https://www.myiconstory.com/product/lisbon-belem-tower/

RESULTS ON DIFFRACTION AND EXCLUSIVE PRODUCTION

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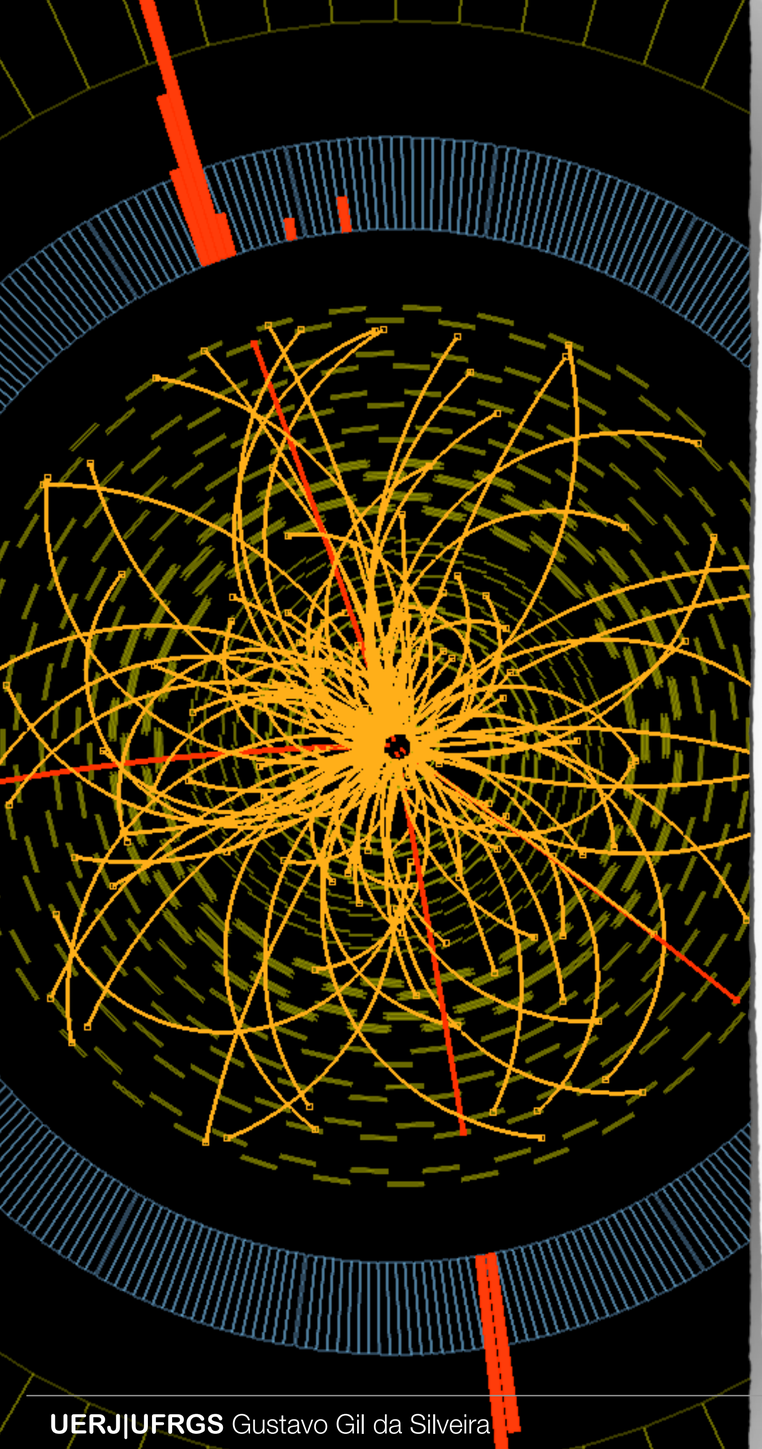
on behalf of the CMS and TOTEM Collaborations

11–15 October 2021, LIP Lisboa

12th MPI at LHC



Outline

- Forward detectors of the CMS and TOTEM experiments
  - Kinematical domain of forward processes
  - Setup of TOTEM Roman Pots
- Dijet measurements
  - Analysis based on the CMS data
  - Additional topology with an intact proton
- Precision Proton Spectrometer (PPS)
  - Physics programme
  - Operation during CERN-LHC Run2
  - Matching criteria between CMS and PPS information
  - Results on (semi)exclusive dileption production
- Exclusive diphoton production
  - Latest results on diphoton production
  - New Physics searches of aQGC

CMS results on exclusive and diffraction production

- The CMS experiment has proven its capability of measuring exclusive and diffractive processes during the last years:

1. Exclusive **dilepton** production
   [FWD-10-005 FWD-11-004 FSQ-12-010 FSQ-13-008 PPS-17-001 HIN-19-014]
2. Exclusive production of **dibosons** [FWD-11-004 FSQ-12-010 FSQ-13-008 FSQ-16-012]
3. Searches for **New Physics** [FSQ-12-010 FSQ-13-008 FSQ-16-012 EXO-18-014]
4. Diffractive **dijet** production
   [FWD-10-004 FWD-10-014 FSQ-12-001 FSQ-12-002 FSQ-12-033 SMP-18-006]
5. Photoproduction of **vector mesons** [FSQ-13-009 FSQ-16-007]
6. Diffractive production of **pions** [FSQ-16-006]
7. Pseudorapidity **gaps** [FWD-10-008]
8. Diffraction **cross section** [FSQ-12-005]

over the years

	pp	*p*Pb PbPb
Run 1	11	2
Run 2	4	1

Measurement of single-diffractive dijet production in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the CMS and TOTEM experiments

EPJC 80 (2020) 1164
e-Print: 2002.12146 [hep-ex]

$$pp \to jj \oplus p$$

Hard color-singlet exchange in dijet events in proton-proton collisions at $\sqrt{s}$ = 13 TeV

PRD 104 (2021) 032009
e-Print: 2102.06945 [hep-ex]

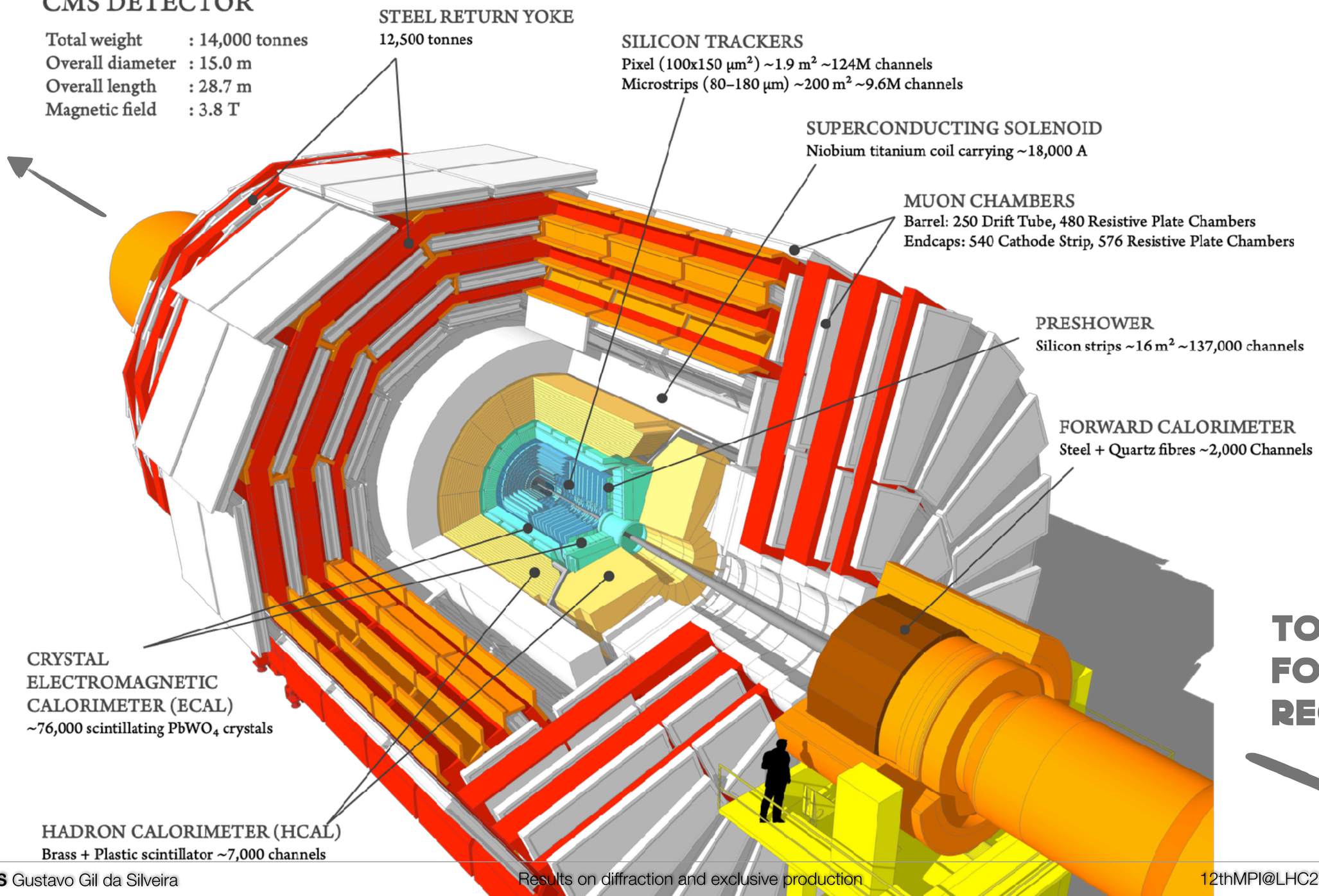
$$pp \to j \oplus j$$
$$pp \to j \oplus j \oplus p$$

$$pp \to p\gamma\gamma p$$

First search for exclusive diphoton production at high mass with intact protons in proton-proton collisions at $\sqrt{s}$ =13 TeV at the LHC

