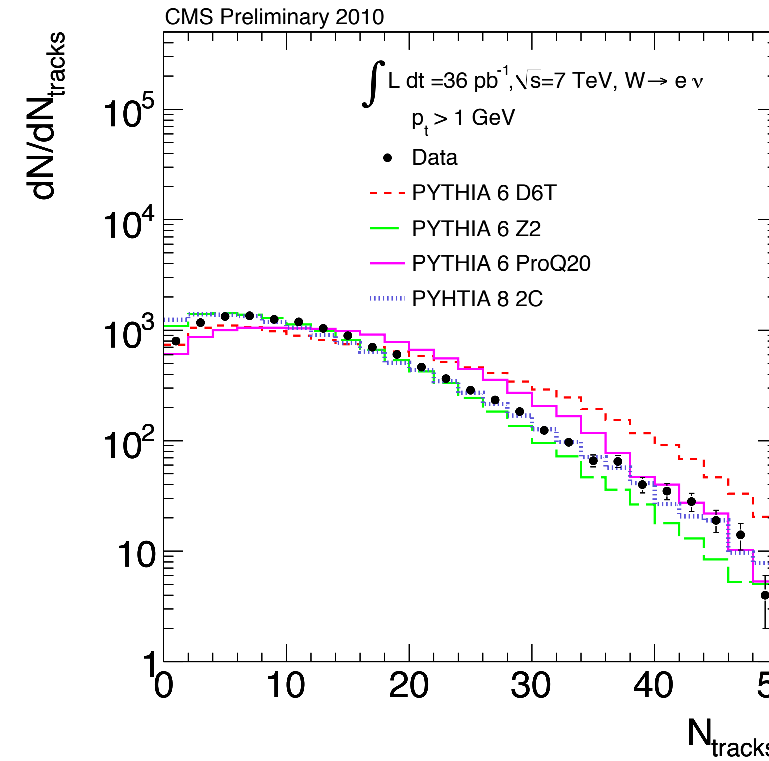
Central vs Forward energy flow

Minimum bias

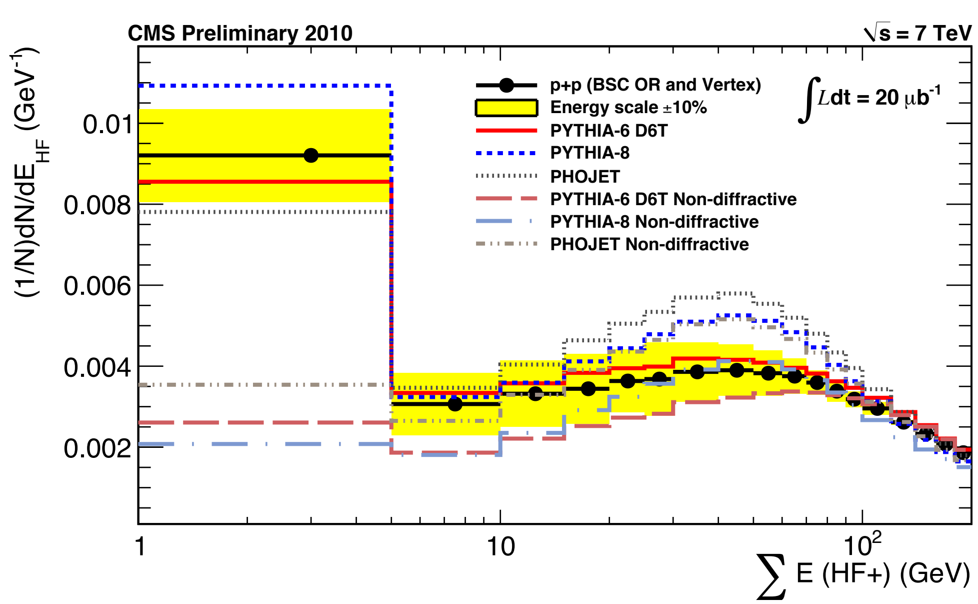
$pp \to W X$

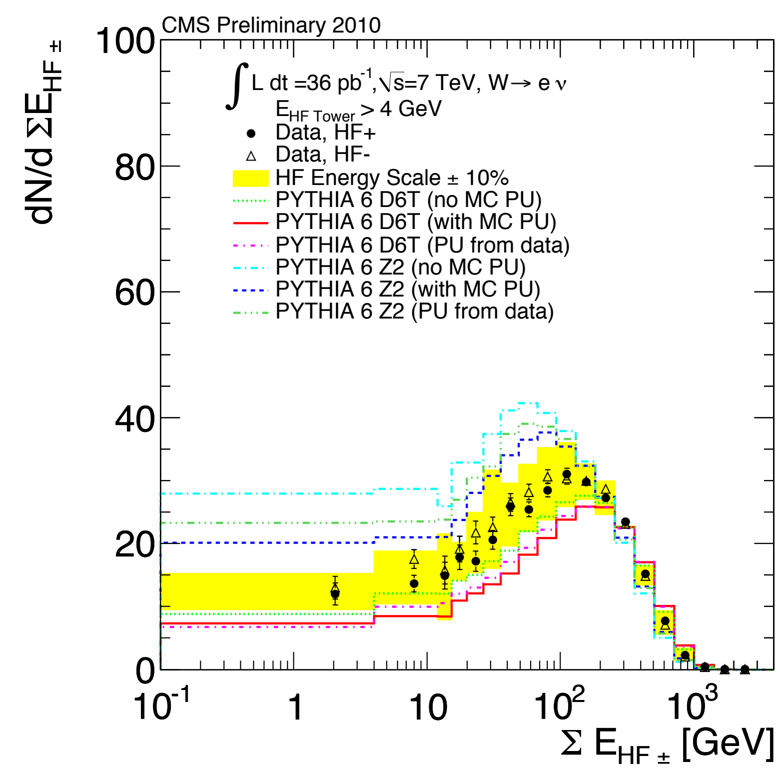
Central track multiplicity





