Review of diffractive and electromagnetic processes in CMS/LHC

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for the CMS collaboration

International Wilhelm and Else Heraeus Physics School
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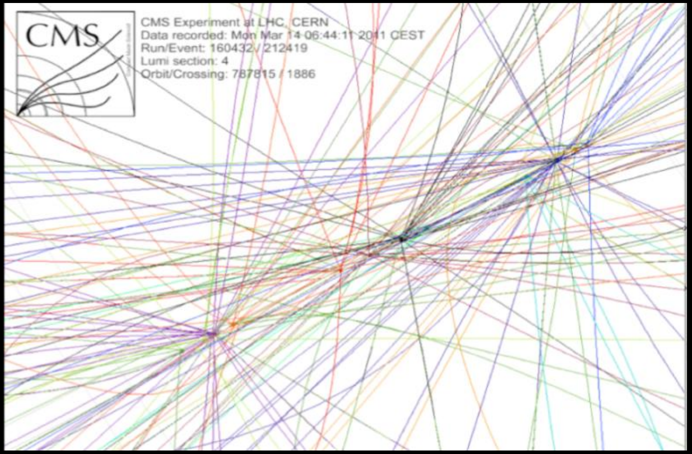
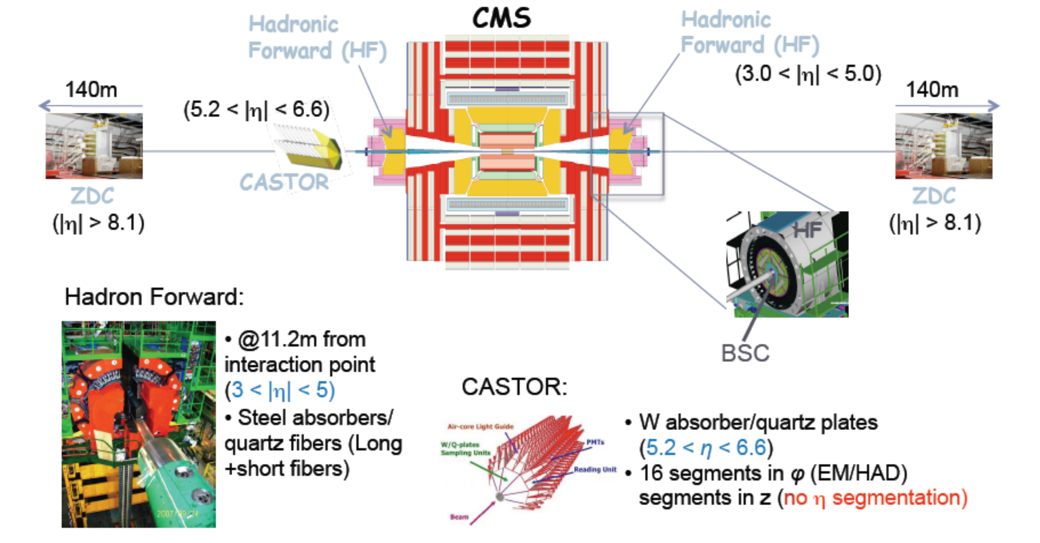
The setting:CMS@LHC

- 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 2-8 in 2010/2011, 21 in 2012
  - Low pileup needed for some analysis





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

Overview

- Studying the exclusive production at CMS
  - $\gamma\gamma \rightarrow W^{+}W^{-}$
- Measurement of diffraction dissociation
  - SD
  - DD
- Z and $\gamma + jets$ *production*
- DY in association with jets

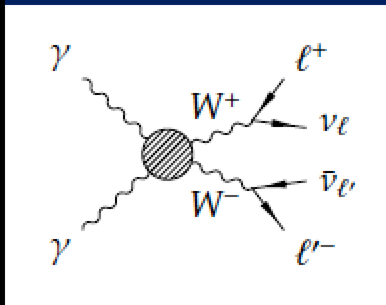
- Many other interesting results not covered here
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

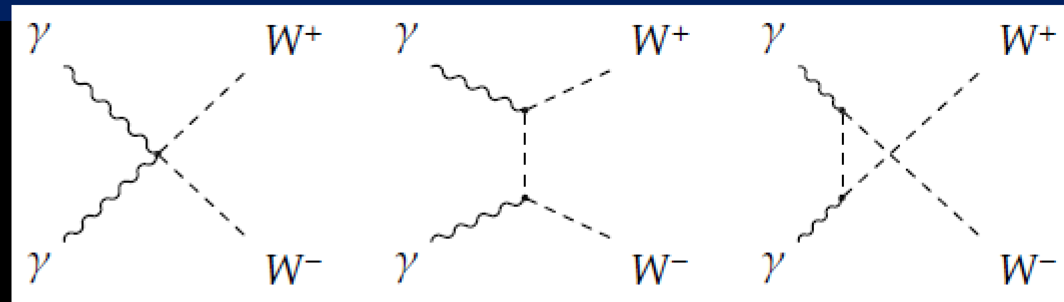
Studying the exclusive production

CMS-PAS-FSQ-13-008

Exclusive $\gamma\gamma \to WW$

CMS-PAS-FSQ-13-008





- Triple and quartic coupling in SM
  - Any deviation can signal new physics
- BSM contributions via effective Lagrangian (dimension 6+8 operators)

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha,$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta - W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta,$$

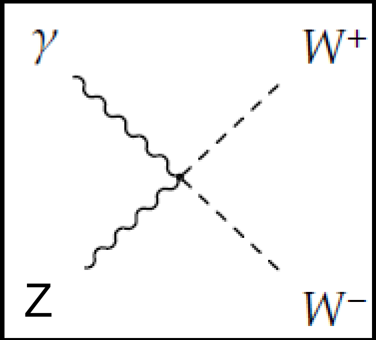
AQGC† parameters

Λ: scale for New Physics

- Form factors introduced to preserve unitarity
  - $W_{\gamma\gamma}$: γγ center of mass energy
  - Λ_{cutoff}: energy cutoff scale ($\Lambda_{cutoff} \to \infty$ = no form factor)

$$a_{0,C}^W \to a_{0,C}^W(W_{\gamma\gamma}^2) = a_{0,C}^W\left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda_{cutoff}^2}\right)^{-2}$$

Anomalous couplings $\gamma\gamma \to WW$



- Anomalous quartic coupling include $Z\gamma WW$ vertex
  - Constrain this vertex (null) give relations between 6 -8 operators

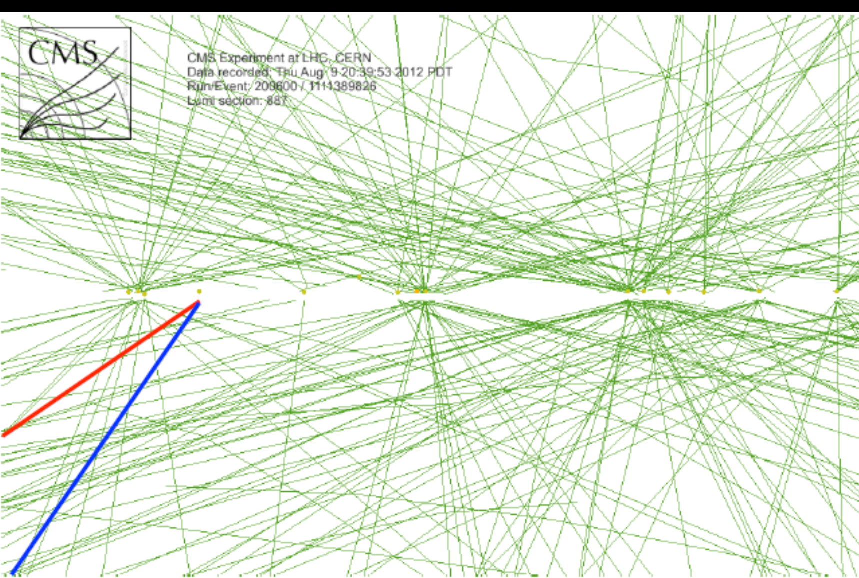
$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda^4}$$

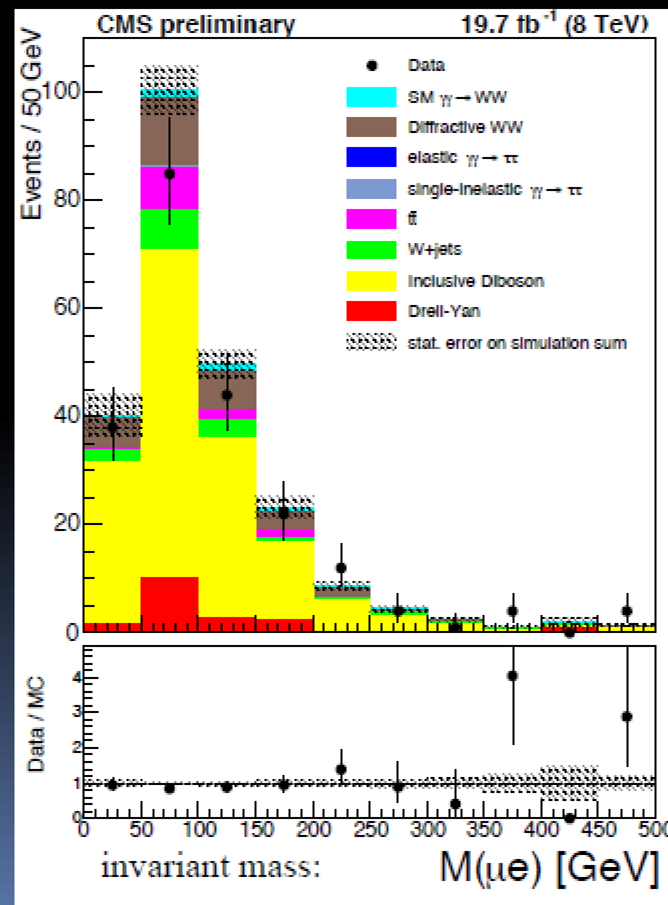
$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda^4}$$

  - $g = e/\sin \Theta_w$
  - $g' = e/\cos \Theta_w$

Sample selection $\gamma\gamma \to WW$

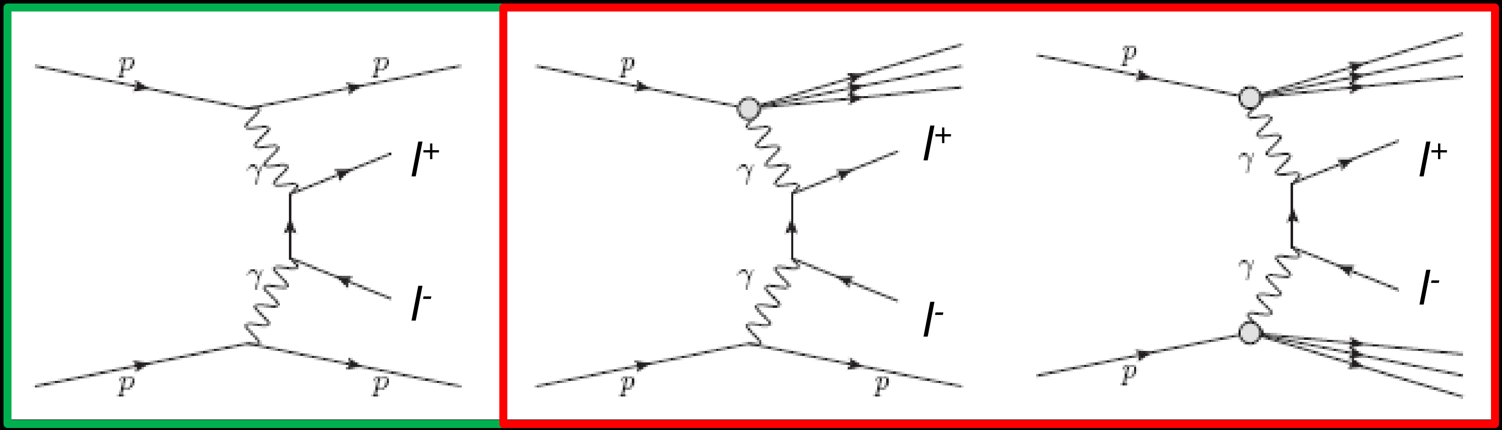
- Elastic and proton-dissociative contributions
  - $pp \to p\, W^+W^- p$
  - $pp \to p^{(*)}\, W^+W^- p^{(*)}$
- Unlike-flavor dilepton decay channel: $\gamma\gamma \to W^+W^- \to \mu \; e^-_+ \, \nu \, \bar{\nu}$
  - Avoid large backgrounds
- Data sample – 19.7 fb^{-1} @ 8 TeV
  - $p_T(\mu, e) > 20$ GeV
  - No other track in vertex





$\gamma\gamma\rightarrow\mu\mu$, ee control samples

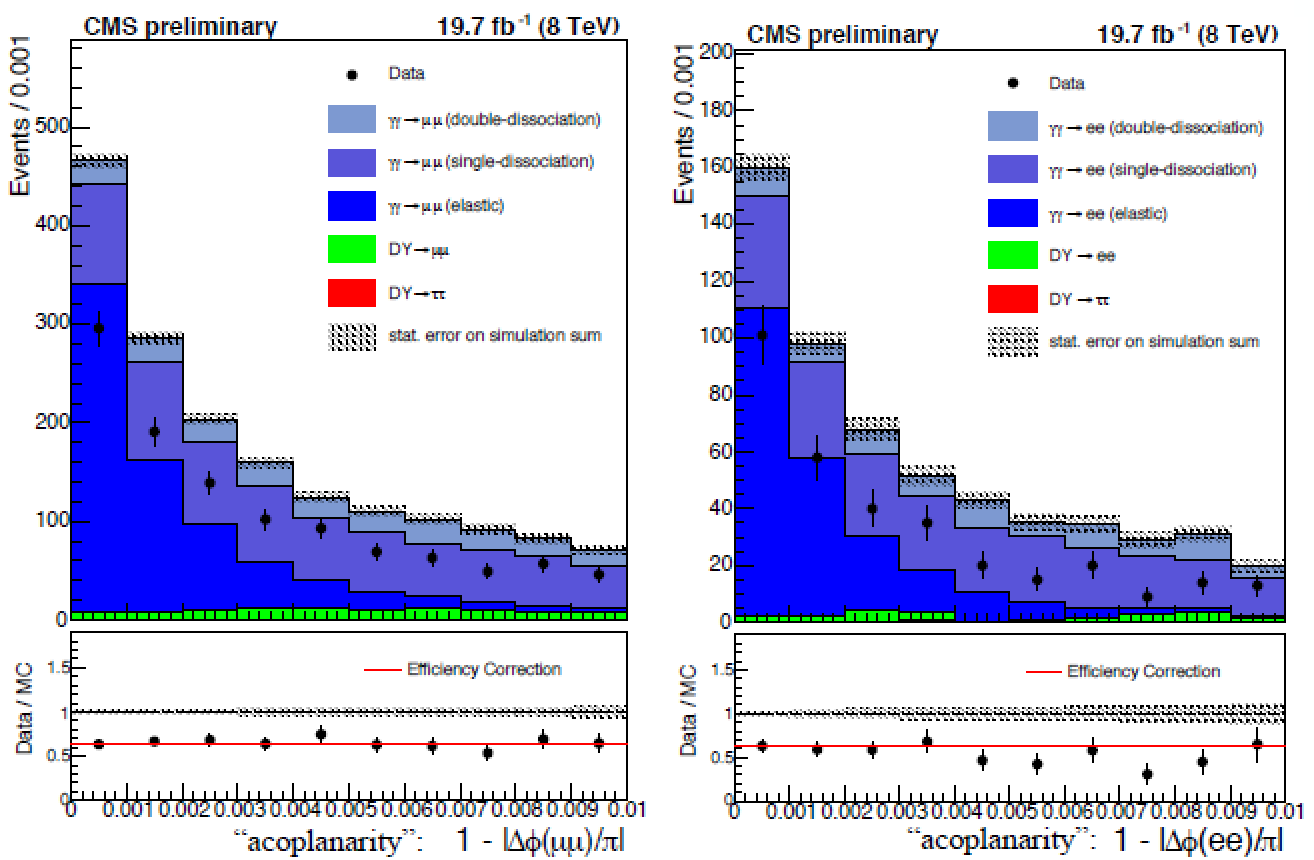
Exclusive production | Proton dissociation