EXO-18-014
CMS & TOTEM Collaborations

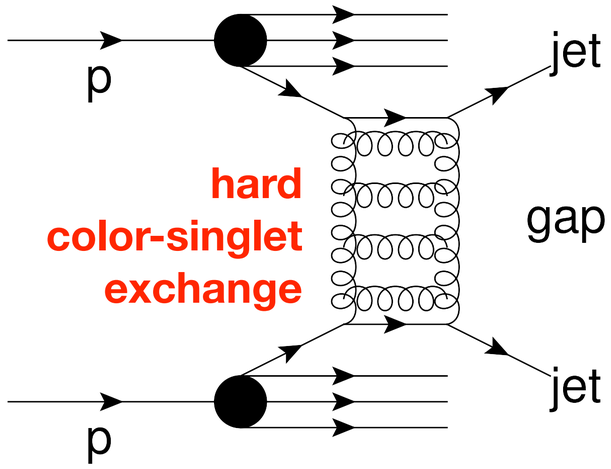
CMS DETECTOR

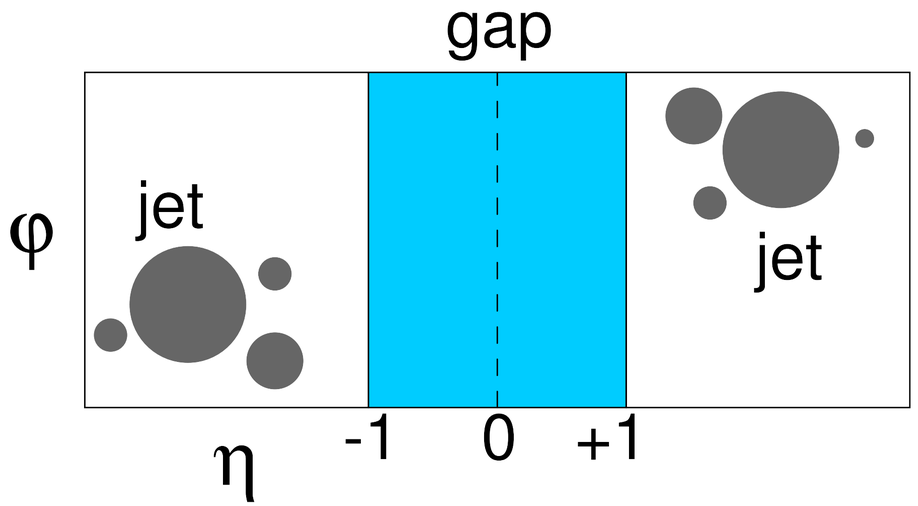


Jet-gap-Jet

PRD 104 (2021) 032009
SMP-19-006

- Diffrative dijet production has been measured via **pseudorapidity gaps** as experimental signature
  - Important measurement for testing pQCD and the **BFKL dynamics** at energy of 13 TeV





MPI can further decrease it

may not be entirely kinematic independent

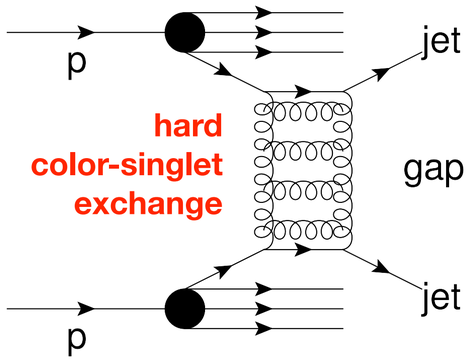
- Soft rescattering corrections are accounted by a **survival probability** of $|\mathcal{S}|^2 = 1 - 10\,\%$
- Measurements in CMS+TOTEM common data-taking at **13 TeV** (2015) of **0.66/pb** + **0.40/pb** (TOTEM)
  - Special run with $\beta^* = 90\,\mathrm{m}$ where $-4 < t < -0.025\,\mathrm{GeV}^2$ and $0.05 - 0.10$ pileup/event
- Intact proton largely reduces the soft interactions and improves **survivability** of the gaps

Marquet *et al*
PRD 87 (2013) 034010

Event selection for CMS data

PRD 104 (2021) 032009
SMP-19-006

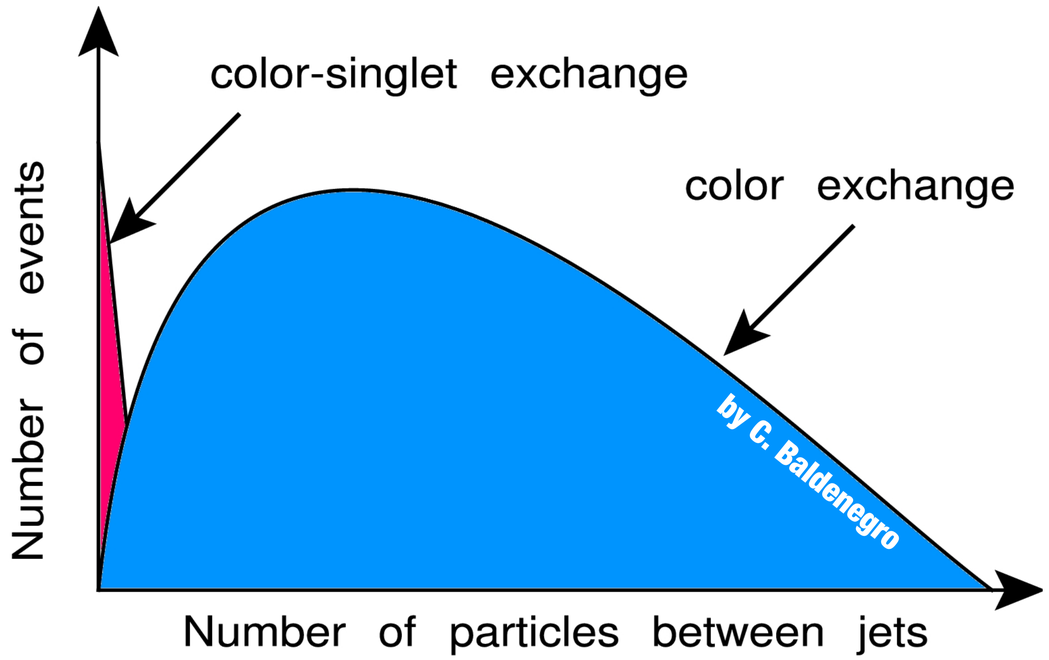
- **Leading jet** criteria for CMS: 360k+ events