Forward energy





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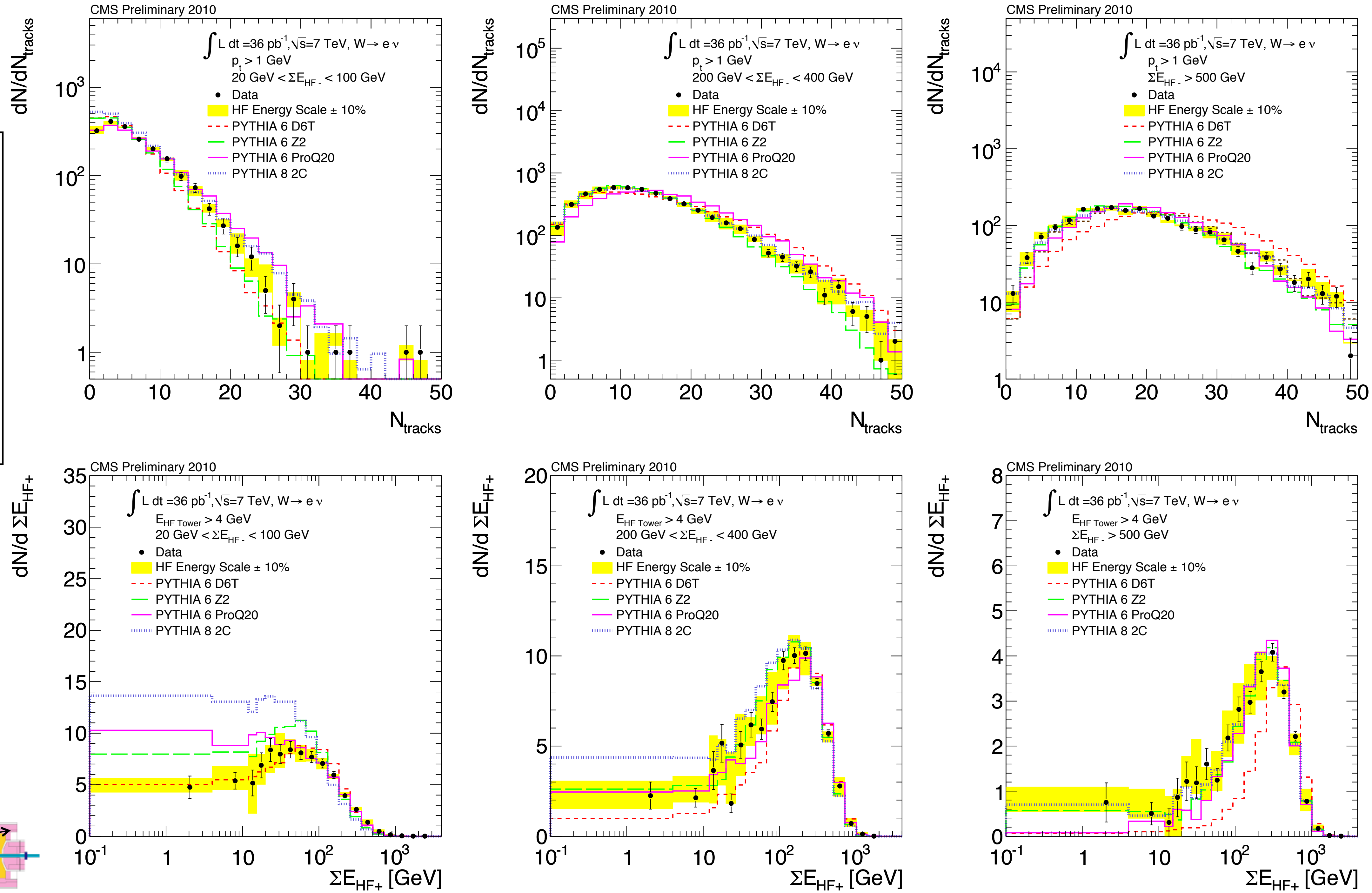
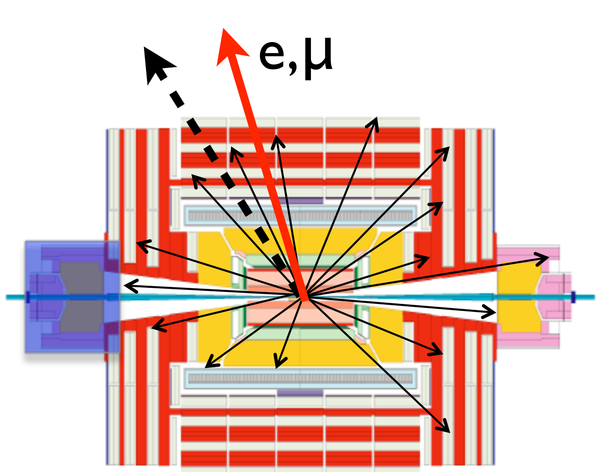
Central vs Forward energy flow