- Exclusive lepton production $pp \rightarrow p\, l^+ l^-\, p$
  - Well known QED like "Standard Candle"
  - Study exclusive selection efficiency
- Extract proton dissociation factor from $\gamma\gamma\rightarrow l^+ l^-$ *control sample*
  - *$\gamma\gamma\rightarrow WW$ simulation do not include proton dissociation*
  - Apply dissociation factor from control sample

$\gamma\gamma \to \mu\mu$, ee control samples

- Select high purity elastic events
  - Acoplanarity 1–|Δϕ(ℓ+ℓ–)/π| < 0.01 (back to back leptons)
  - Invariant mass outside Z resonance -> $m(l^+l^-)$<70 GeV, $m(l^+l^-)$>106 GeV



- data-simulation ratio: 0.63
- apply as efficiency correction

$\gamma\gamma\rightarrow\mu\mu$, ee proton dissociation

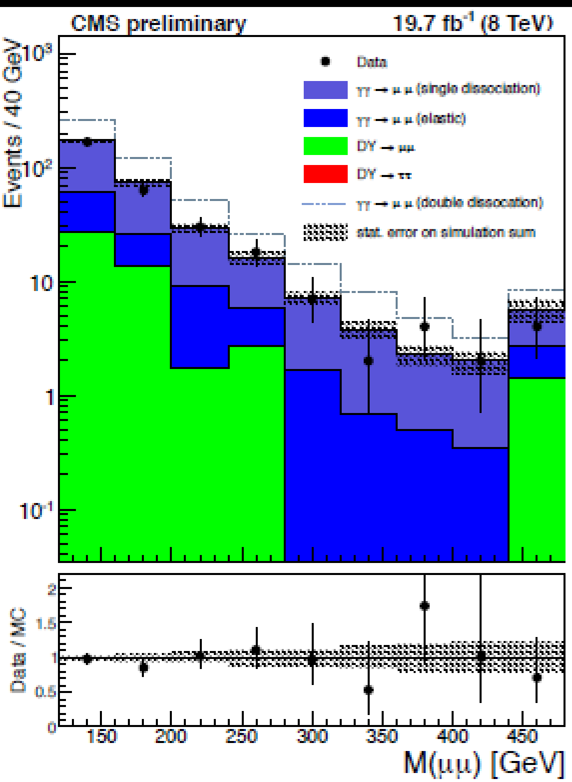
→ Use kinematic region close to $\gamma\gamma\rightarrow W^+W^-$ $m(l^+l^-) > 160$ GeV

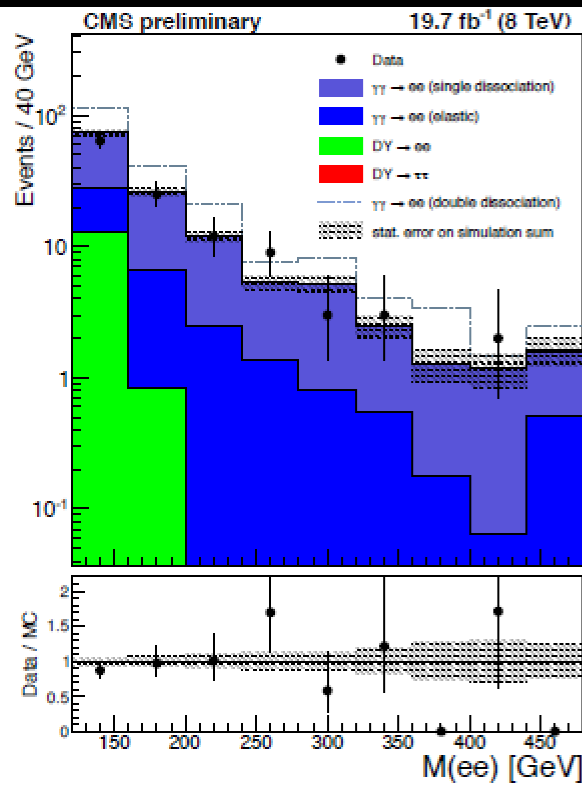
→ A correction factor is estimated from data / MC elastic

→ This factor applied to the predicted cross section for $\gamma\gamma\rightarrow W^+W^-$

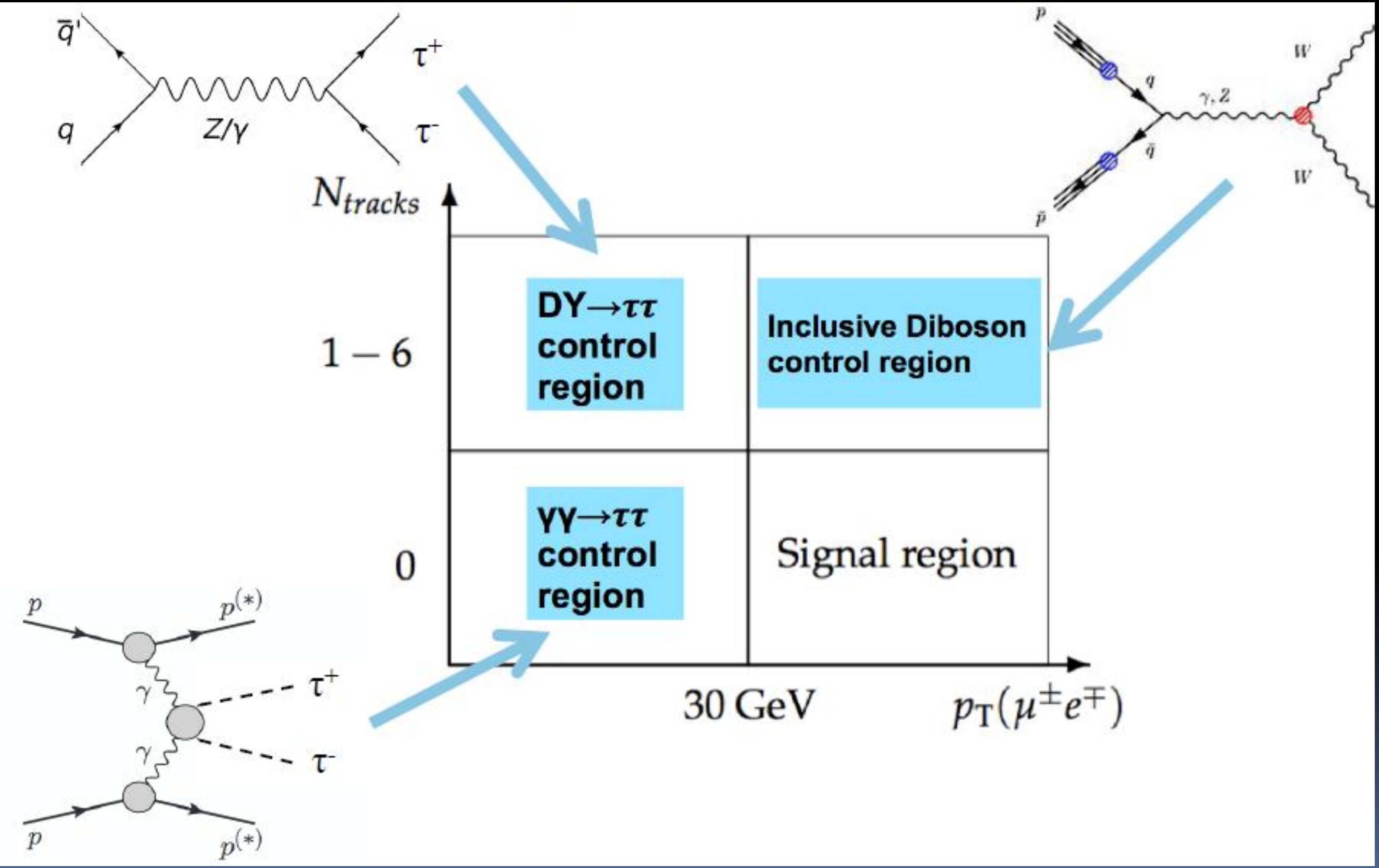
$$F = \left.\frac{N_{\mu\mu\ \text{data}} - N_{\text{DY}}}{N_{\text{elastic}}}\right|_{m(\mu^+\mu^-)>160\,\text{GeV}}$$

$$F = 4.10\pm0.43$$





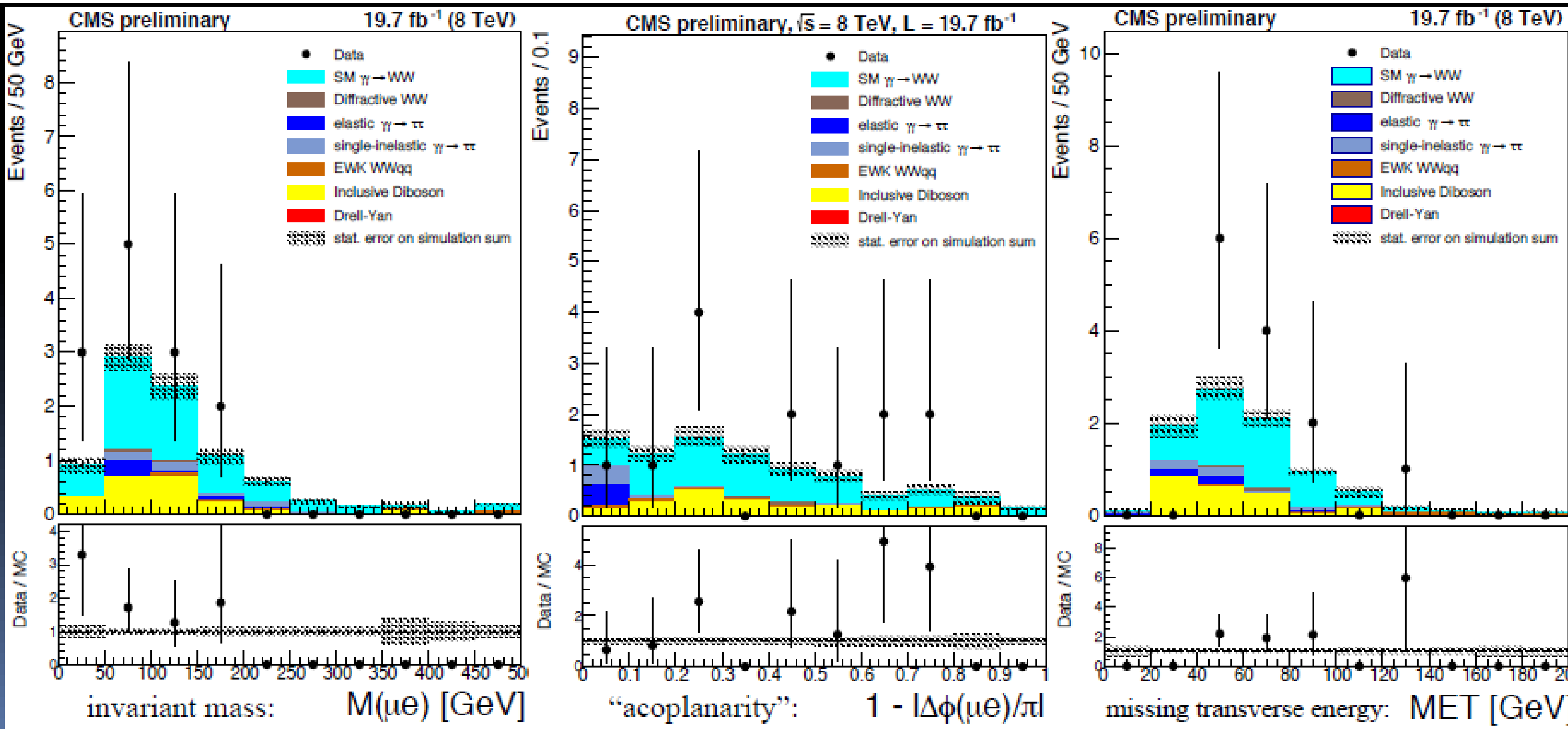
Signal and background $\gamma\gamma \to WW$



Signal and background $\gamma\gamma \rightarrow WW$

Number of expected signal and background events in simulation passing each selection step, normalized to an integrated luminosity of 19.7 fb^{-1} :

Selection step	Excl. $\gamma\gamma \rightarrow WW$	Total Background	WW+jets	$\gamma\gamma \rightarrow \tau\tau$	DY $\rightarrow \tau\tau$	Pompyt WW	Other Backgrounds
Trigger and preselection	26.9±0.2	12560±230	1057.5±8.1	18.1±0.8	7000±75	206.2±3.0	4280±210
$m(\mu^{\pm}e^{\mp}) > 20$ GeV	26.6±0.2	12370±220	1035.5±8.0	18.1±0.8	6974±75	202.2±3.0	4140±210
Electron and Muon ID	22.5±0.2	6458±93	1027.9±8.0	12.6±0.7	4172±58	197.2±2.9	1048±72
$\mu^{\pm}e^{\mp}$ vertex with 0 extra tracks	6.7±0.2	14.9±2.5	2.8±0.4	4.3±0.5	6.5±2.3	0.3±0.1	1.1±0.6
$p_T(\mu^{\pm}e^{\mp}) > 30$ GeV	5.3±0.1	3.5±0.5	2.0±0.4	0.9±0.2	0	0.1±0.1	0.5±0.2



Results $\gamma\gamma \to WW$

- 13 events observed
  - Expected 5.3 ± 0.1 signal plus 3.5 ± 0.5 background events
  - Data is 3.6 σ above background only hypothesis