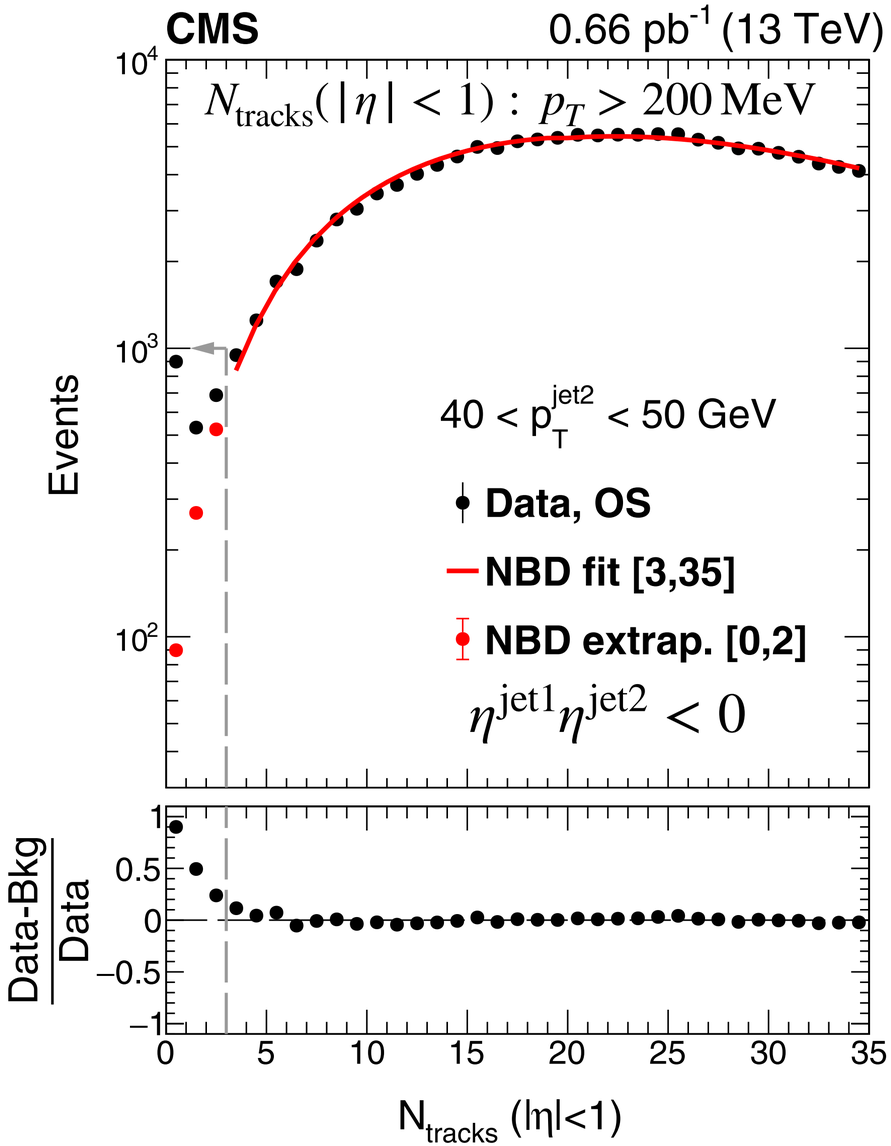


$$p_T^{\text{jet}} > 40\,\text{GeV}$$

$$1.4 < |\eta^{\text{jet}}| < 4.7$$

$$\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$$





Color-singlet exchange Fraction with CMS data

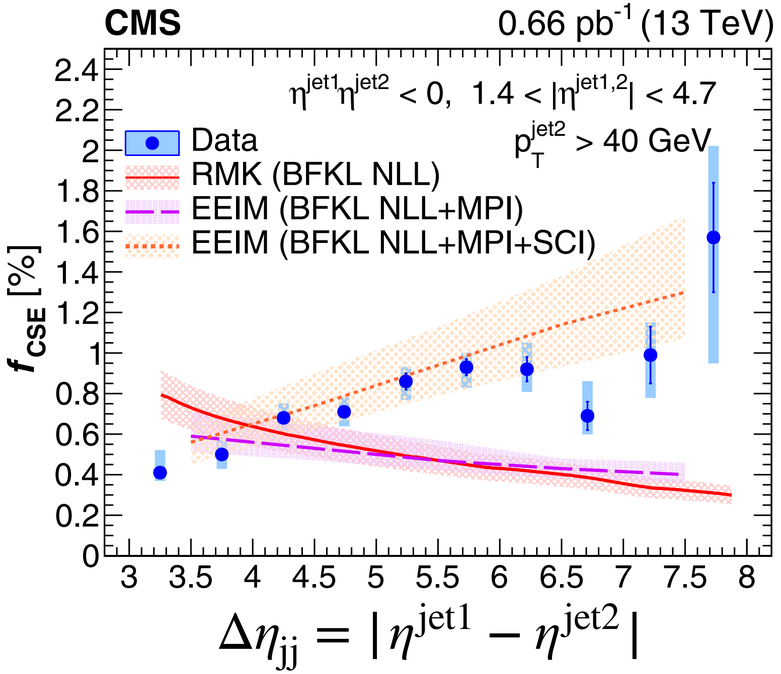
PRD 104 (2021) 032009
SMP-19-006

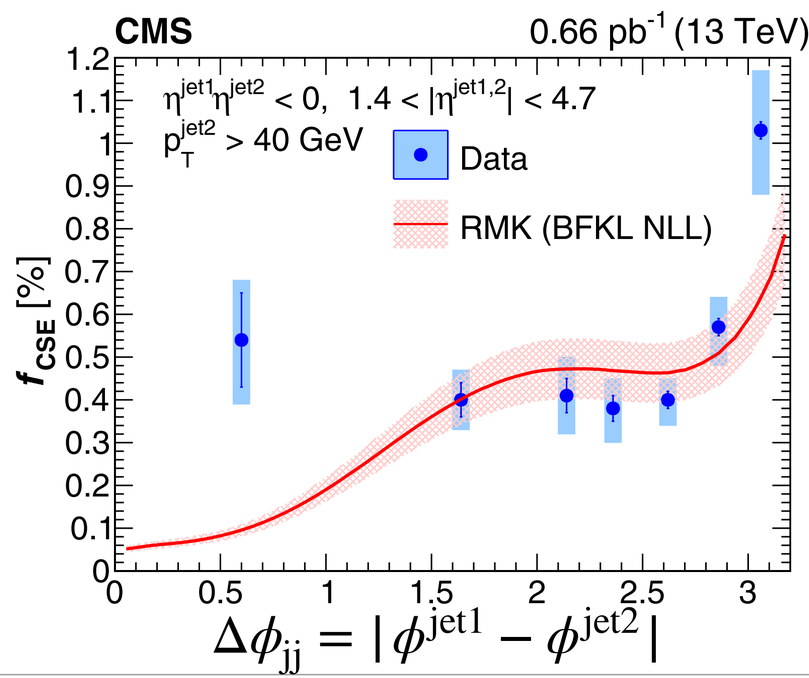
- CSE events are accounted for $N_{\text{tracks}} < 3$ based on background studies:

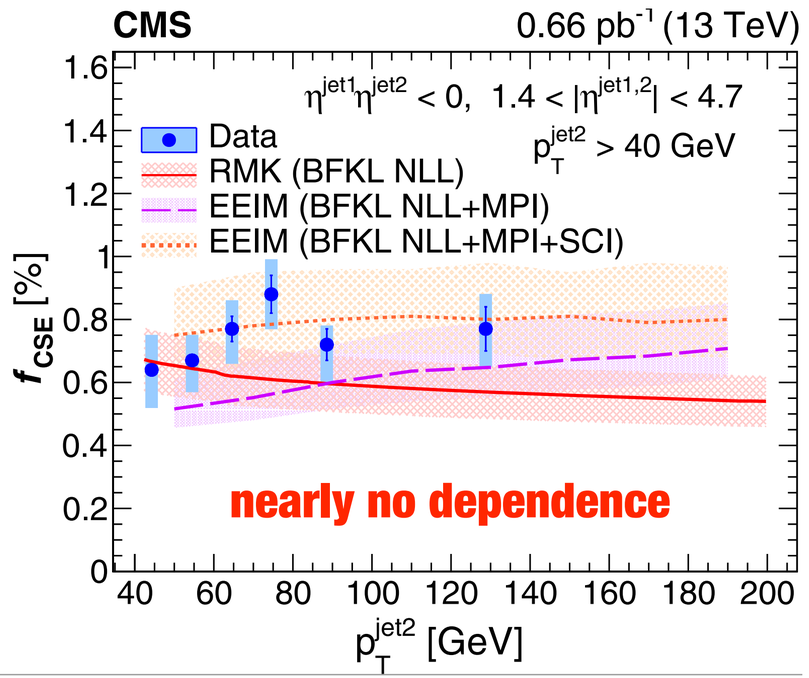
$$f_{\text{CSE}}(N_{\text{tracks}} < 3) = \frac{N^{\text{F}} - N^{\text{F}}_{\text{non-CSE}}}{N}$$

- Full NLL calculation of BFKL + NLO impact factor in progress
  - BFKL predictions **strongly** depends on the η gap definition

$p_{\text{T}}^{\text{jet2}}$ [GeV]	$\langle p_{\text{T}}^{\text{jet2}} \rangle$ [GeV]	f_{CSE} [%]
40–50	44.3	$0.64 \pm 0.01^{+0.11}_{-0.12}$
50–60	54.5	$0.67 \pm 0.02^{+0.08}_{-0.10}$
60–70	64.6	$0.77 \pm 0.04^{+0.08}_{-0.10}$
70–80	74.5	$0.88 \pm 0.06^{+0.09}_{-0.09}$
80–100	88.6	$0.72 \pm 0.05^{+0.04}_{-0.11}$
100–200	128.8	$0.77 \pm 0.07^{+0.09}_{-0.10}$