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





$\sum E_{HF-}$

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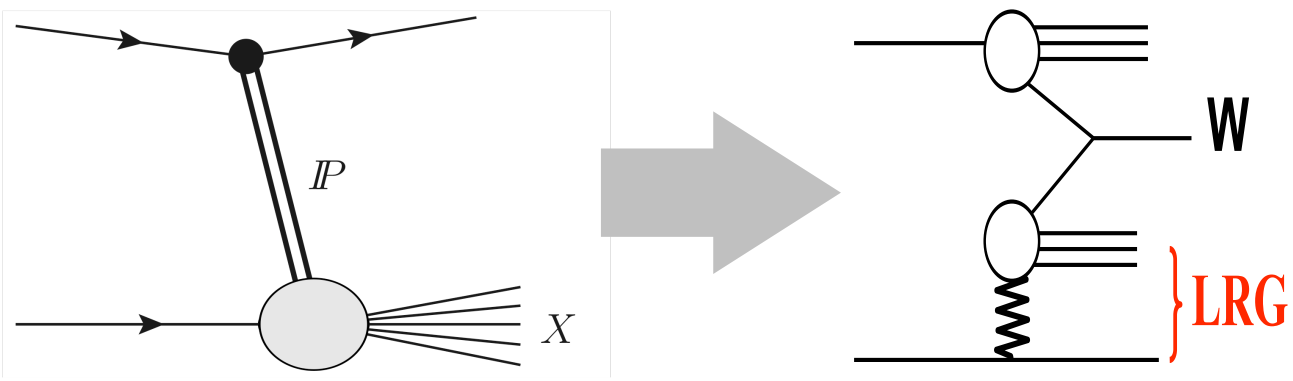
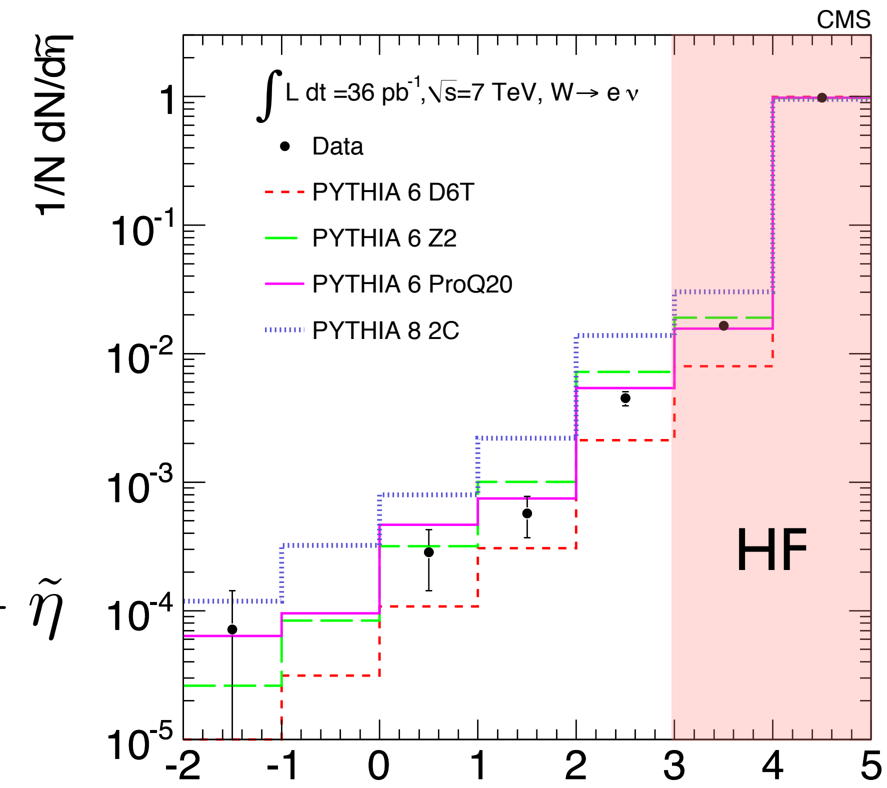
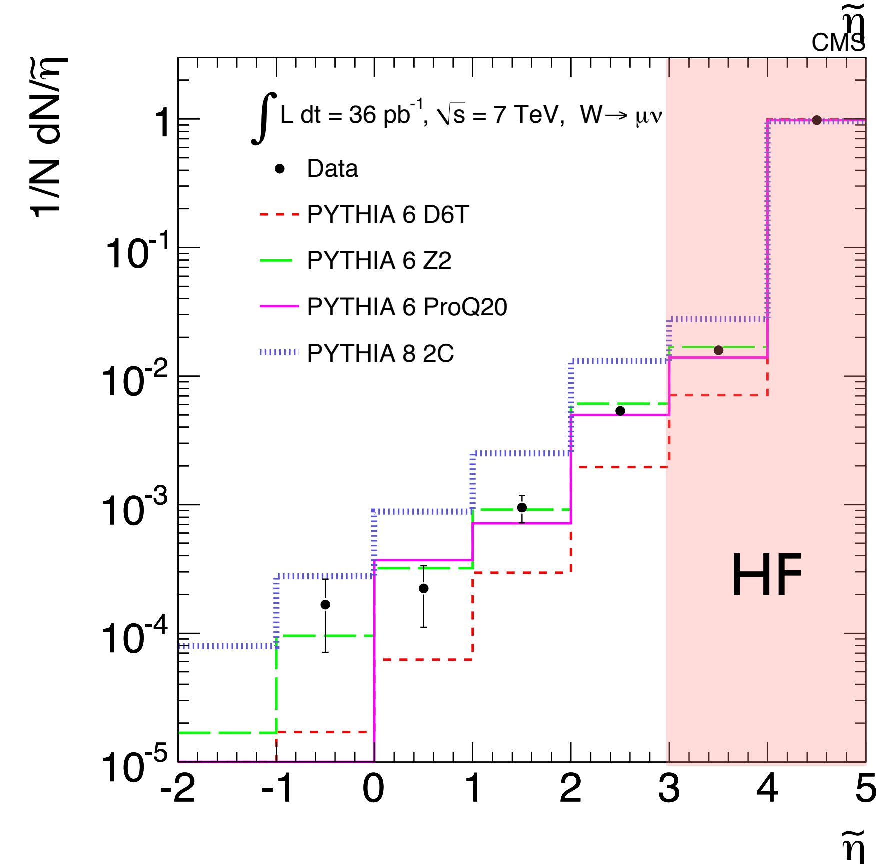
W→eν(μν) gap distributions