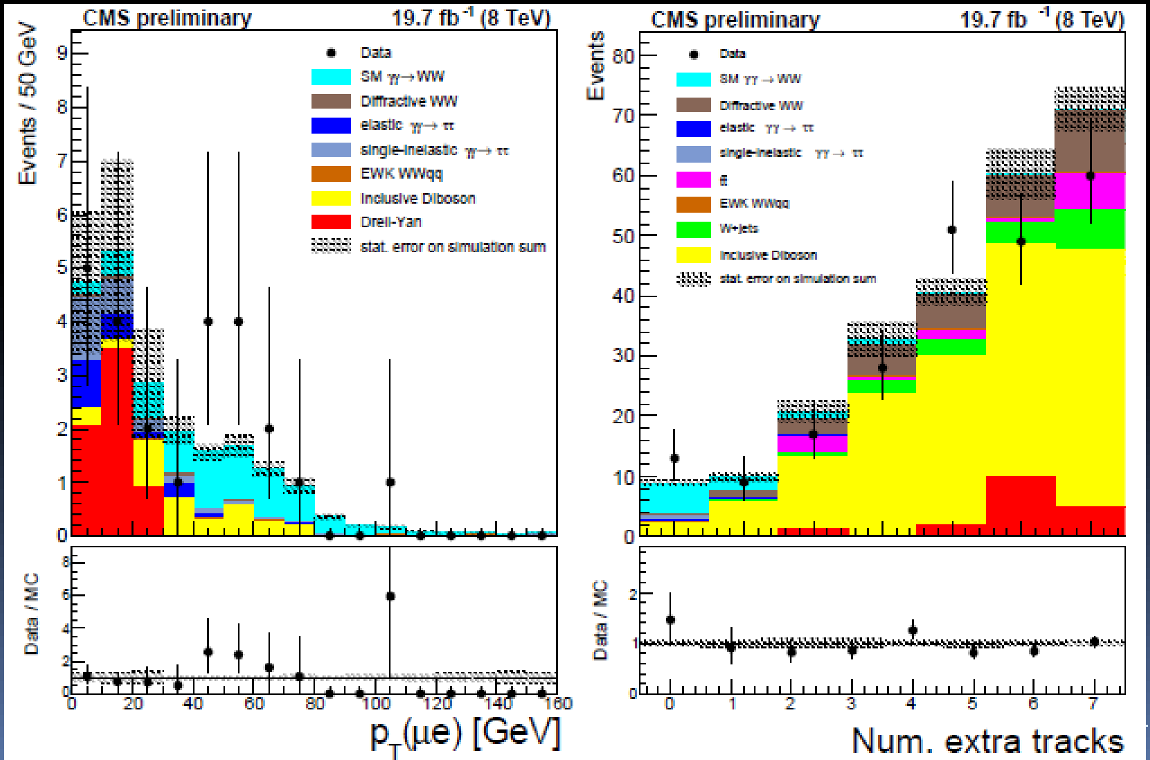
measured exclusive W^+W^- production cross section times branching ratio:

$$\sigma\ (pp \to p^{(*)}W^+W^-\ p^{(*)} \to p^{(*)}\mu^\pm e^\mp\ p^{(*)}) = 12.3^{+5.5}_{-4.4}\ \mathrm{fb}$$

- SM – 6.9 ± 0.6 fb

Search for AQGC $\gamma\gamma \to WW$

- Two bins are used looking for excess over SM
  - 30 GeV < $p_T(\mu^- e^+)$ < 130 GeV (SM dominated)
  - $p_T(\mu^- e^+)$ > 130 GeV (Anomalous dominated)



95% CL intervals $\gamma\gamma \to WW$

- Dimension 6 operators

$$-1.1\times10^{-4} < a_0^W/\Lambda^2 < 1.0\times10^{-4}\,\mathrm{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-4.2\times10^{-4} < a_C^W/\Lambda^2 < 3.4\times10^{-4}\,\mathrm{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}).$$

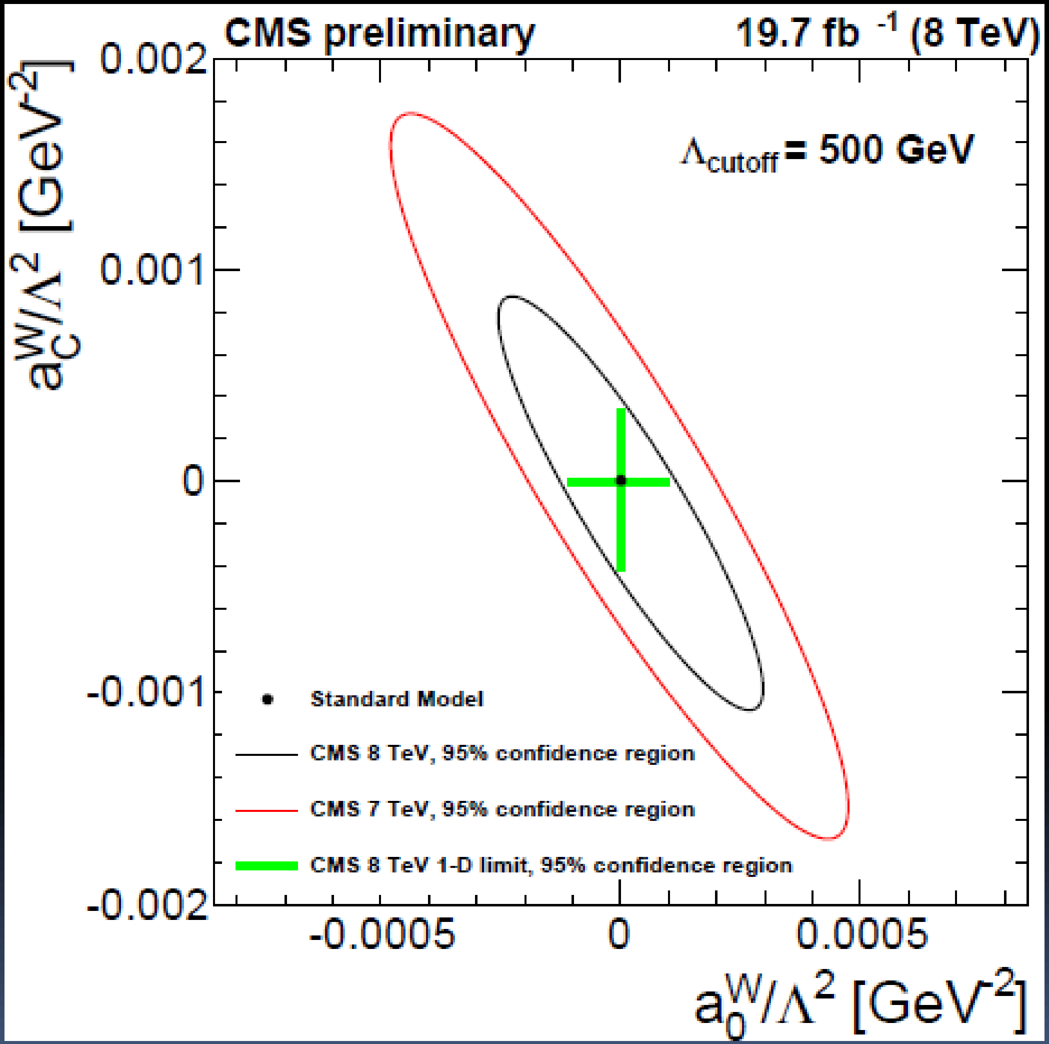
  - Compare to:

		OPAL (2004)	DØ (2013)	CMS (2013)
a_0^W/Λ^2	no form factor	$\pm2\times10^{-2}$	$\pm4.3\times10^{-4}$	$\pm4.0\times10^{-6}$
	$\Lambda_{\mathrm{cutoff}} = 500$ GeV		$\pm2.5\times10^{-3}$	$\pm1.5\times10^{-4}$
a_c^W/Λ^2	no form factor	$^{+3.7}_{-5.2}\times10^{-2}$	$\pm1.5\times10^{-3}$	$\pm1.5\times10^{-5}$
	$\Lambda_{\mathrm{cutoff}} = 500$ GeV		$\pm9.2\times10^{-3}$	$\pm5.0\times10^{-4}$

- Dimension 8 operators (new from 8 TeV data)

$$-4.2\times10^{-10} < f_{M,0}/\Lambda^4 < 3.8\times10^{-10}\,\mathrm{GeV}^{-4}\ (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-16\times10^{-10} < f_{M,1}/\Lambda^4 < 13\times10^{-10}\,\mathrm{GeV}^{-4}\ (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-2.1\times10^{-10} < f_{M,2}/\Lambda^4 < 1.9\times10^{-10}\,\mathrm{GeV}^{-4}\ (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-8.0\times10^{-10} < f_{M,3}/\Lambda^4 < 6.4\times10^{-10}\,\mathrm{GeV}^{-4}\ (\Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}).$$

95% 2D limits $\gamma\gamma \rightarrow WW$



Diffractive Dissociation @ 7 TeV

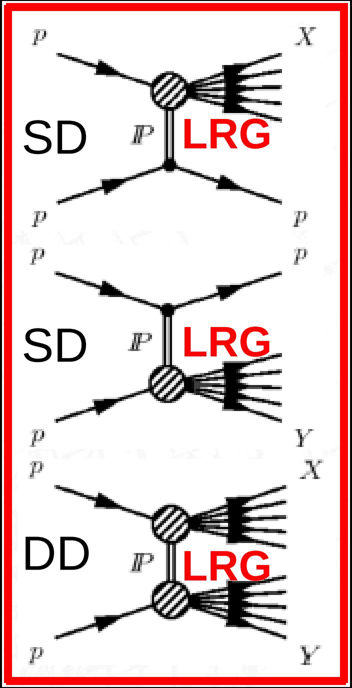
CMS PAS FSQ 12-005

Phys. Rev. D 92, 012003 (2015)

Measurement of diffractive dissociation

CMS PAS FSQ 12-005

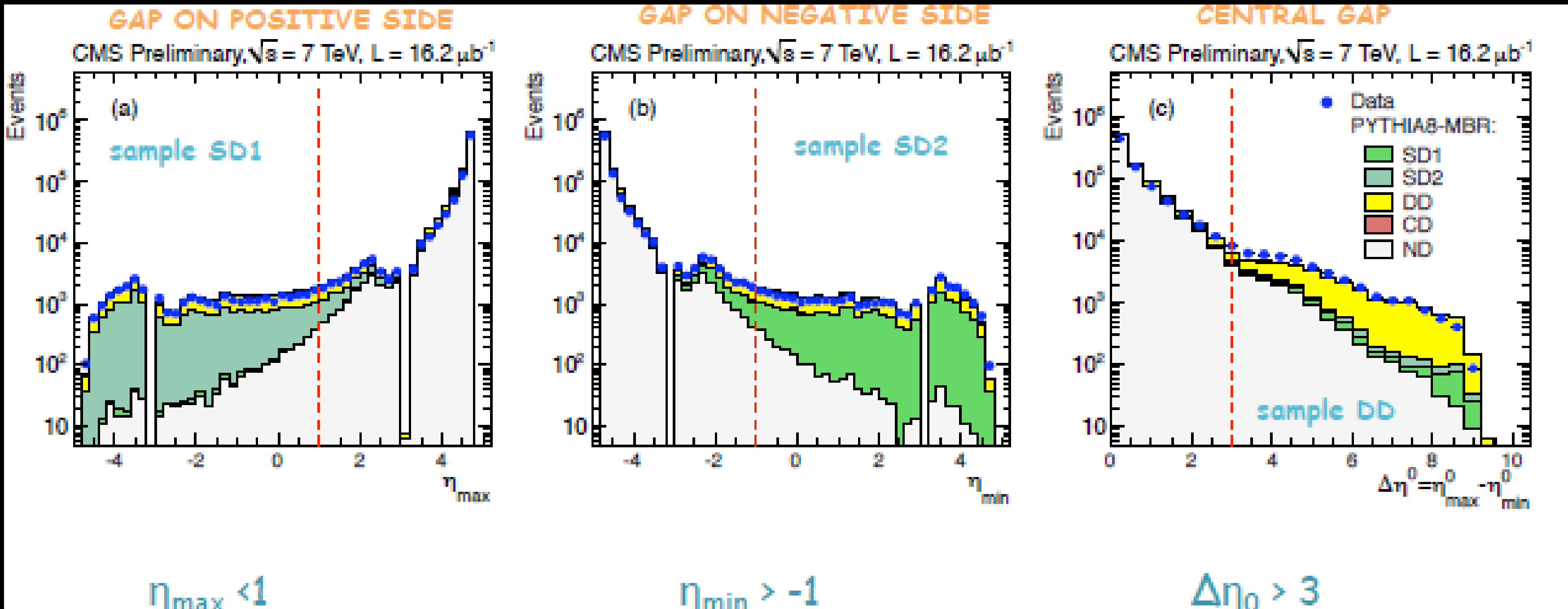
- ≈ 25% of inelastic cross section can be attributed to diffractive processes → LRG
- Description based on Regge type models
- Diffractive measurements important for improving models

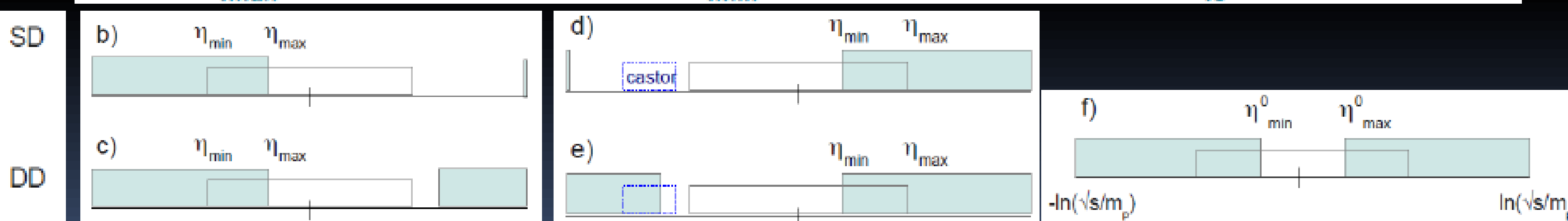


- Data sample – 16.5 μb^{-1} low pileup (μ=0.14) @ 7 TeV
  - Minimum bias trigger
    - Hit in both BPTX and either BSC
- Offline selection
  - Large Rapidity Gap (LRG) tagging
  - At least 2 PF objects in BSC acceptance
  - No vertex requirement (low mass)
- MC simulation
  - PYTHIA8-MBR – Minimum Bias Rockefeller model
  - PYTHIA8-4C – for systematic studies