Color-singlet exchange Fraction with CMS data

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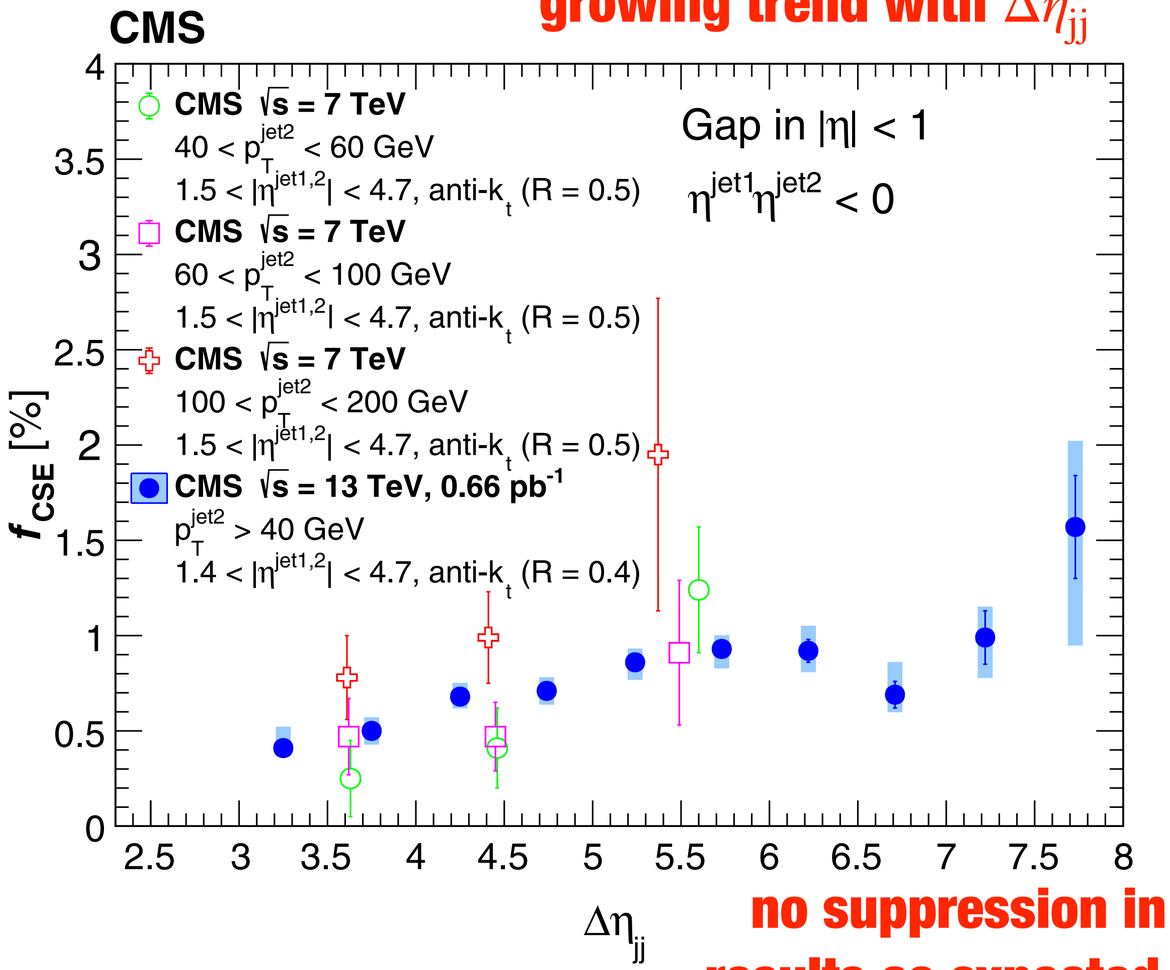
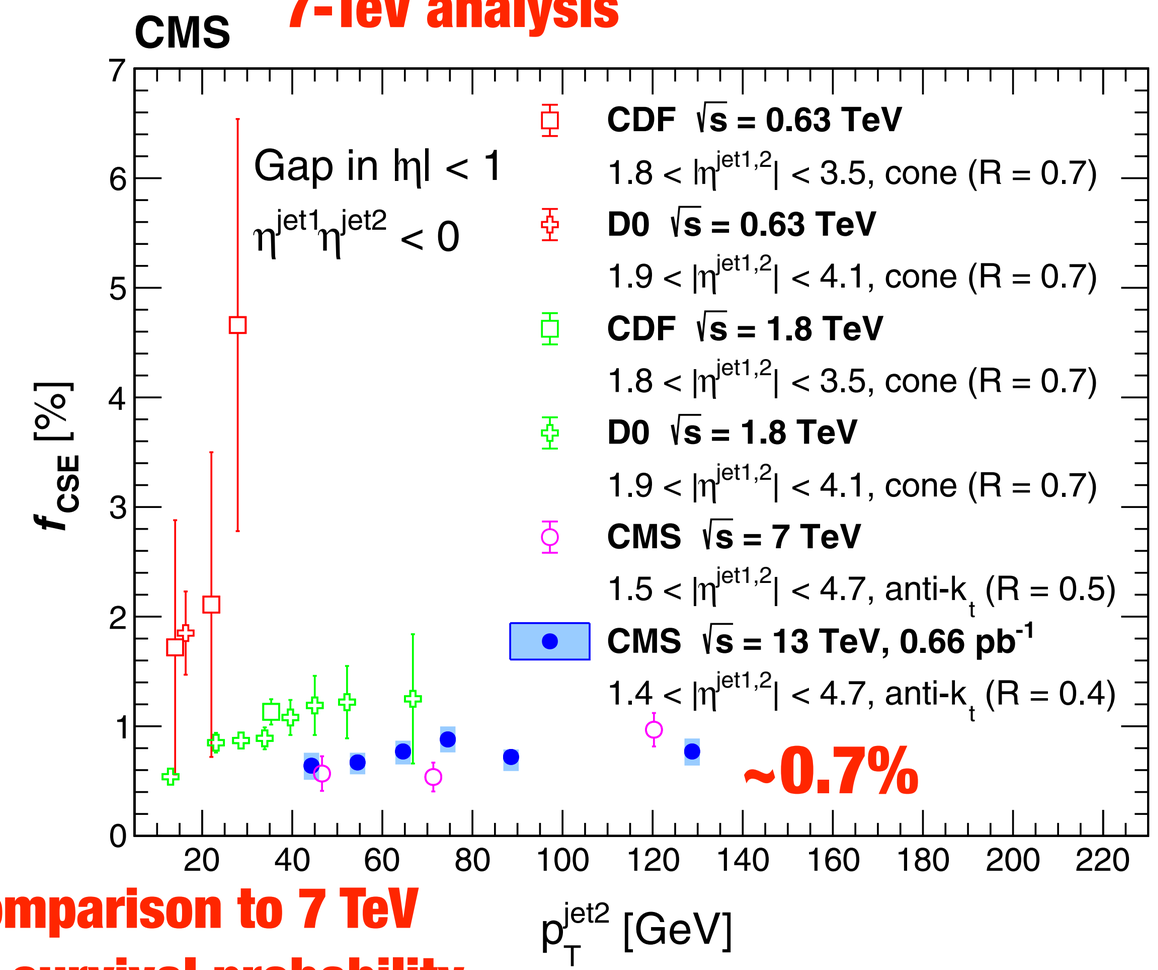
Latest data confirm growing trend with $\Delta\eta_{jj}$