$$\Delta\eta^{\mathrm{Gap}} \equiv 4.9 - \tilde{\eta}$$





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

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

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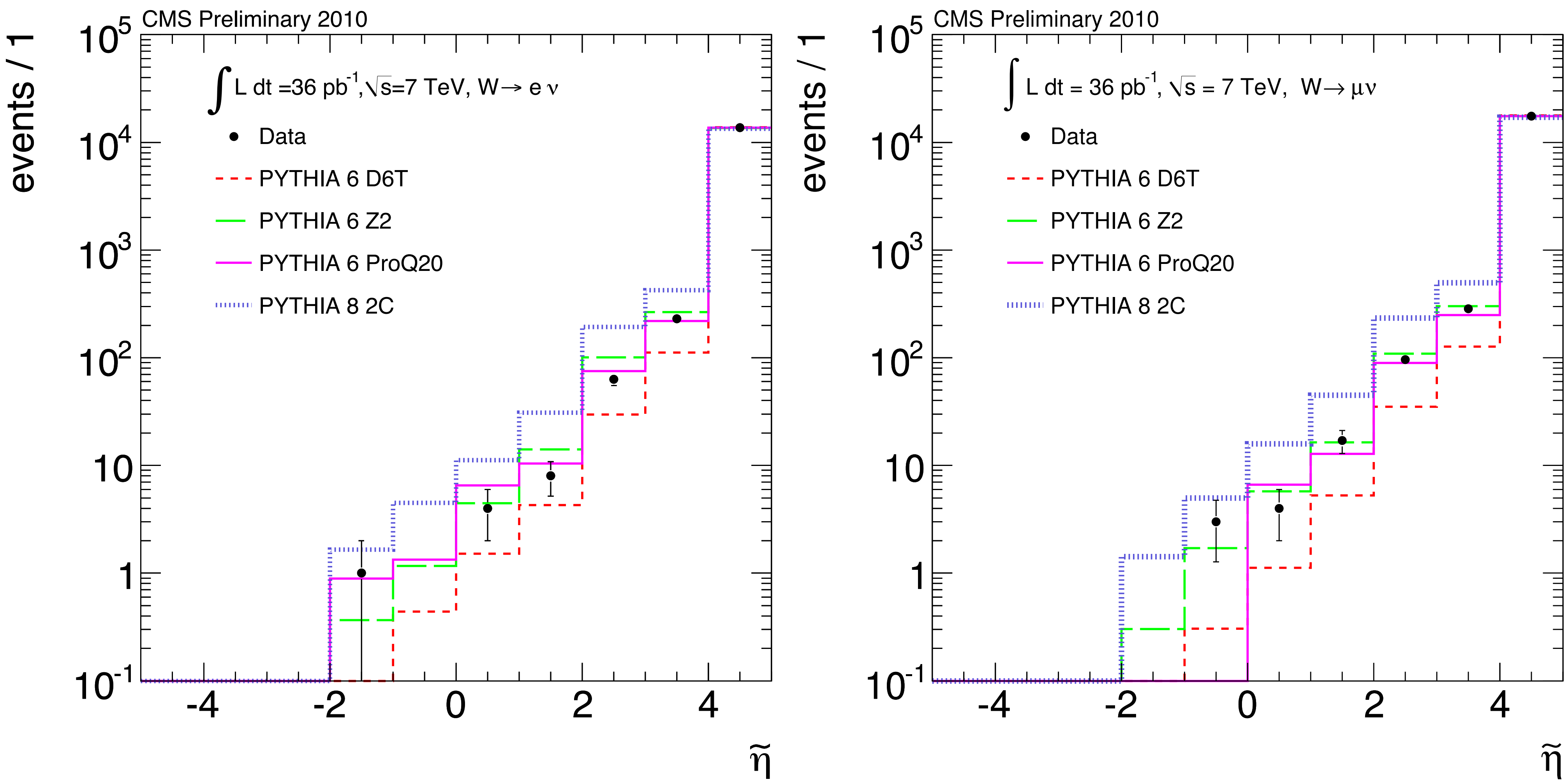
W→eν(μν) gap distributions



[CMS PAS FWD-10-008]()