Experimental Topologies

- Based on the LRG position





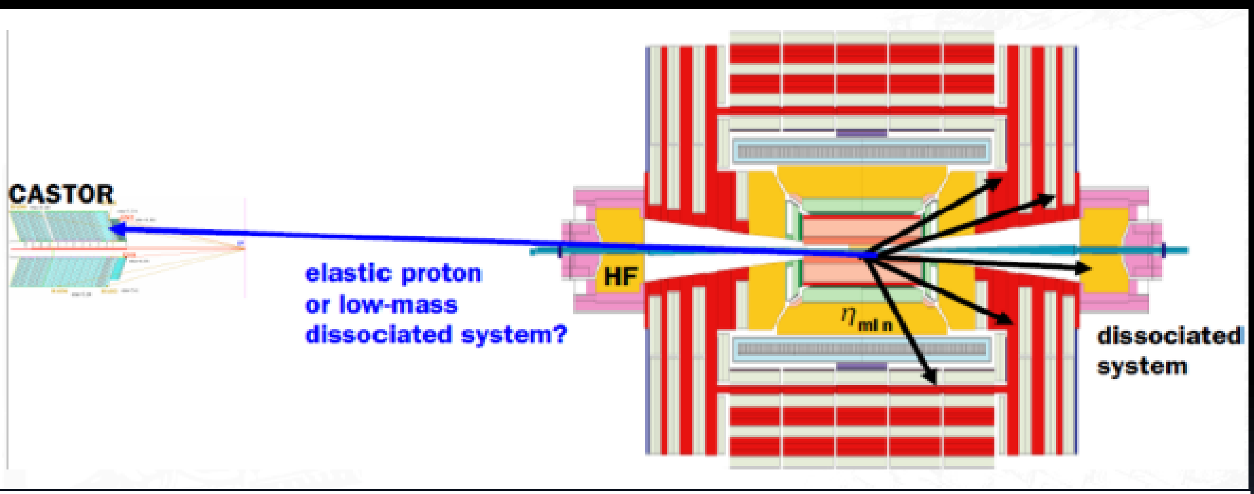
Control sample

SD & DD σ

DD σ

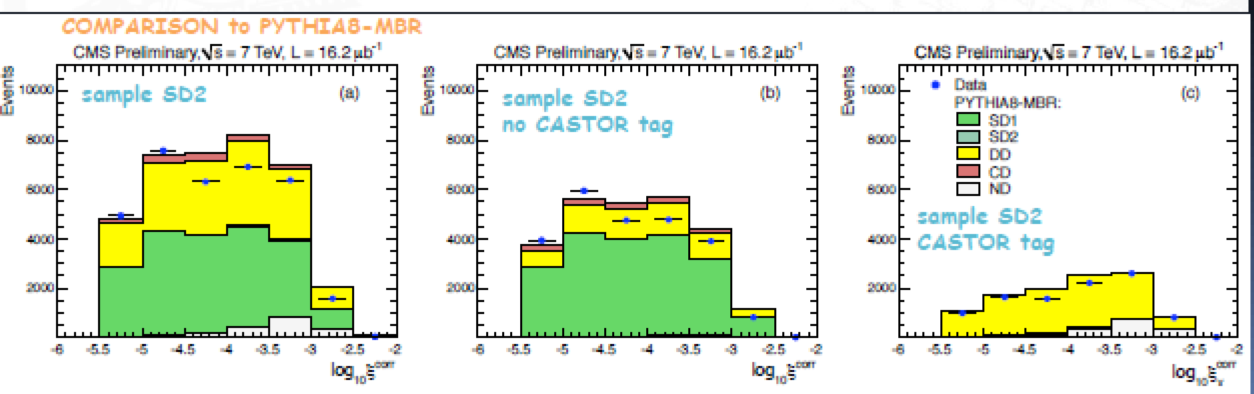
Detector level distributions

- Proton fractional momentum loss $\xi = M^2x/s$
  - M^2x – Mass of the dissociated system
- At detector level it is reconstructed as $\xi = \Sigma\, E^i - p^i_z/\sqrt{s}$
  - Sum over all PF objects
  - ξ corrected (MC) for undetected particles (low E, low η)



Castor tag selects low mass systems Mx ≈ 3.2 GeV

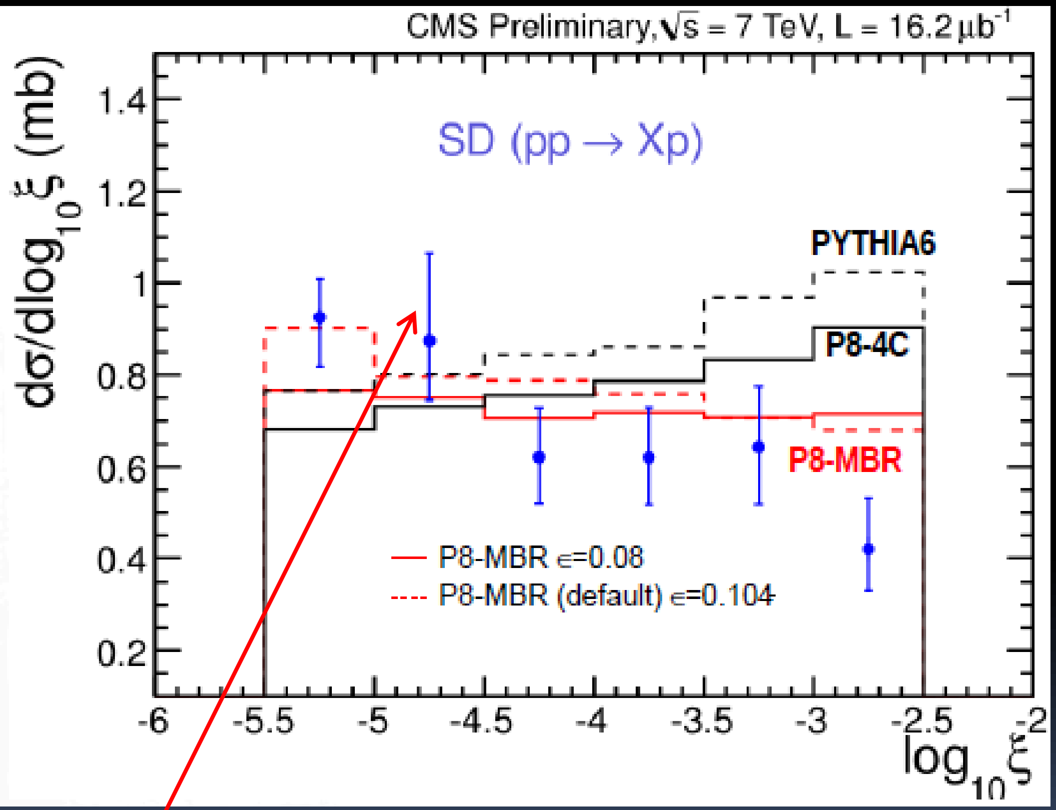
Separate SD & DD



Measurements: SD cross section

$$\frac{d\sigma^{SD}}{d\log_{10}\xi} = \frac{N^{data}_{noCASTOR} - (N_{DD} + N_{CD} + N_{ND})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi)_{bin}},$$

SD2 Sample only

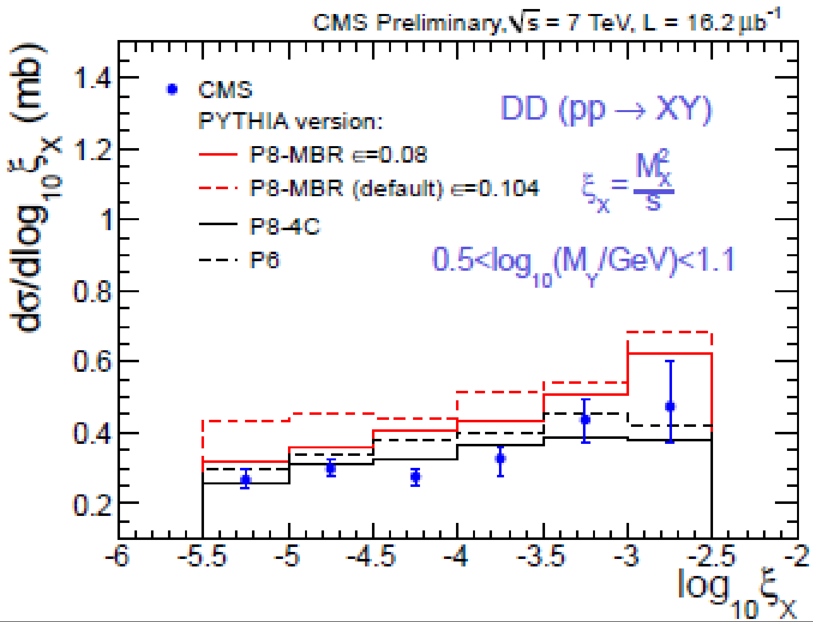


- SD falling behaviour well modeled by PYTHIA8-MBR
- PYTHIA8-4C and PYTHIA 6 do not follow the data trend
- Integrating over -5.5 < logξ < -2.5 (X 2)

$\sigma_{vis}^{SD} = 4.27 \pm 0.04 \text{ (stat)} \pm^{0.65}_{0.58} \text{ (syst) mb}$

- Systematic dominated by energy scale and background subtraction

Measurements: DD cross section

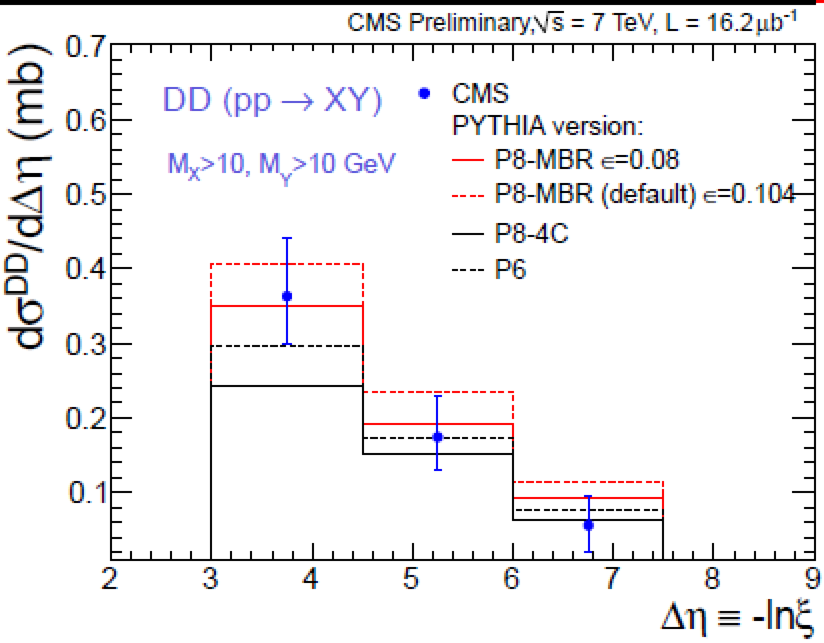


$$\frac{d\sigma^{DD}}{d\log_{10}\xi_X} = \frac{N^{data}_{CASTOR} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi_X)_{bin}}$$

SD2 Sample only

Trajectory with ε = 0.08 is favored in DD events

$$\alpha(t) = 1 + \varepsilon + \alpha' t,$$
$$\alpha' = 0.25\ \mathrm{GeV}^{-2}$$



$$\frac{d\sigma^{DD}}{d\Delta\eta} = \frac{N^{data} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta\eta)_{bin}}$$

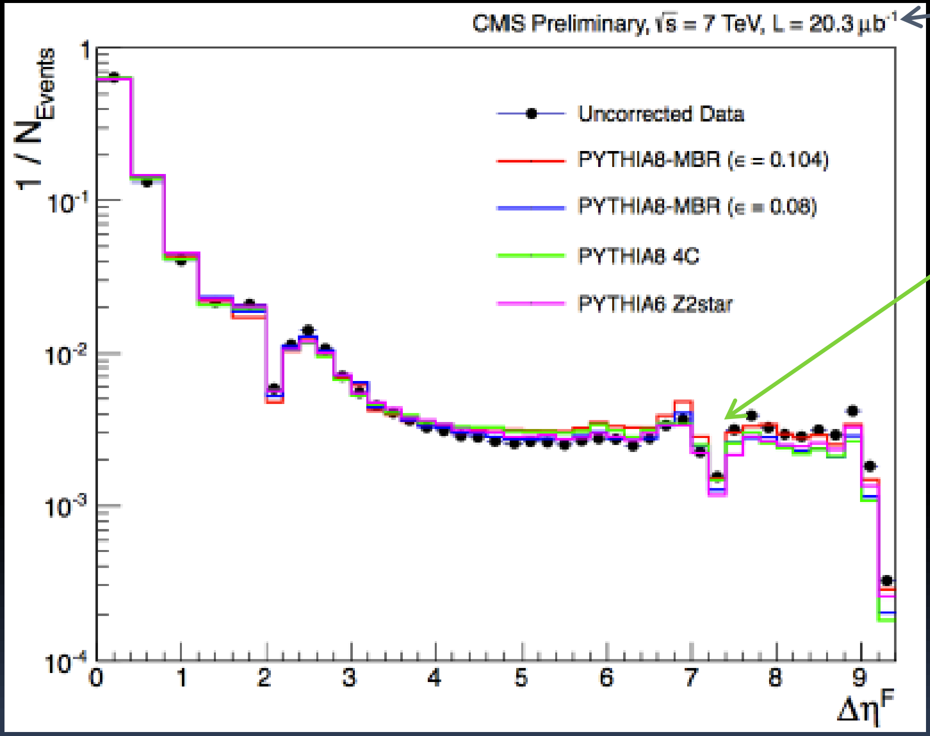
DD Sample only

- Integrating over $\Delta\eta > 3$ and Mx,y > 10 GeV

$\sigma_{vis}^{DD} = 0.93 \pm 0.01\ (\mathrm{stat}) \pm {}^{0.26}_{0..22}\ (\mathrm{syst})$ mb

Measurements: LRG cross section

- Difficult to measure the whole Mx → measure size of LRG
  - Inclusive – measure the largest forward gap $\Delta\eta_F = \max(4.7-\eta_{max}, 4.7+\eta_{min})$
  - largest gap between each edge of the detector and the position in η of the first particle moving away from the edge