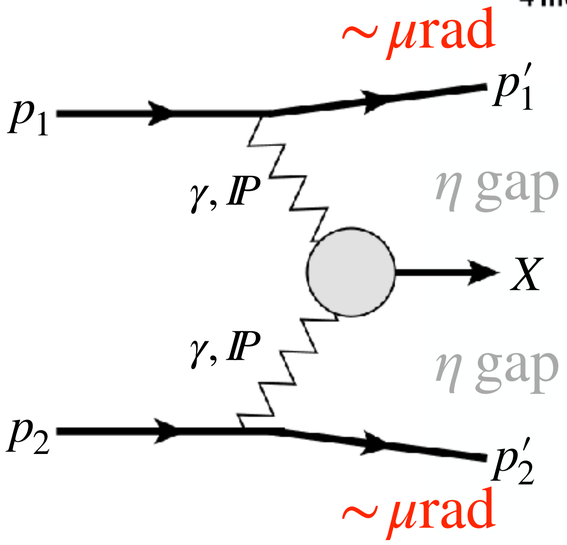
Improvement compared to 7-TeV analysis

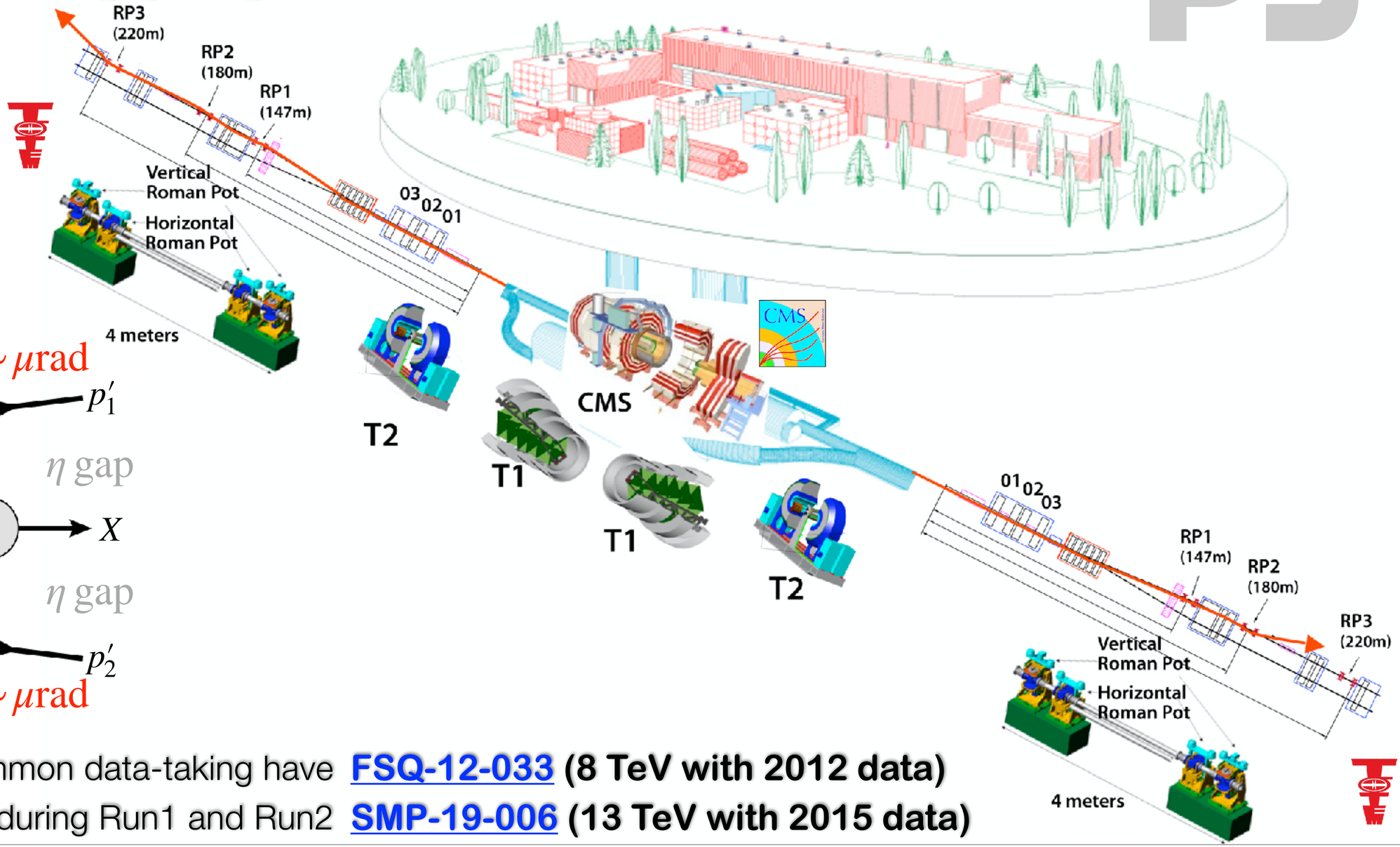


no suppression in comparison to 7 TeV results as expected by survival probability

Proton tagging

P5

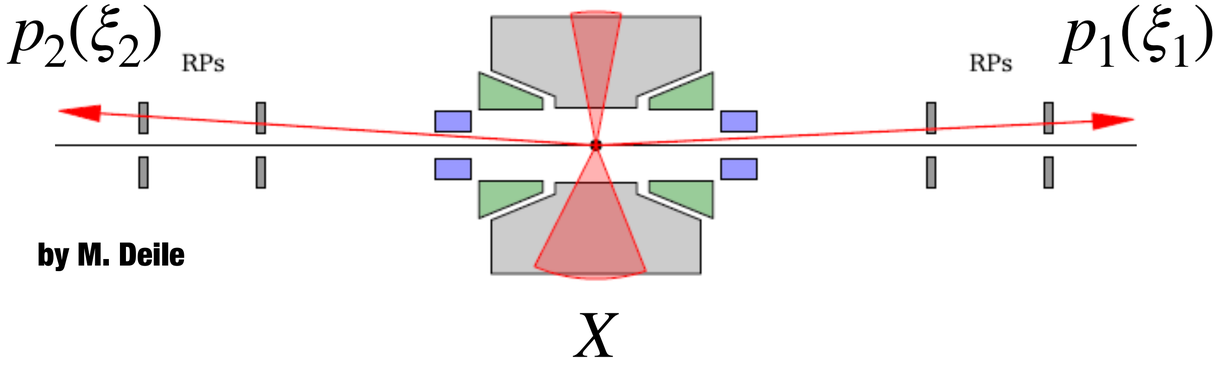


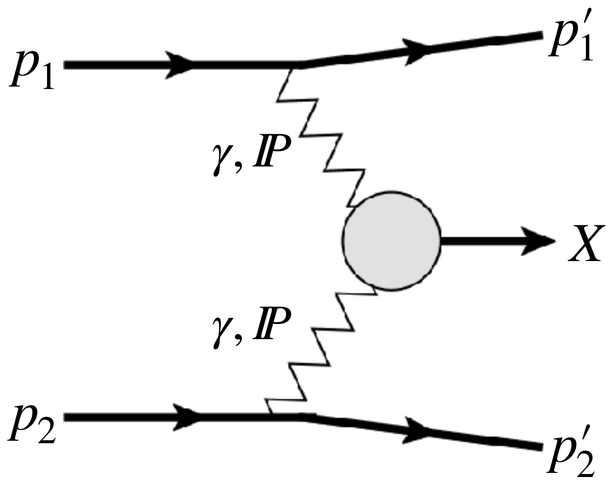


CMS-TOTEM common data-taking have **FSQ-12-033 (8 TeV with 2012 data)**
taken place during Run1 and Run2 **SMP-19-006 (13 TeV with 2015 data)**