Outline

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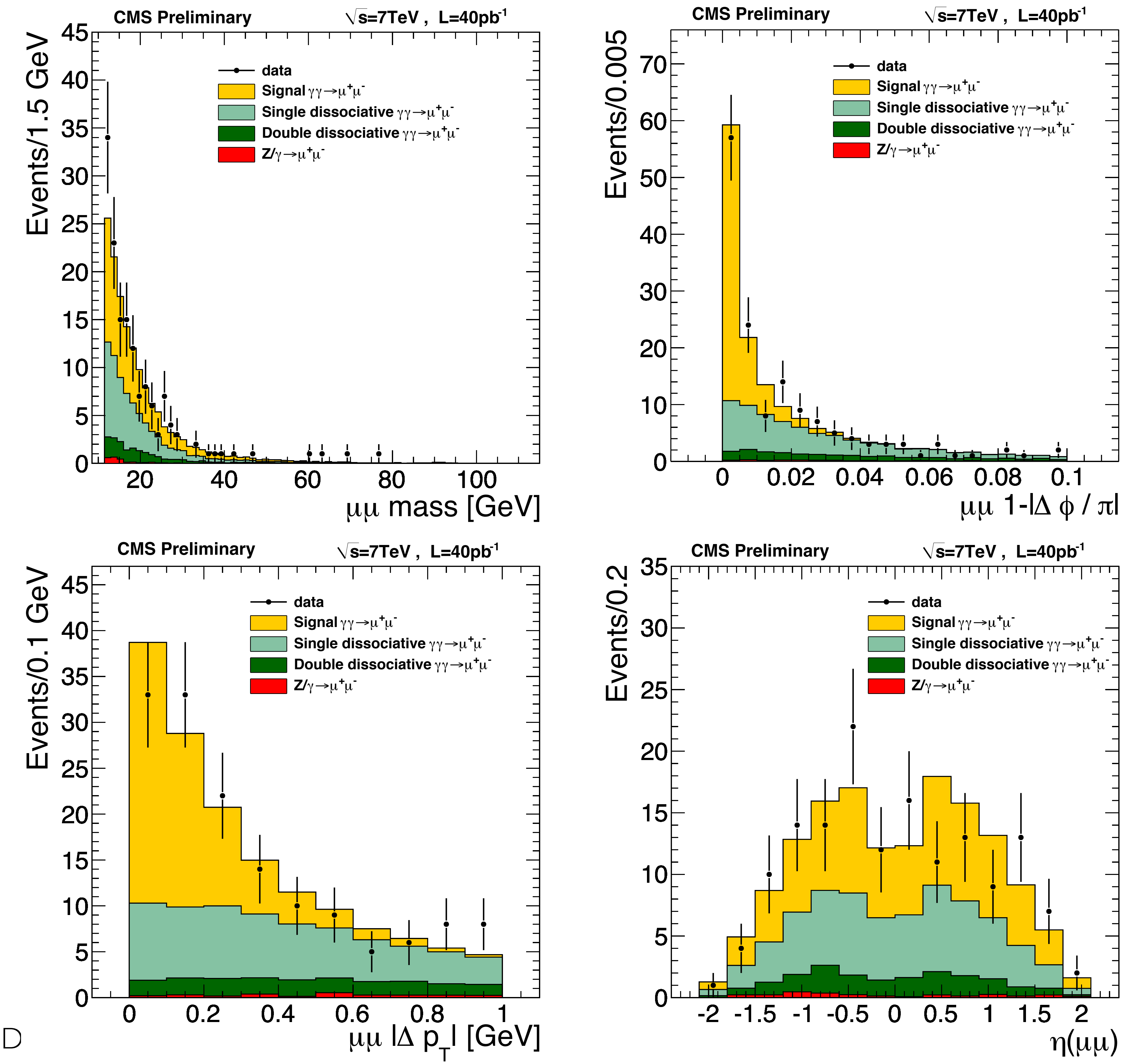