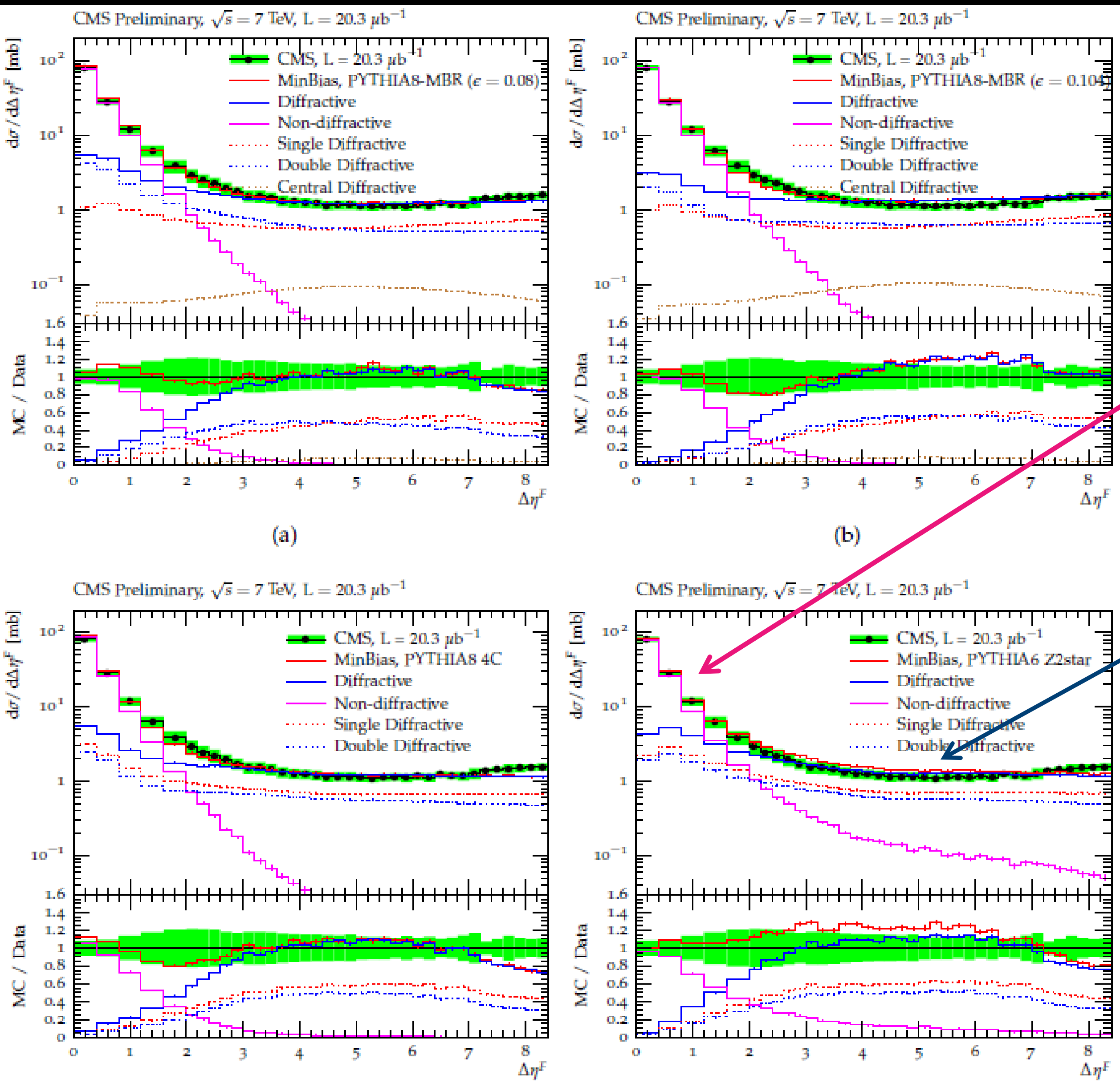
Larger data sample
Negligible pileup

Uncorrected distribution

Has to be corrected by detector resolution and beam backgrounds

$$\frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} = \frac{A(\Delta\eta^F)}{\Delta\eta_{bin}} \frac{N(\Delta\eta^F) - N_{BG}(\Delta\eta^F)}{\epsilon(\Delta\eta^F) \times \mathcal{L}}$$

Measurements: LRG cross section



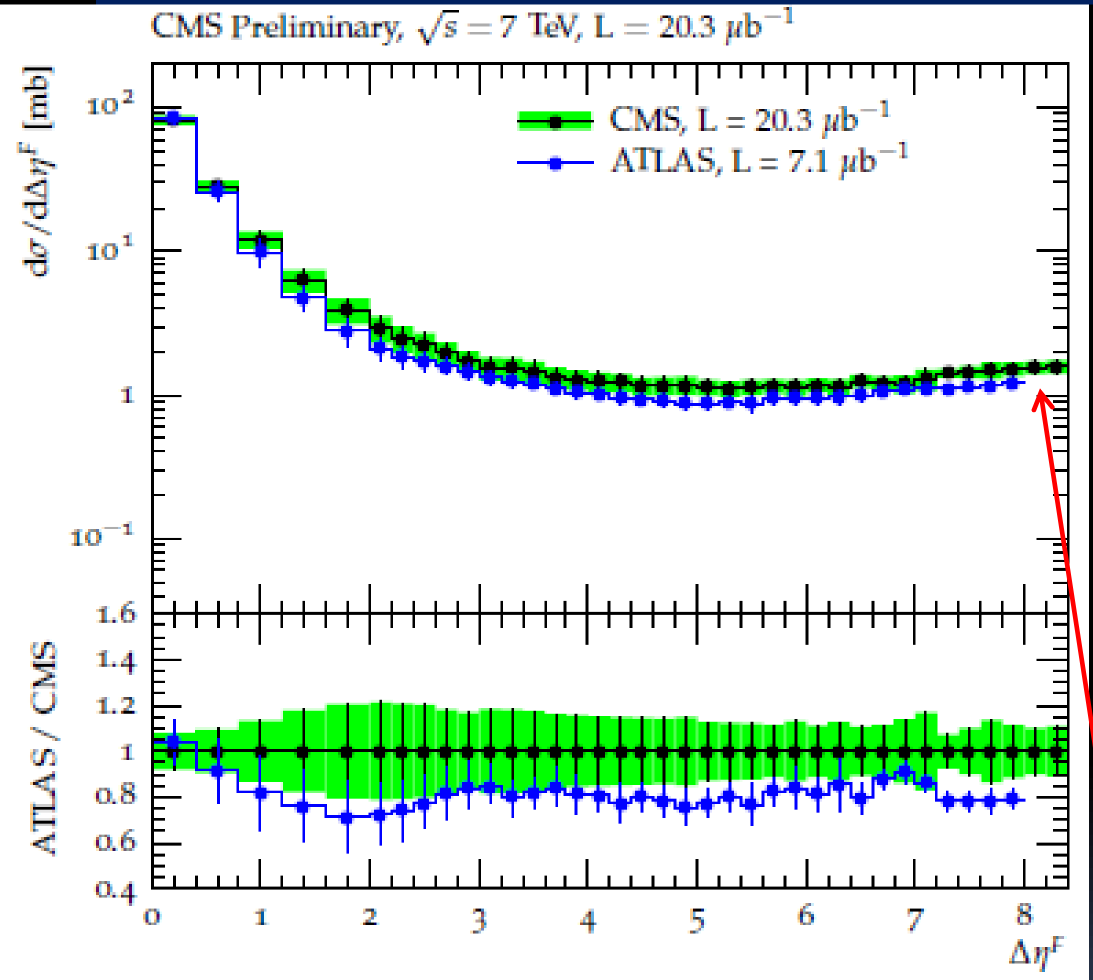
Unfolded and fully corrected distribution compared to MC

Exponential suppression (ND)

Diffractive plateau ~ 1mb/ $\Delta\eta_F$

Best description of the data by PYTHIA8-MBR with smaller intercept

Measurements: LRG cross section



Comparison with ATLAS

- Different hadron level definition: |η| < 4.7 (CMS) vs |η| < 4.9 (ATLAS)
→ up to 5% effect

- Unfolding based on different MCs: PYTHIA8-MBR (CMS) vs PYTHIA8 (ATLAS)
→ up to 10% effect

→ Agreement within uncertainties

→ CMS result extends ATLAS measurement by 0.4 unit of gap size

Z+jets and γ + jets production @ 8 TeV

CMS PAS SMP-14-005

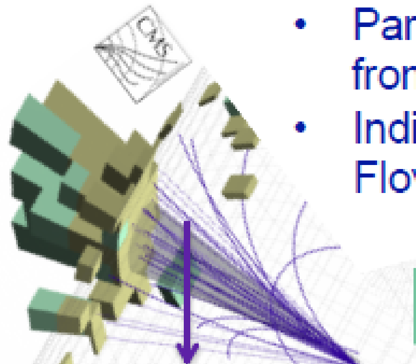
Z+jets / γ + jets Motivation

- Important test of the SM as well BSM searches
  - NLO calculation available (BLACKHAT)
  - Cross section ratio useful for estimate higher order effects
  - Can help reduce uncertainties on Z -> invisible
    - Used in BSM searches
  - Measure cross sections and ratio as function of p_T
- Data sample & selection
  - 19.7 fb^{-1} collected @ 8 TeV
  - Trigger on high p_T isolated leptons (Z -> l^+l^-) and photons (~17 GeV)
  - Offline
    - $m(l^+l^-)$ compatible with a Z boson (71 GeV< $m(l^+l^-)$ <111 GeV)
    - photons in barrel ($|\eta| < 1.4$)
    - PF-jets, anti-k_T clustering R=0.5, p_T>30 GeV
  - Z+jets and γ+jets analyzed separately
  - Comparison with MADGRAPH+PHYTHIA 6(LO+PS+K_{FEWZ}) and BLACKHAT

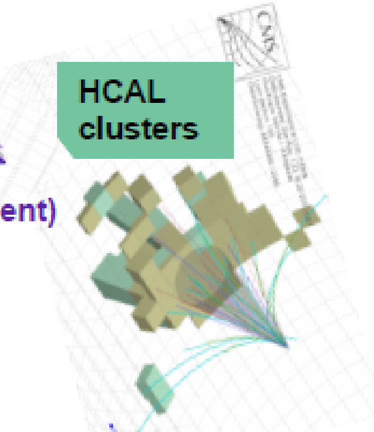
Jet Reconstruction @ CMS

CMS

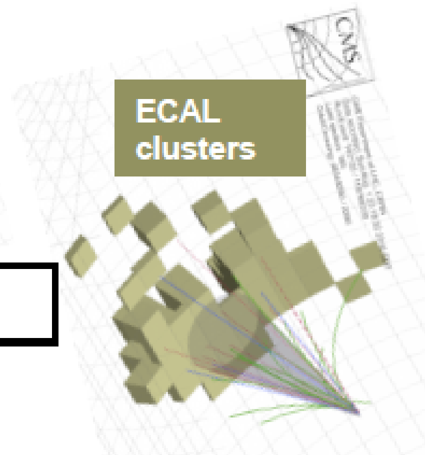
- Particle Flow Algorithm combines all information from several sub-detector systems
- Individual particles are reconstructed with Particle Flow Algorithm and then clustered into jets.



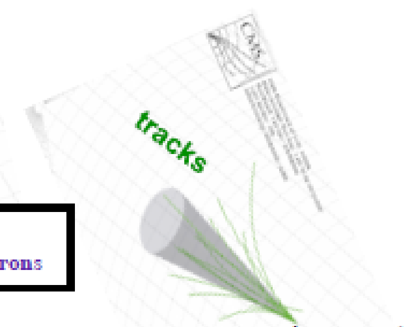
HCAL+ECAL+Tracker info
μ, $e^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, p, K^0, π^0,…



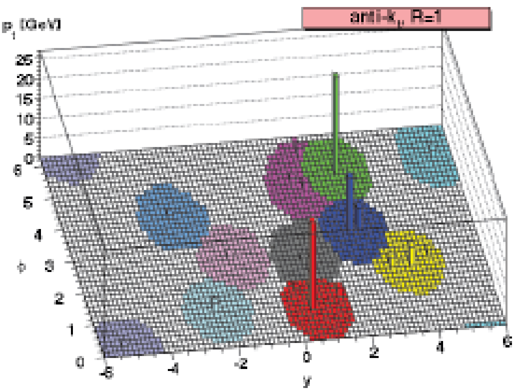
HCAL info
Charged and neutral hadrons



ECAL info
$e^{\pm}$, γ and neutral and charged hadrons



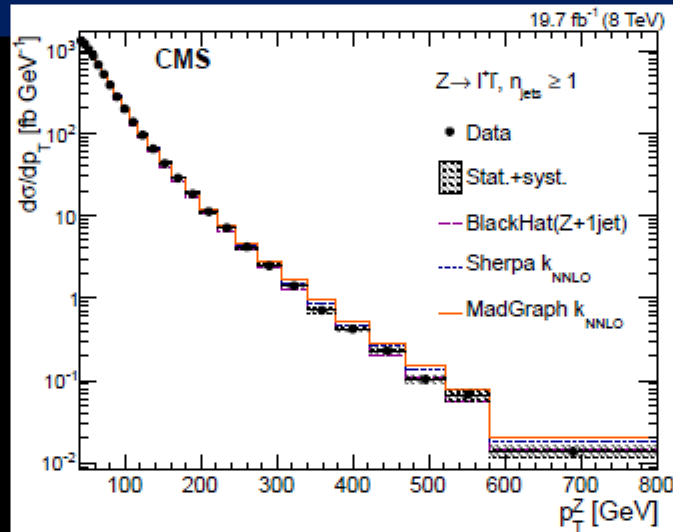
Silicon Tracker info
μ, $e^{\pm}$, and all charged hadrons

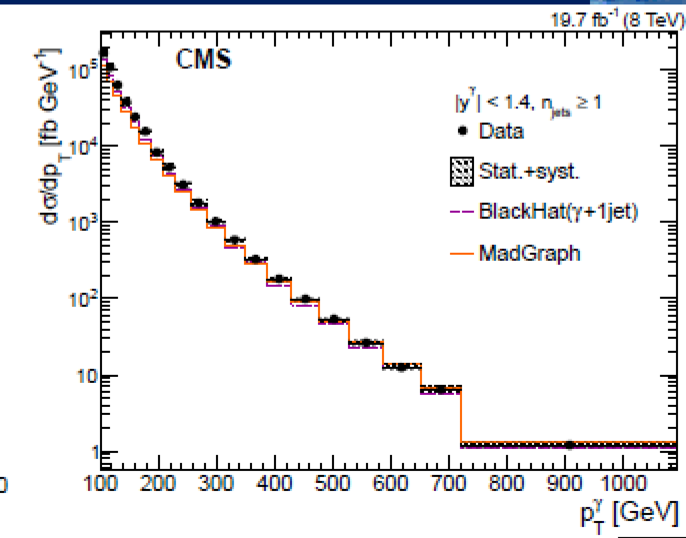


Anti-kt clustering algorithm : with R = 0.5
It is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