TOTEM Roman Pots

$$p + p \rightarrow p \oplus X \oplus p$$





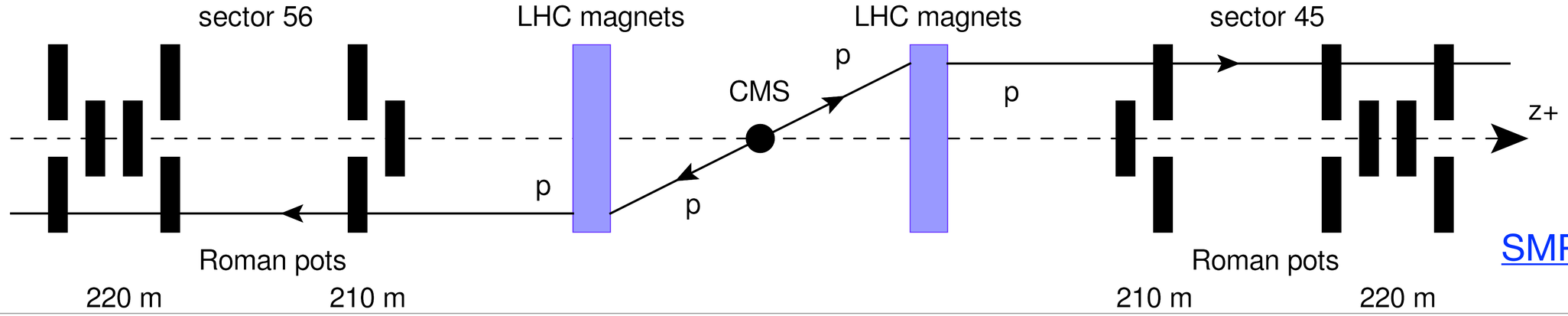
fractional momentum loss

$$\xi_1 = \frac{\Delta p_1}{p}$$

$$M_X = \sqrt{\xi_1 \xi_2 s}$$

$$\xi_2 = \frac{\Delta p_2}{p}$$

$M_X \gtrsim 300\,\text{GeV}$



SMP-19-006

TOTEM Roman Pots

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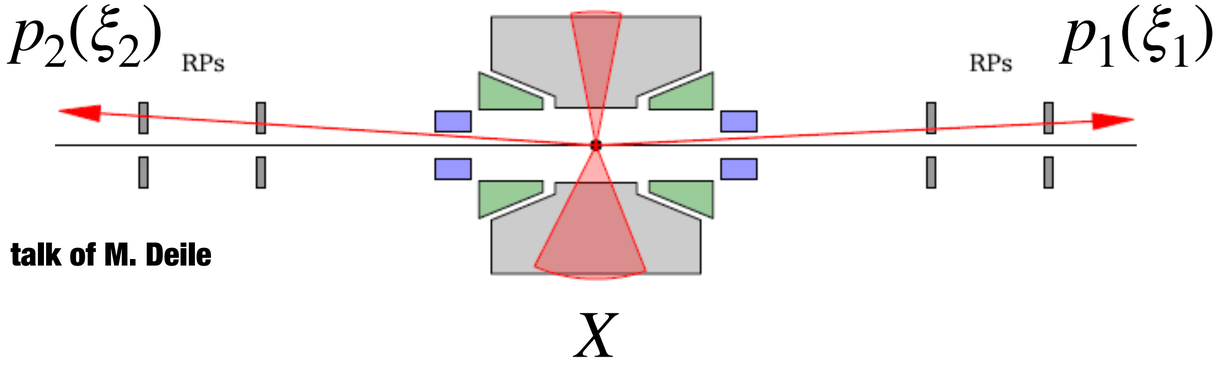
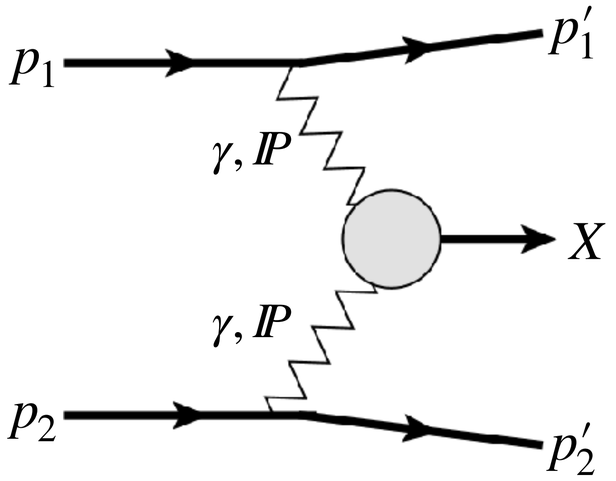


talk of M. Deile



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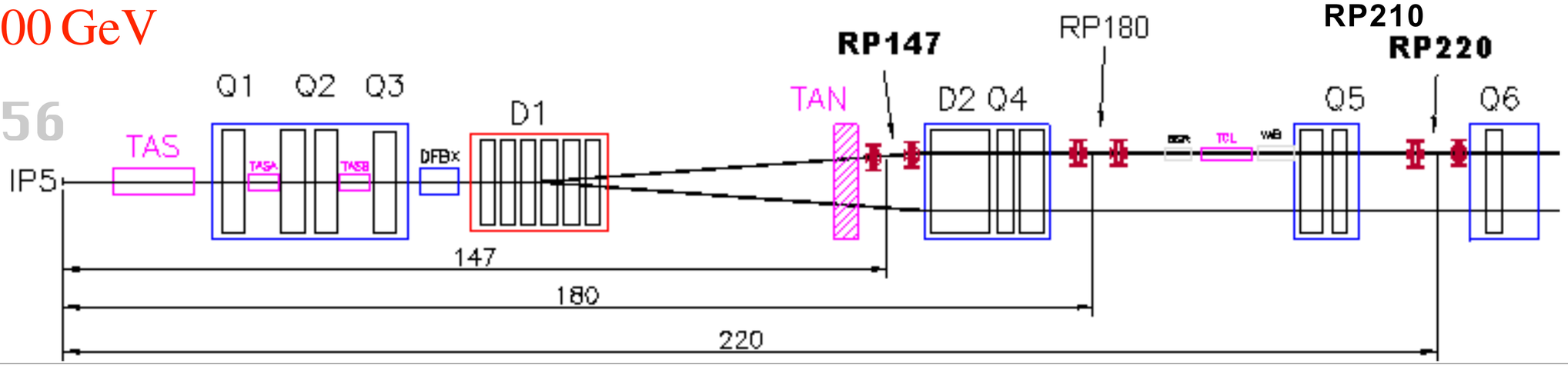
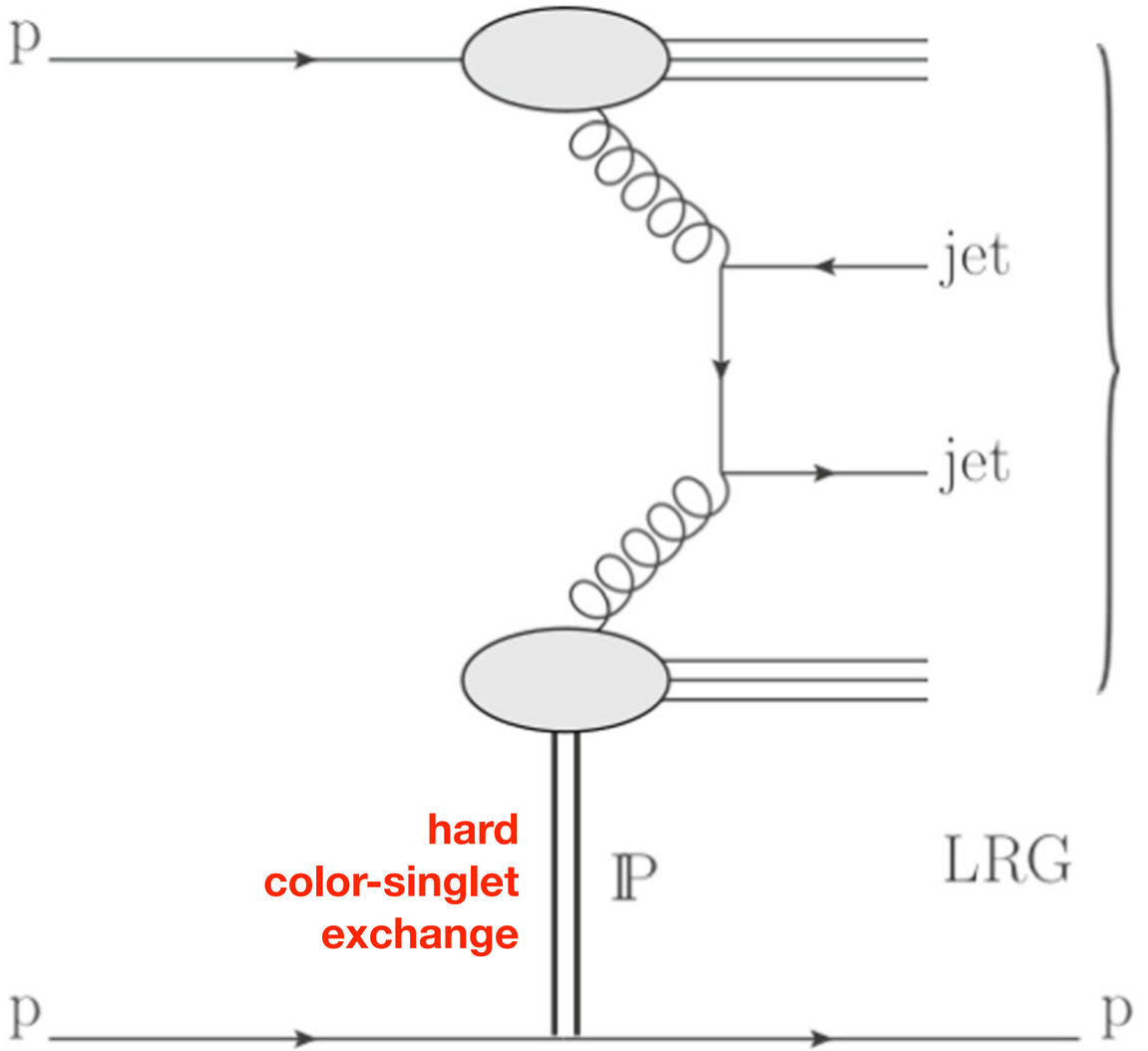
Sector 56



Single-diffractive jets at 8 TeV with proton tagging

EPJC 80 (2020) 1164
FSQ-12-033



Single-diff jets at 8 TeV + proton tagging

EPJC 80 (2020) 1164
FSQ-12-033

- **Leading jets** on a data sample with 37.5/nb

$$p_T^{\text{jet}} > 40\,\text{GeV}$$

$$|\eta^{\text{jet}}| < 4.4$$

$$\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$$

- Intact **proton** criteria:

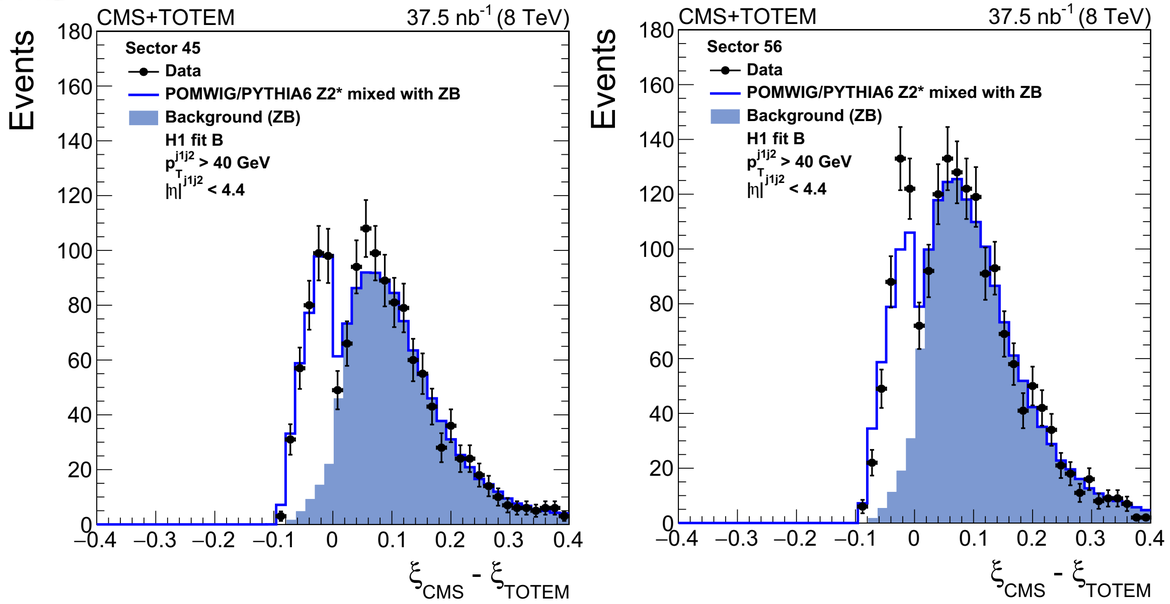
proton at RP45 or RP56

$$0 < \xi(\text{RP}) < 0.1$$

$$0.03 < |t| < 1\,\text{GeV}^2$$

VERTICAL RPS
HORIZONTAL RPS

$$8.4 < |y(\text{RP})| < 27\,\text{mm}$$
$$0 < x(\text{RP}) < 7\,\text{mm}$$



- **Final selection:**

$$\xi_p(\text{PF}) = \sum_i \frac{E^i \pm p_z^i}{\sqrt{s}}$$

$$\xi_p(\text{PF}) - \xi_p(\text{RP}) \leq 0$$

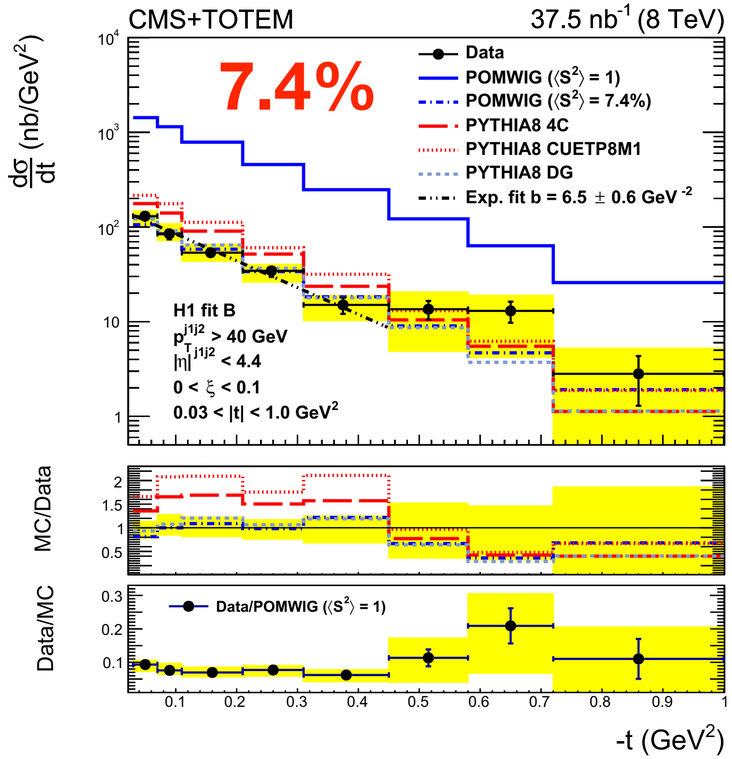
$$|\eta(\text{PF})| < 5.2$$

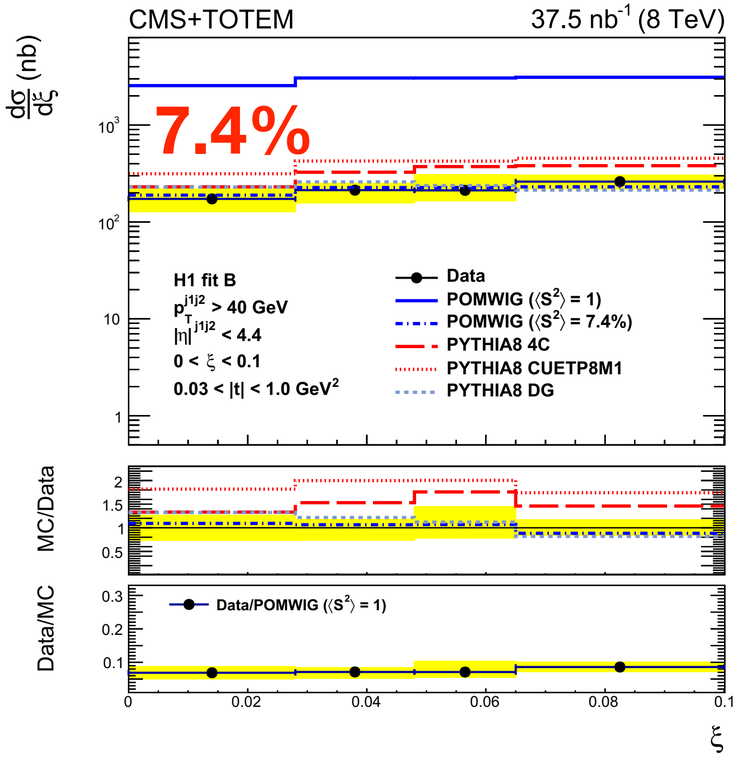
- **Events passing both CMS and TOTEM criteria:**

RP45 : 368 events
RP56 : 420 events

Single-diff jets at 8 TeV + proton tagging

EPJC 80 (2020) 1164
FSQ-12-033





good agreement with PYTHIA8 DG

- Cross section for single-diffractive dijet production: $\sigma_{jj}^{pX} = 21.7 \pm 0.9\,(\text{stat})^{+3.0}_{-3.3}\,(\text{syst}) \pm 0.9\,(\text{lumi})\,\text{nb}$
- Fit to data for $d\sigma/dt \propto \exp(-b\,|t|)$: $b = 6.5 \pm 0.6\,(\text{stat})^{+1.0}_{-0.8}\,(\text{syst})\,\text{GeV}^{-2}$

consistent with CDF result at small *t*

- Ratio normalized per unit of ξ: $R = \left(\sigma_{jj}^{pX}/\Delta\xi\right)/\sigma_{jj} = 0.025 \pm 0.001\,(\text{stat}) \pm 0.003\,(\text{syst})$

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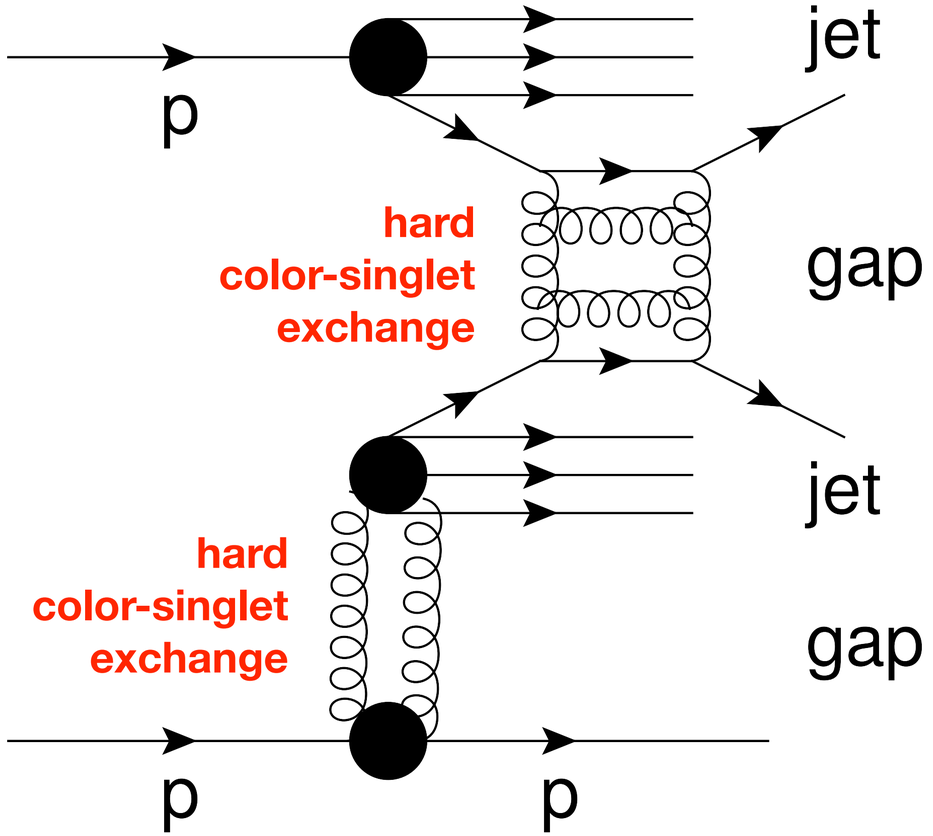
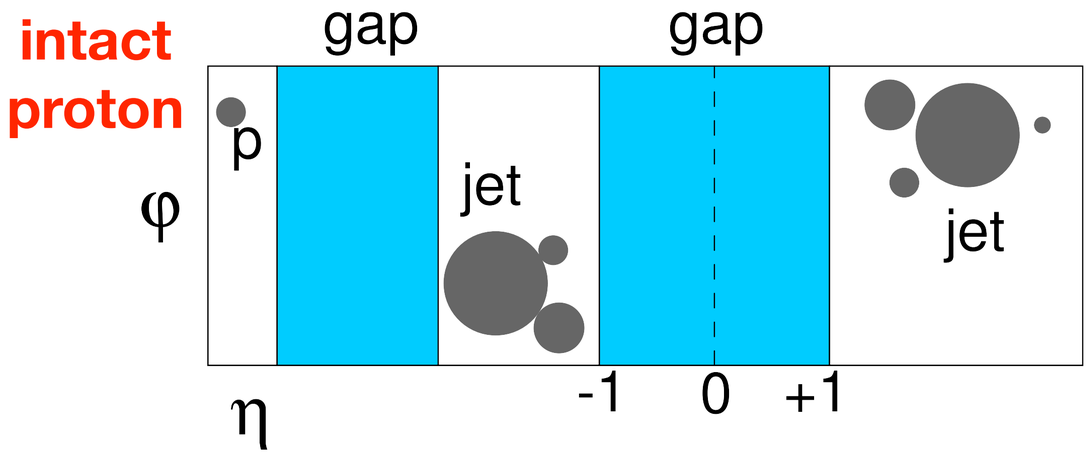
Jet-gap-Jet at 13 TeV with proton tagging