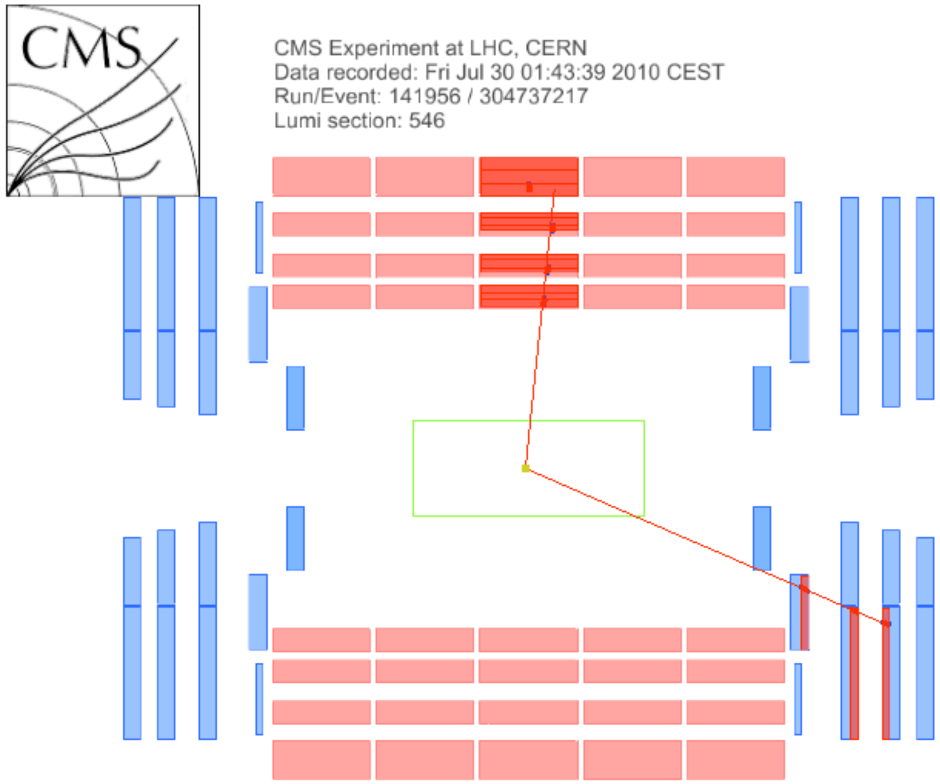
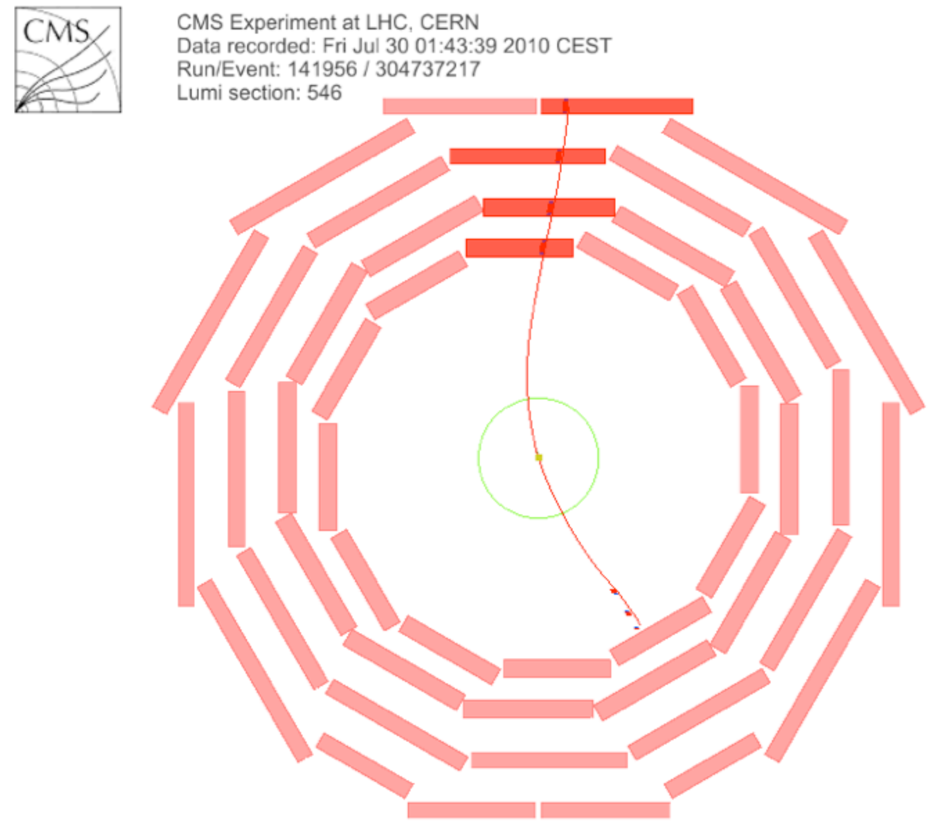