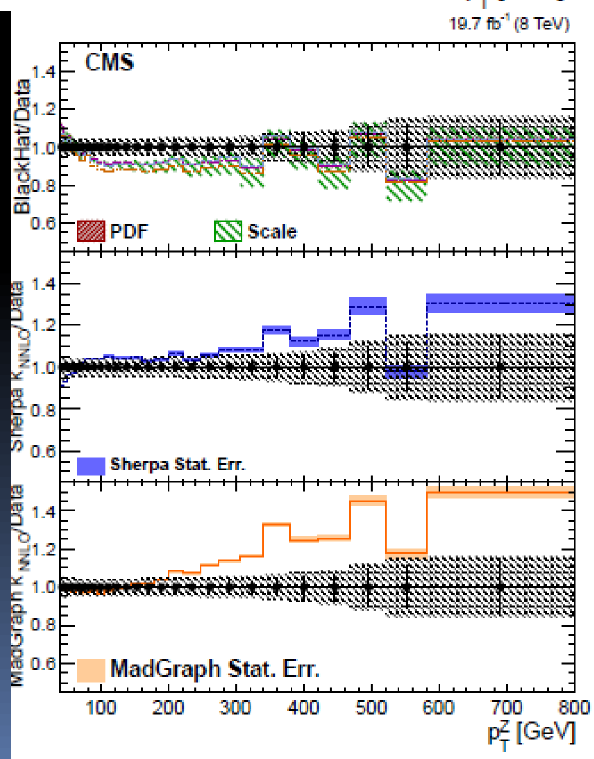
Z+jets / γ+jets Measurements

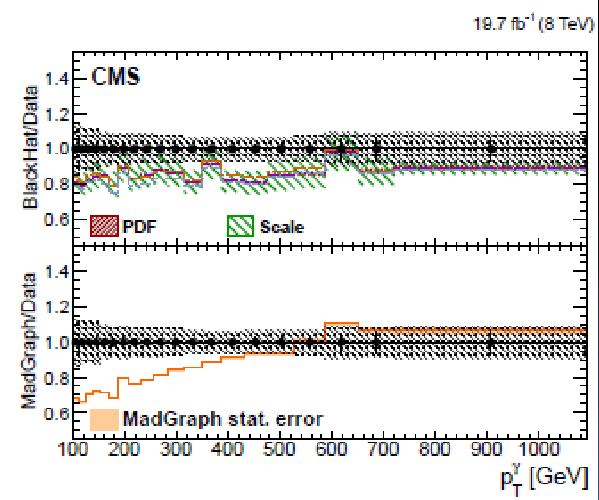
- Z/γ + ≥1 Jet





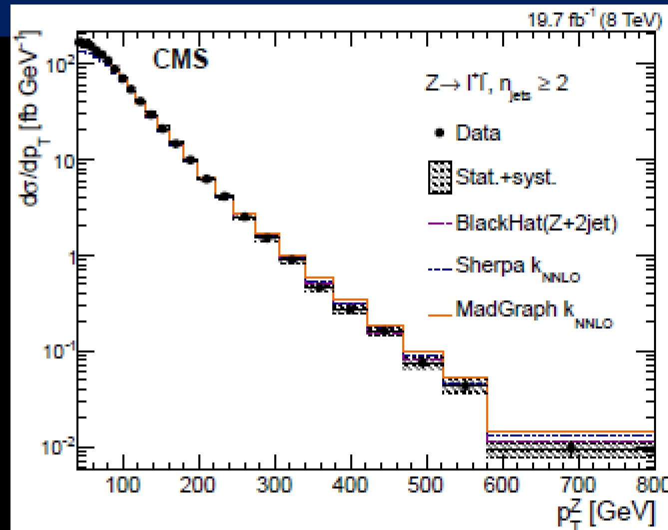
- BLACKHAT
  - Mostly flat
  - Underestimate at low p_T
- MADGRAPH
  - Increase w/ p_T
  - Overestimate at high p_T

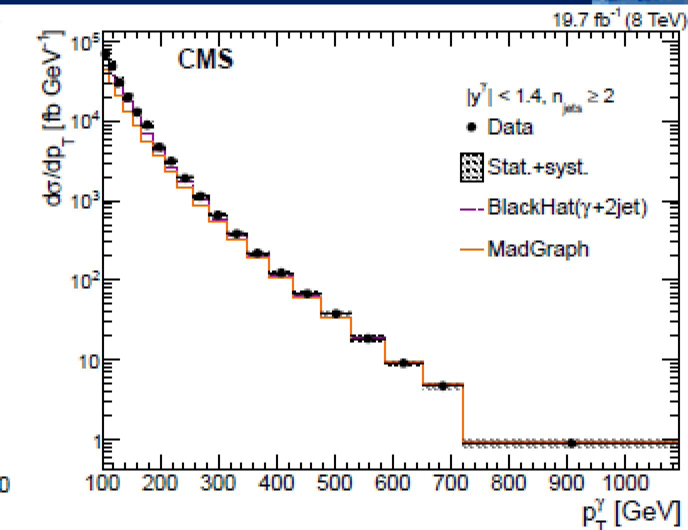


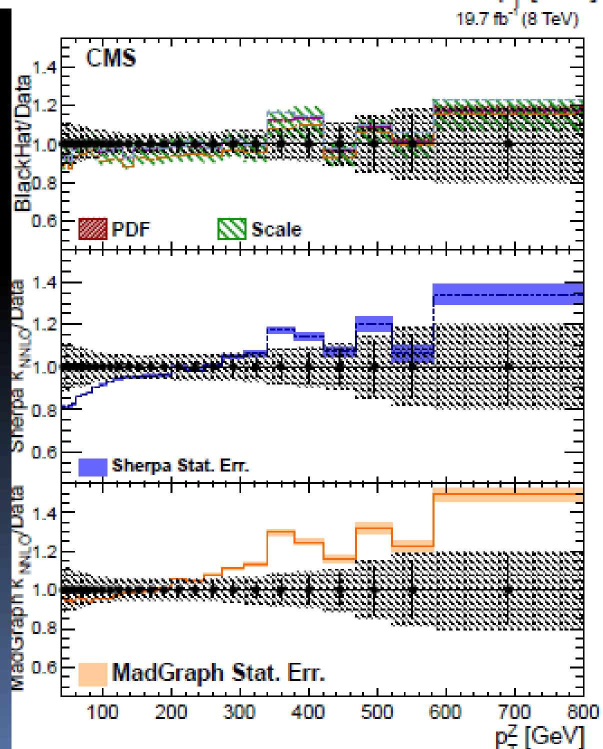


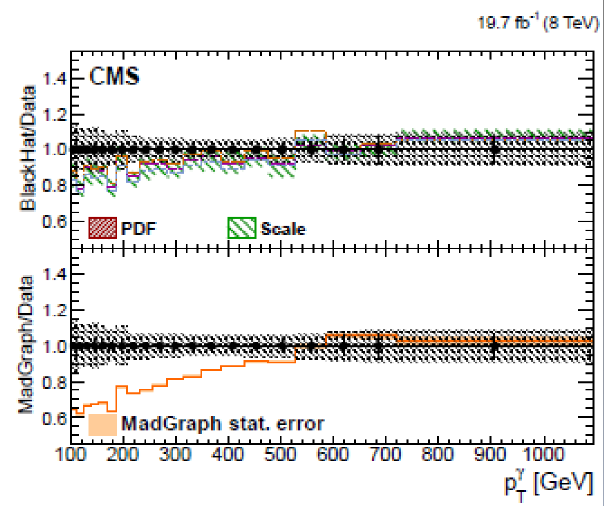
Z+jets /γ+jets Measurements

- Z/γ + ≥2 Jets
- Same behavior







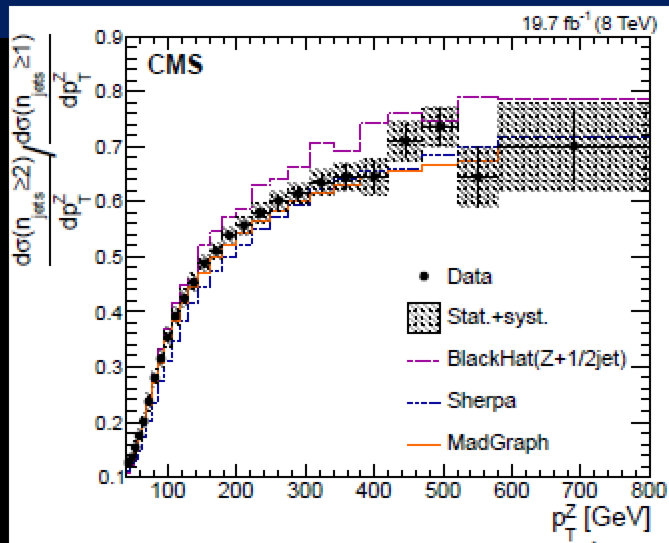


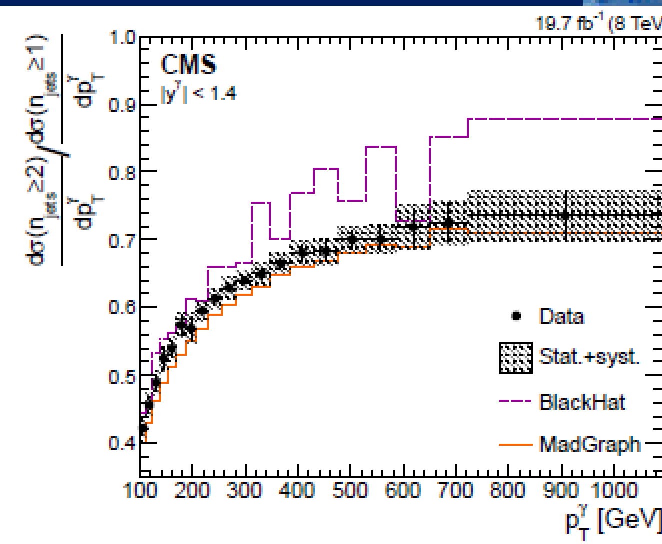
Z+jets / γ + jets Ratio Measurements

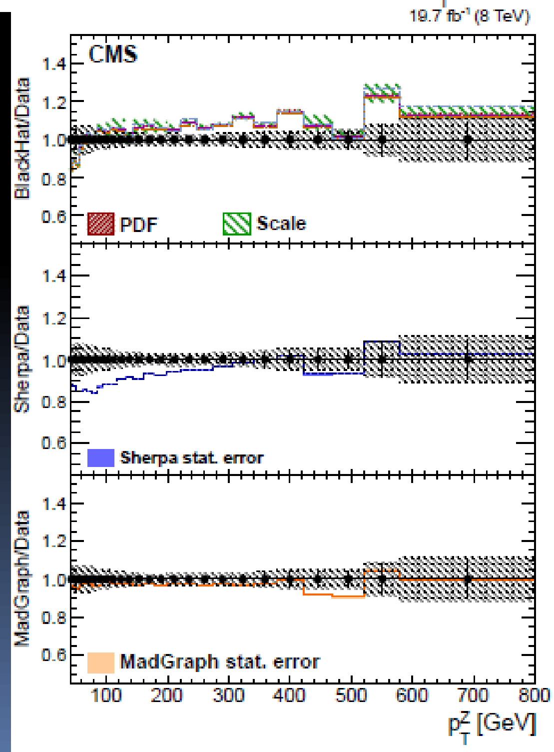
- Z/γ + ≥2 Jets /
  Z/γ + ≥1 Jets

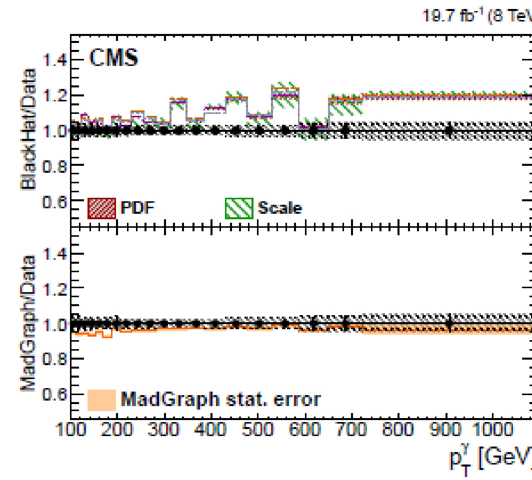
- BLACKHAT
  - Overestimate at high p_T

- MADGRAPH
  - Good agreement



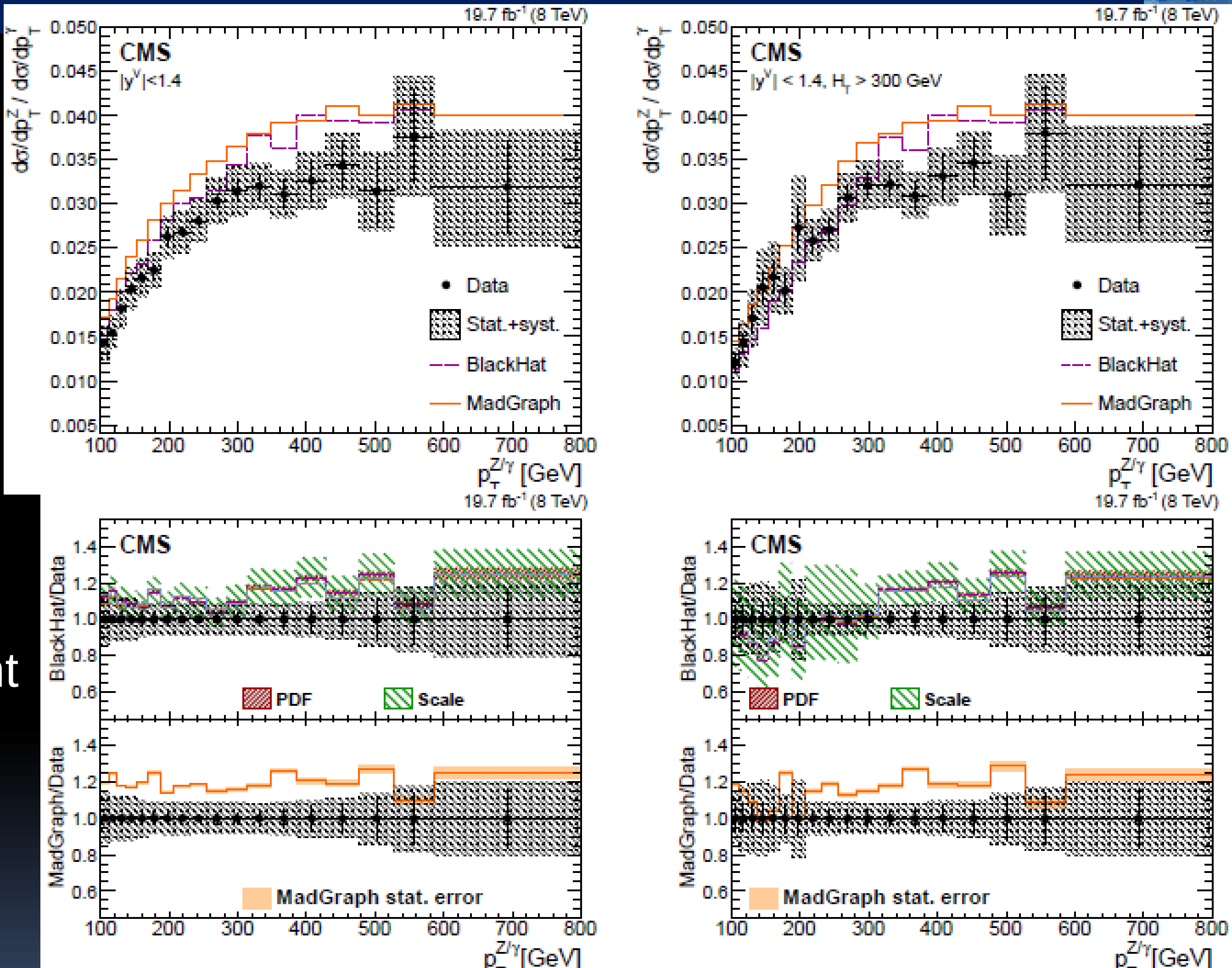






Z+jets / γ + jets Ratio of cross sections

- H_T – scalar p_T sum of all jets
- H_T > 300 GeV used in BSM analysis



- Both MC
  - Overestimate
  - Shape agreement
- Ratio @ plateau

$$R_{\text{dilep}} = \frac{\sigma_{Z\to\ell^+\ell^-}(p_T^Z > 314\,\text{GeV})}{\sigma_\gamma(p_T^\gamma > 314\,\text{GeV})} = 0.0322 \pm 0.0008\,(\text{stat}) \pm 0.0020\,(\text{syst}).$$

Drell -Yan in association with jets

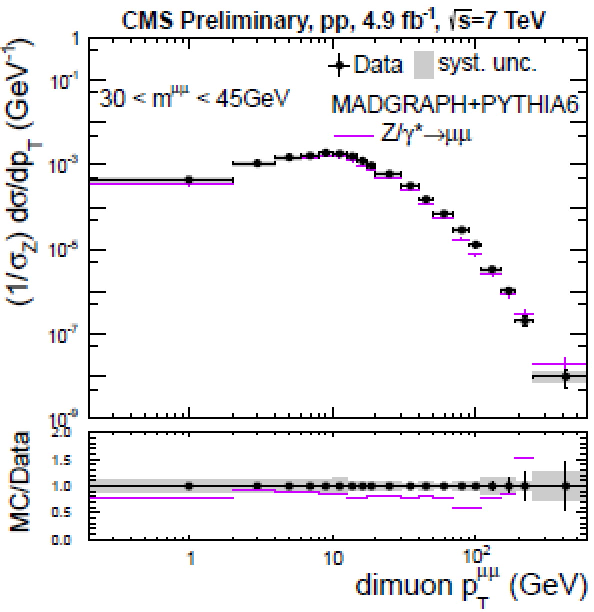
CMS PAS FSQ-13-003

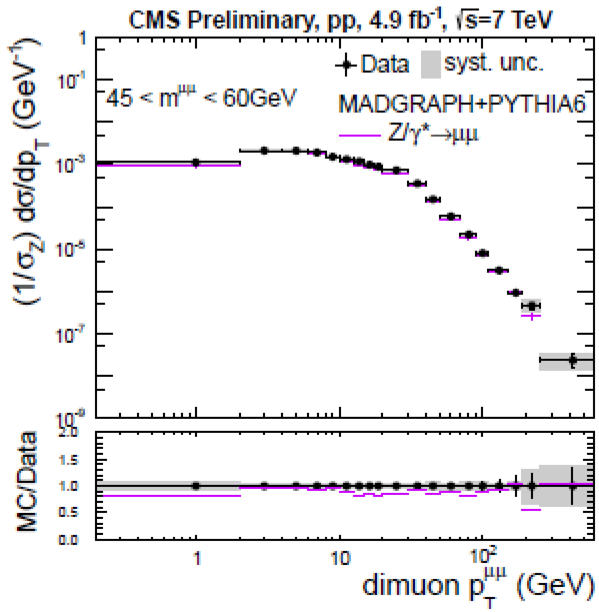
Drell-Yan in association with jets

- DY lepton pair production
  - Well defined in SM (NNLO in pQCD)
  - At small p_T requires soft gluon resummation in all orders
  - DY in association w/ jets shift the pT spectrum
    - Allows resummation effects calculation in perturbative regime
- DY + jets at high mass (~125 GeV)
  - Important for Higgs production comparison

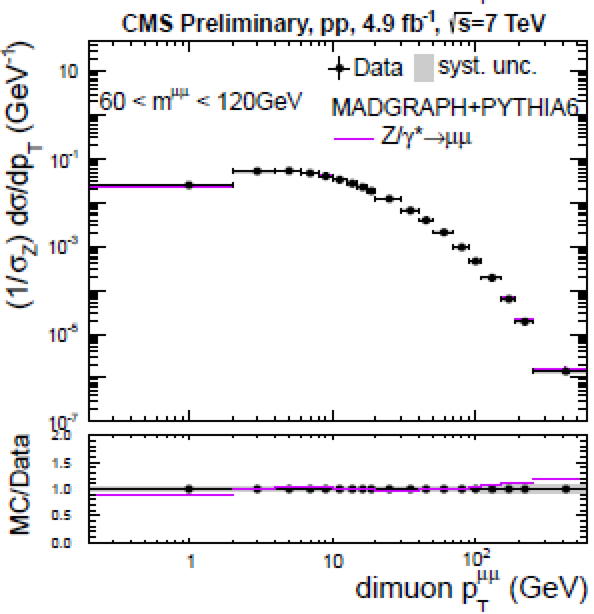
- Data sample and selection
  - 4.9 fb^{-1} collected @ 7 TeV
  - Trigger on 2 high p_T isolated muons (p_T^{lead} > 20 GeV, $p_T^{sublead}$ >10 GeV)
  - Offline
    - 30 GeV < $m(\mu^+\mu^-)$ < 1500 GeV
    - 2 muons w/ $|\eta| < 2.1$; Jets w/ $|\eta| < 4.5$
    - PF-jets, anti-k_T clustering R=0.5, p_T>30 GeV
  - Comparison with MADGRAPH+PHYTHIA 6(LO+PS)

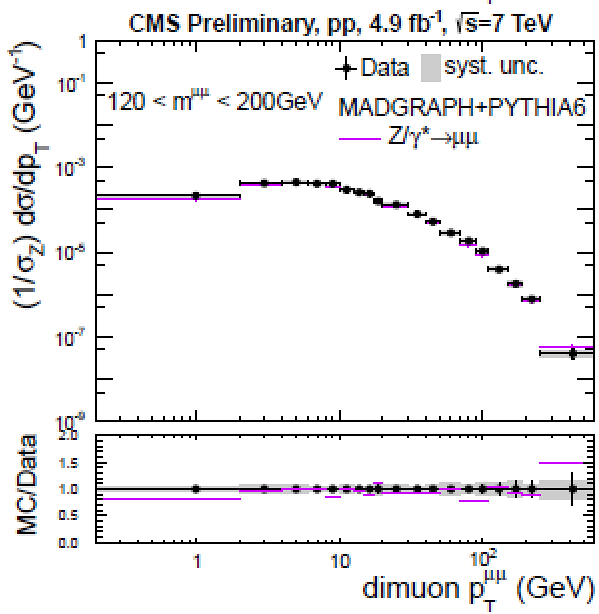
Inclusive Drell-Yan -> $\mu^+\mu^-$

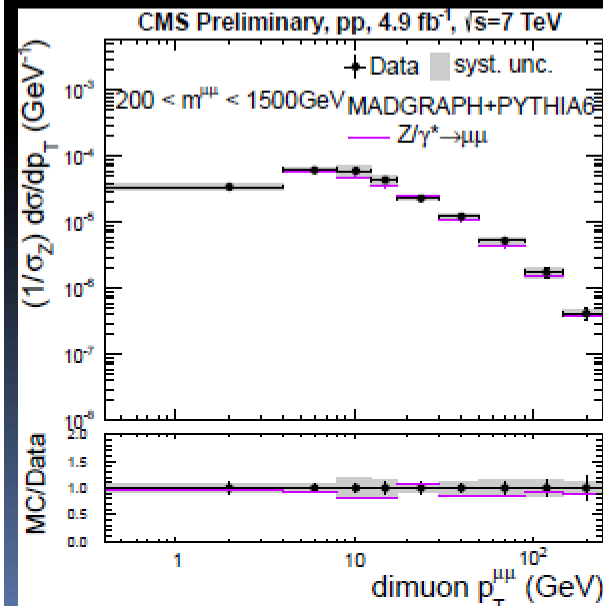




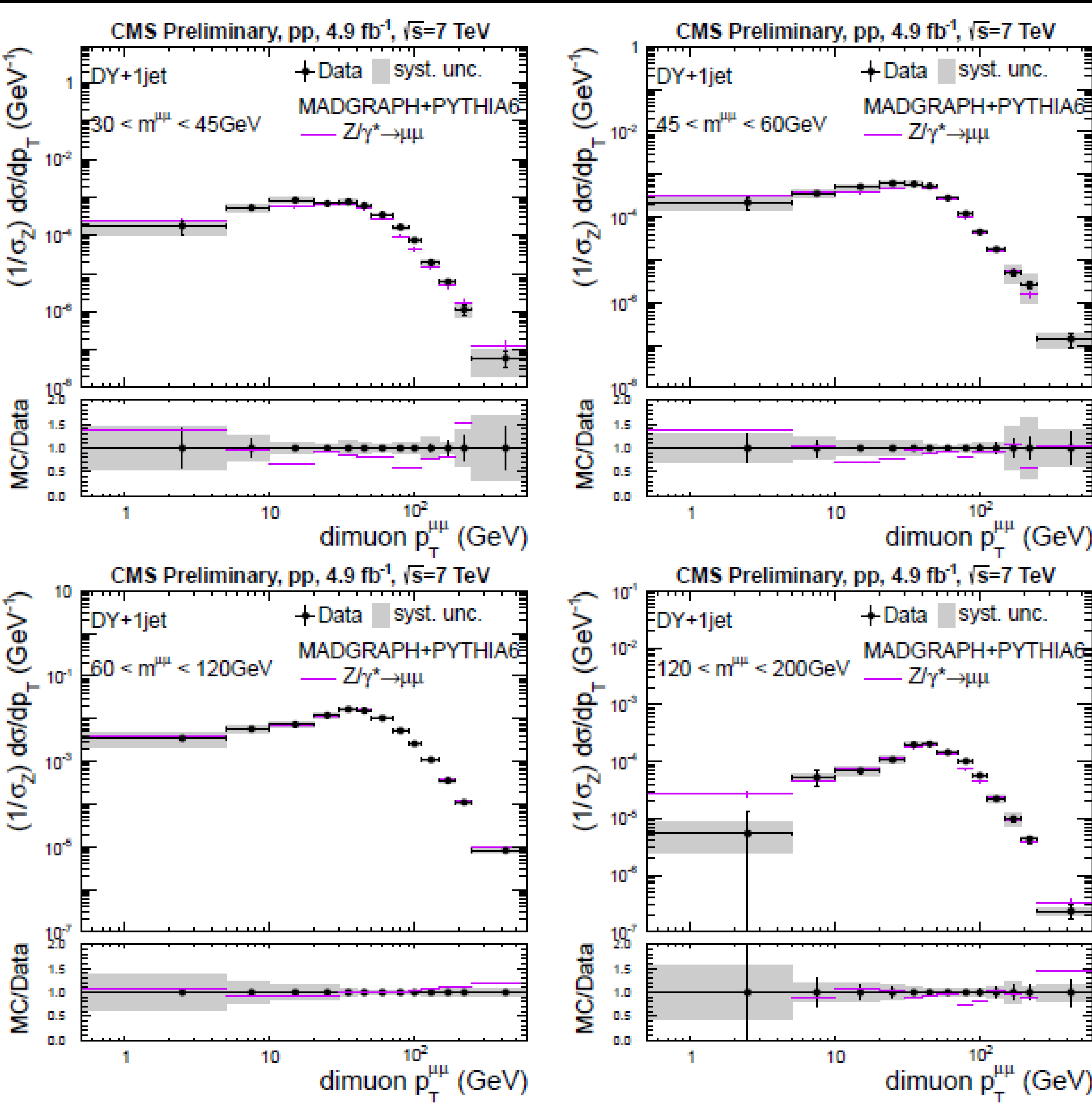
- MADGRAPH + PYTHIA6 tune Z2
  - Good agreement overall
  - Discrepancy at low mass bin
  - Rising behavior -> gluon resummation