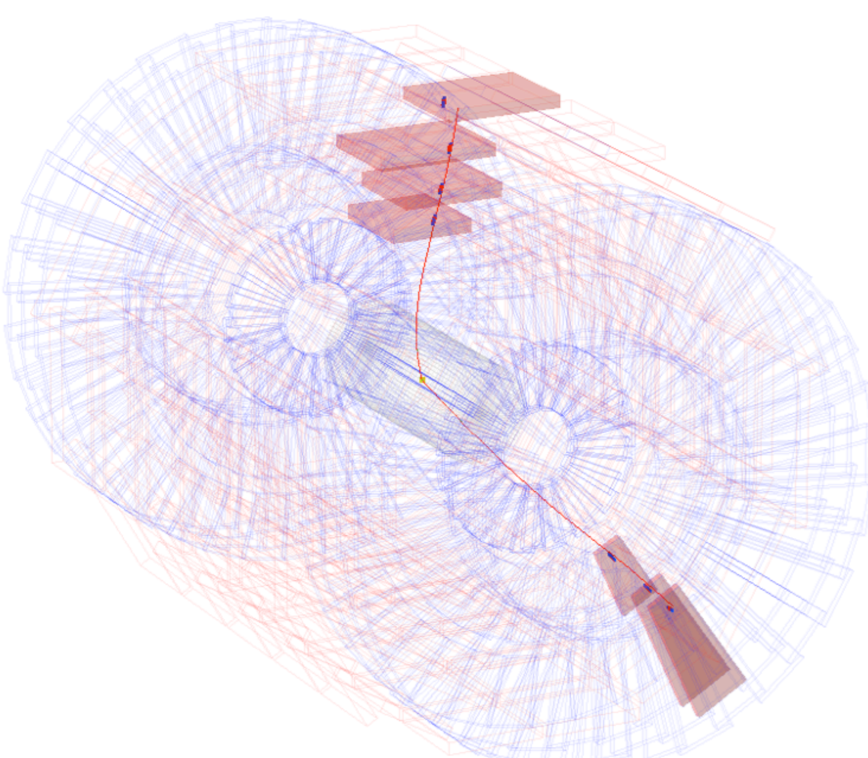
Exclusive γγ→μμ production