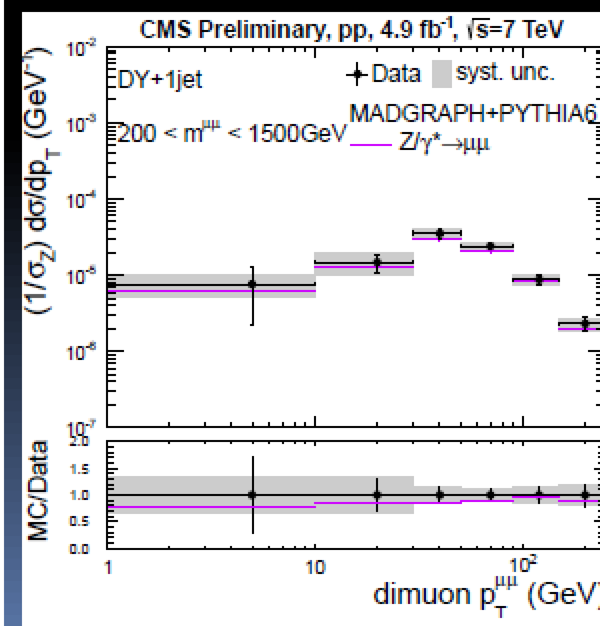




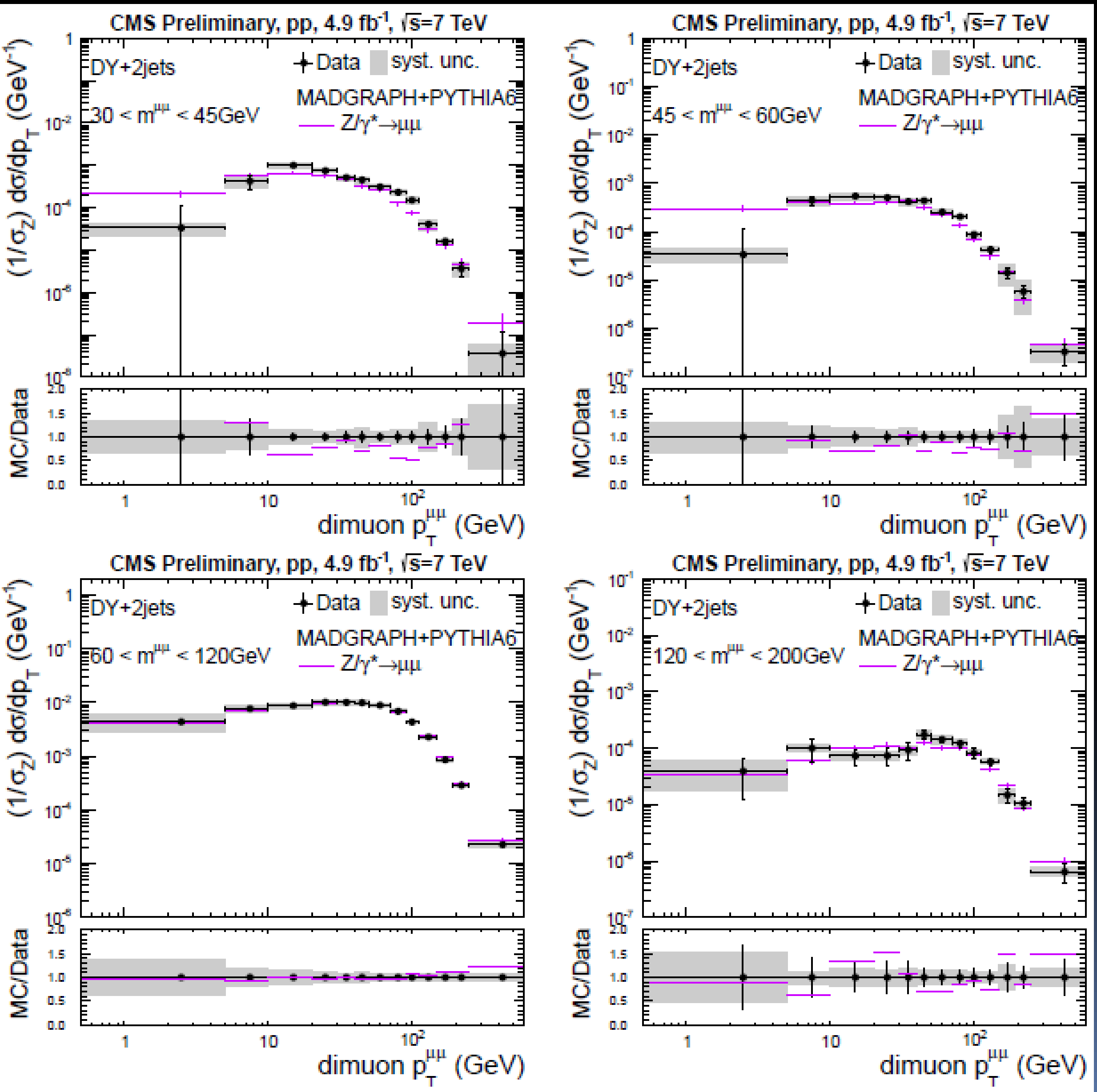
Drell-Yan -> $\mu^+\mu^-$+ 1 Jet



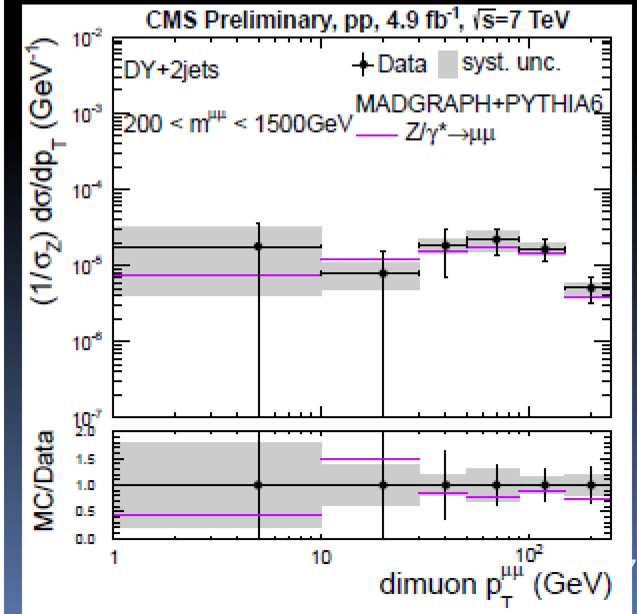
- MADGRAPH + PYTHIA6 tune Z2
  - Good agreement overall
  - Rising behavior -> gluon resummation shifted to higher p_T



Drell-Yan -> $\mu^+\mu^-$+ 2 Jets

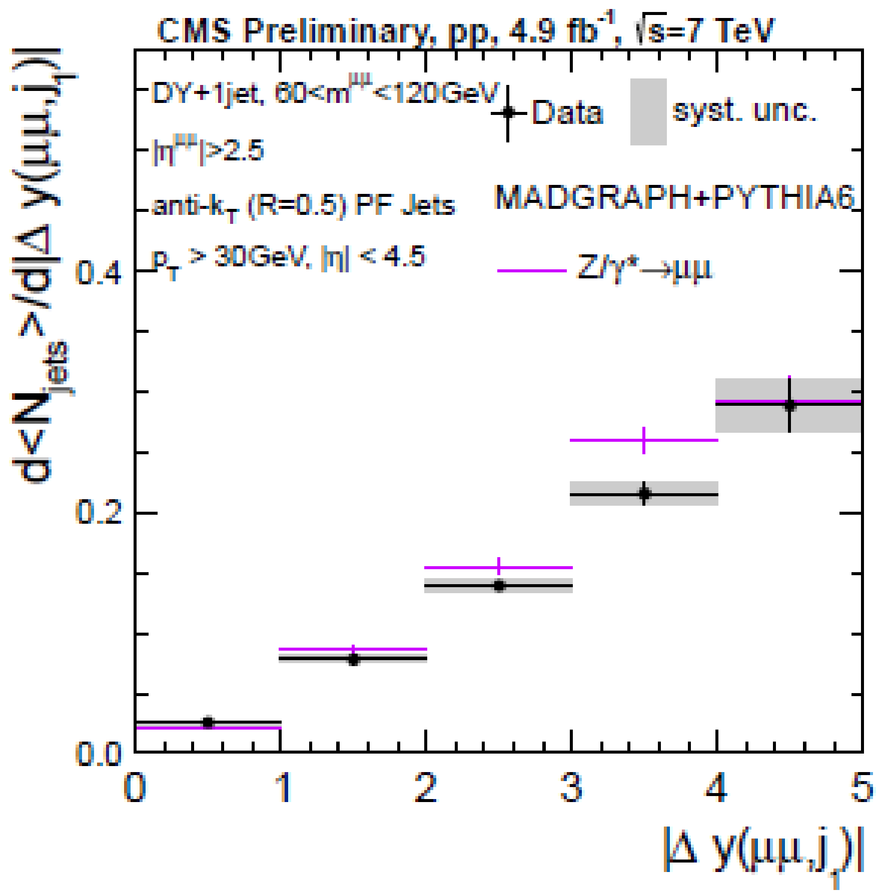


- MADGRAPH + PYTHIA6 tune Z2
  - Good agreement overall
  - Rising behavior -> gluon resummation shifted to higher p_T



Jet Multiplicity in Drell-Yan +Jets

- Average number of jets in forward Drell-Yan production as function of rapidity separation
- $\Delta y(\mu\mu, j_1)$ DY dimuon and leading jet separation
  - increase in jet multiplicity in data is slower than predicted from the simulation



Conclusions

- CMS measured diffractive and EM processes at the LHC
- Exclusive processes
  - Standard candle $\gamma\gamma \rightarrow l^+l^-$ used to correct for proton dissociation
  - *Evidence for $\gamma\gamma \rightarrow WW$* → 13 candidates → agreement with SM

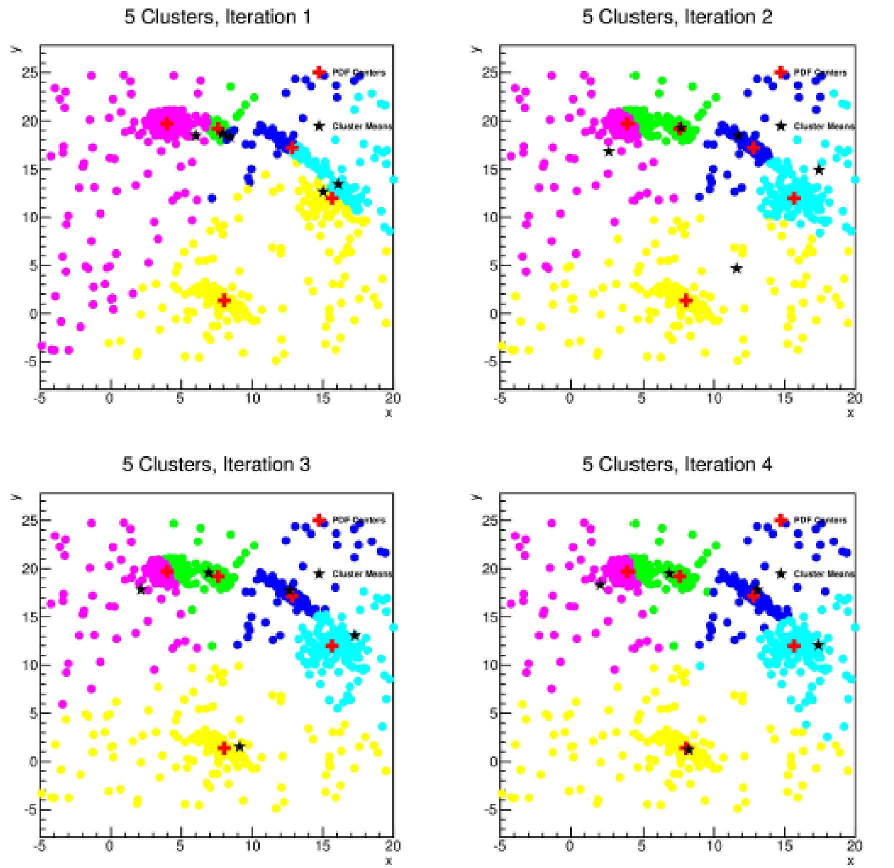
$$\sigma\,(pp \rightarrow p^{(*)}W^+W^-\,p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}\,p^{(*)}) = 12.3^{+5.5}_{-4.4}\ \text{fb}$$

  - AQGC limits two orders of magnitude more stringent than LEP and Tevatron
- Diffractive cross sections measured at 7 TeV
  - $\sigma_{vis}^{SD} = 4.27 \pm 0.04(stat.) + 0.65/-0.58(syst.)$ mb for $-5.5 < \log \xi < -2.5$
  - $\sigma_{vis}^{DD} = 0.93 \pm 0.01(stat.) + 0.26/-0.22(syst.)$ mb for $\Delta\eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV
  - Good agreement with ATLAS on LRG cross section
- *Z+jets / γ + jets Measurements*
  - Ratio overestimated by MC

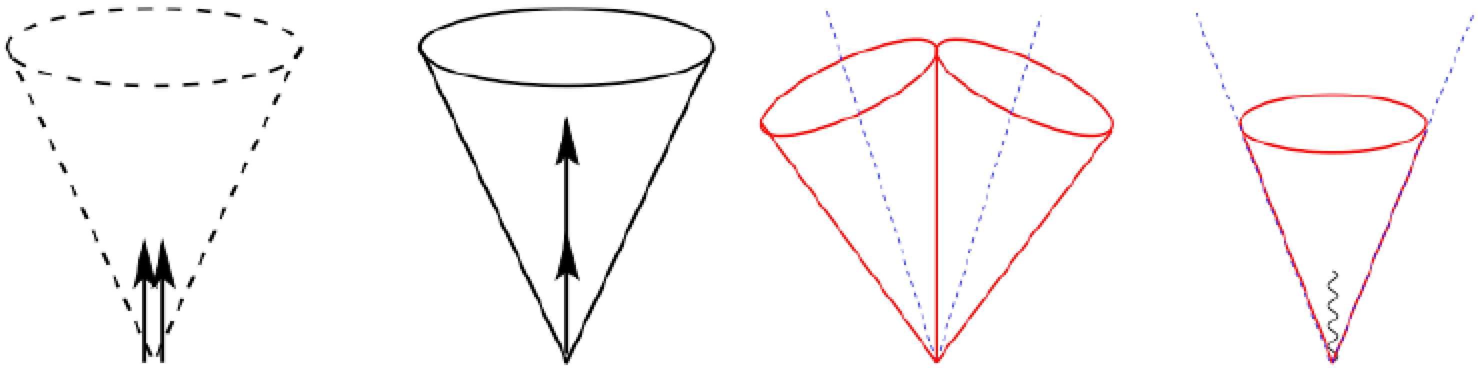
$$R_{\text{dilep}} = \frac{\sigma_{Z\rightarrow\ell^+\ell^-}(p_T^Z > 314\,\text{GeV})}{\sigma_\gamma(p_T^\gamma > 314\,\text{GeV})} = 0.0322 \pm 0.0008\,(\text{stat}) \pm 0.0020\,(\text{syst}).$$

- Drell-Yan in association with jets
  - increase in jet multiplicity in data is slower than predicted from the simulation
- More results coming soon

Extra

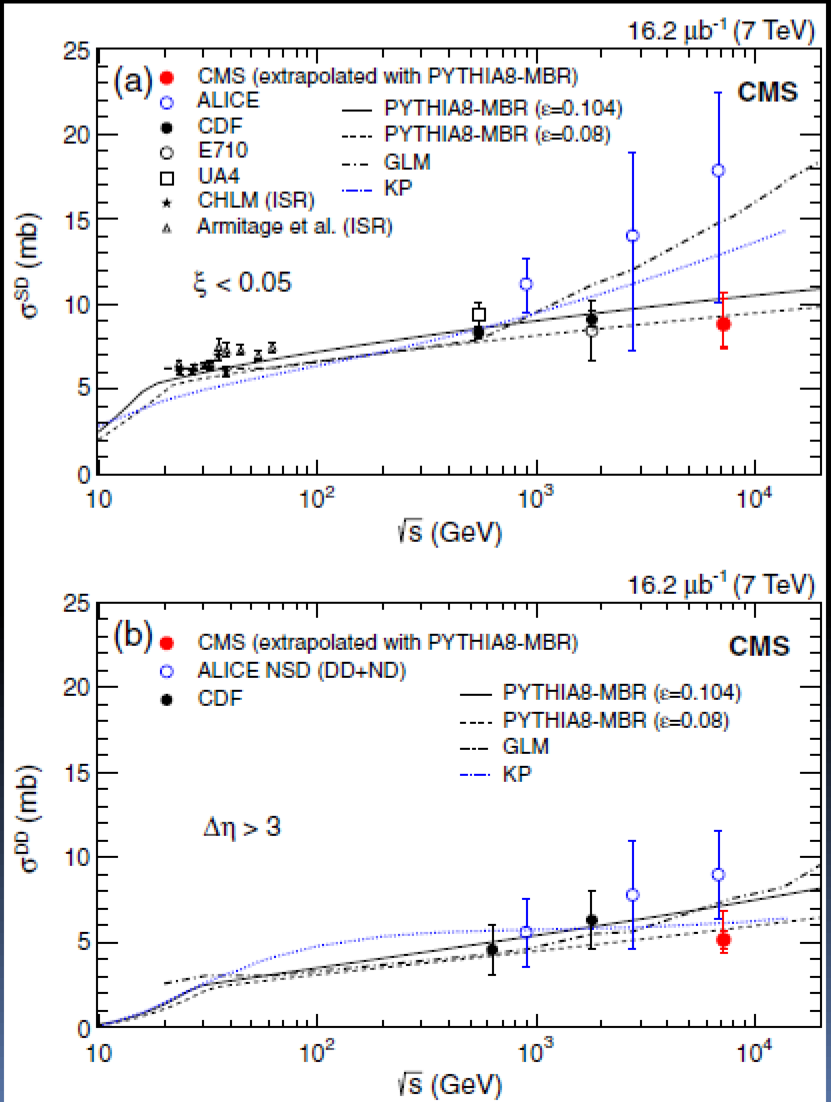


- Collinear- and Infrared-Safe
  - ★ collinear splitting shouldn't change jets
  - ★ soft emissions shouldn't change jets



Collinear-Safety Infrared-Safety

Measurements: SD & DD cross sections



Luminosity and Pile-up

- The integrated luminosity (*L*) is based on the Van der Meer scans
- The uncertainty of the luminosity is 4%: dominates the systematic uncertainties of this analysis
- Number of collisions per bunch crossing follows Poisson - Average λ *(pile-up)*

$$F_{\text{pileup}} = \frac{\Sigma_{i=1}^{\infty} iP(i,\lambda)}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} \cdot \epsilon_{\text{inel}} = \frac{\epsilon_{\text{inel}}\lambda}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} =$$

$$= 1 + \frac{1}{2}\lambda\epsilon_{\text{inel}} + \frac{1}{12}\lambda^2\epsilon_{\text{inel}}^2 + \mathcal{O}(\lambda^3)$$

- Correction factor – accounts for multiple collisions being counted as one.

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.