Exclusive γγ→μμ production







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

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

Exclusive pp → γγ / γγ → e$^+$e$^-$

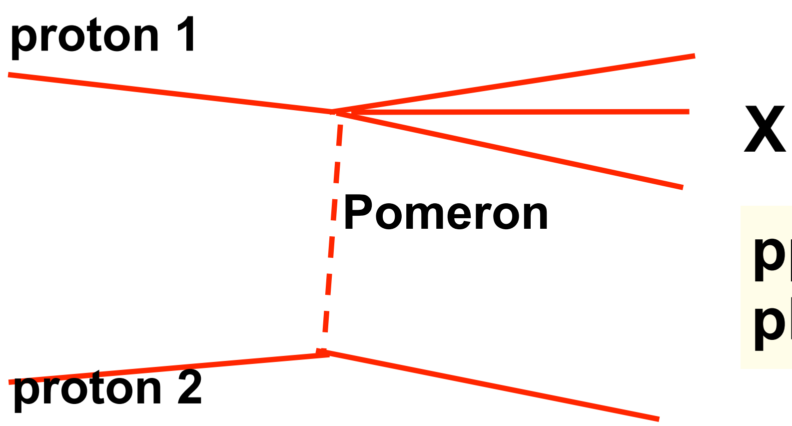
Table 1: Number of diphoton and dielectron candidates remaining after each selection step.

Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Table 4: Background event yields expected for both the diphoton and the dielectron analyses. The quoted uncertainties are statistical.

Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive Υ(1S,2S,3S) $\to e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$ and $\eta\eta$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28

Meaning of $E \pm p_z$



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) $\approx$ 0 (and proton 2, and Pomeron, move in the negative z direction)

Hence:
E(Pomeron) - p_z(Pomeron) $\approx$ 2E(Pomeron) $\approx$ 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) $\approx$ 0, hence:

E(Pomeron) + p_z(Pomeron) $\approx$ 2E(Pomeron) $\approx$ E(X) + p_z(X)

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