Measured for the first time

Jet-Gap-Jet at 13 TeV + proton tagging

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SMP-19-006

- **Leading jet** criteria for CMS: **~360k events**

$$p_T^{\text{jet}} > 40\,\text{GeV}$$

$$1.4 < |\eta^{\text{jet}}| < 4.7$$

$$\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$$

- Intact **proton** criteria:

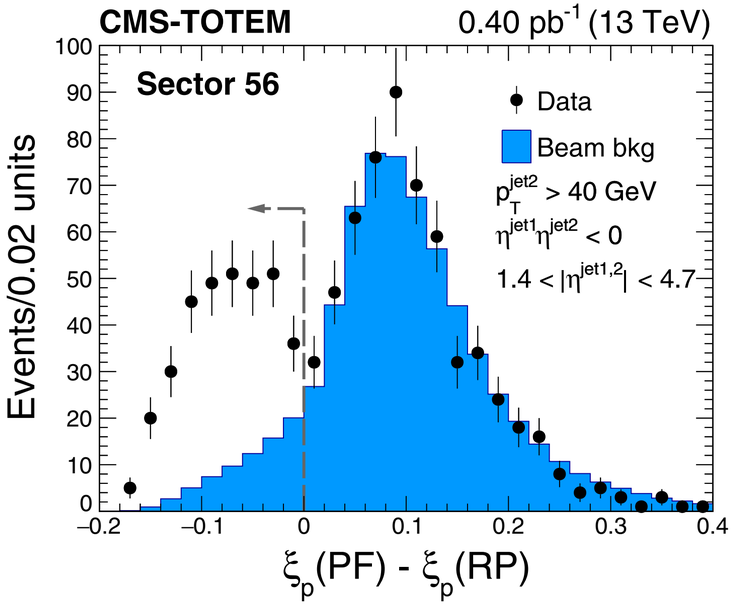
proton at RP45 or RP56

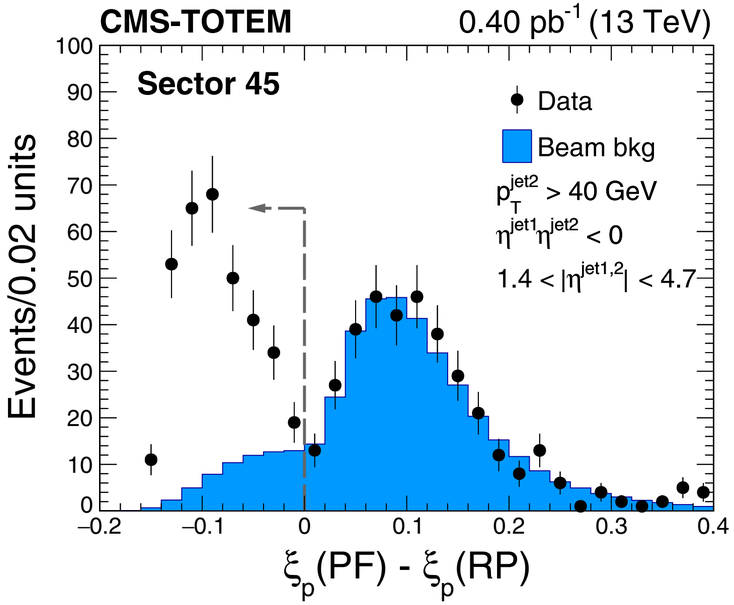
$$\xi_p(\text{RP}) < 0.2$$

$$-4 < t < -0.025\,\text{GeV}^2$$

$$|y(\text{RP})| < 25\,\text{mm}$$
$$7 < x(\text{RP}) < 25\,\text{mm}$$
VERTICAL RPS

$$8 < |y(\text{RP})| < 30\,\text{mm}$$
$$0 < x(\text{RP}) < 20\,\text{mm}$$
HORIZONTAL RPS





- **Final selection:**

$$\xi_p(\text{PF}) = \sum_i \frac{E^i \pm p_z^i}{\sqrt{s}}$$

$$\xi_p(\text{PF}) - \xi_p(\text{RP}) < 0$$

$$|\eta(\text{PF})| < 5.2$$

- **Events passing both CMS and TOTEM criteria:**

RP45 : 341 events

RP56 : 336 events

Jet-Gap-Jet at 13 TeV + proton tagging

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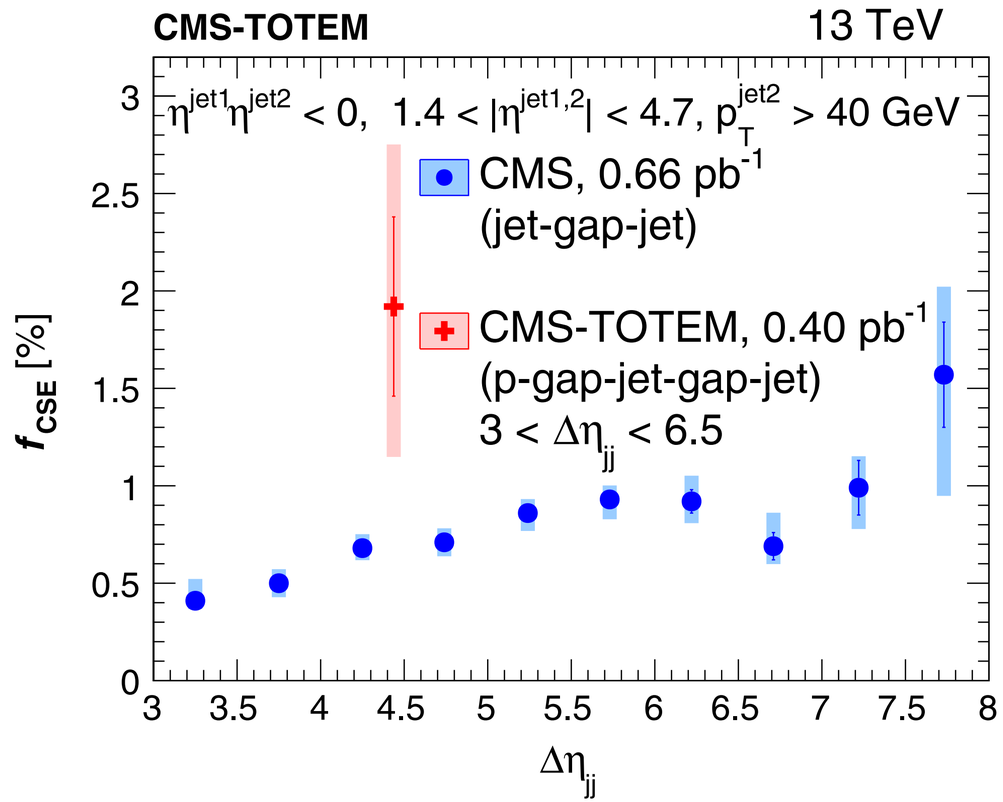
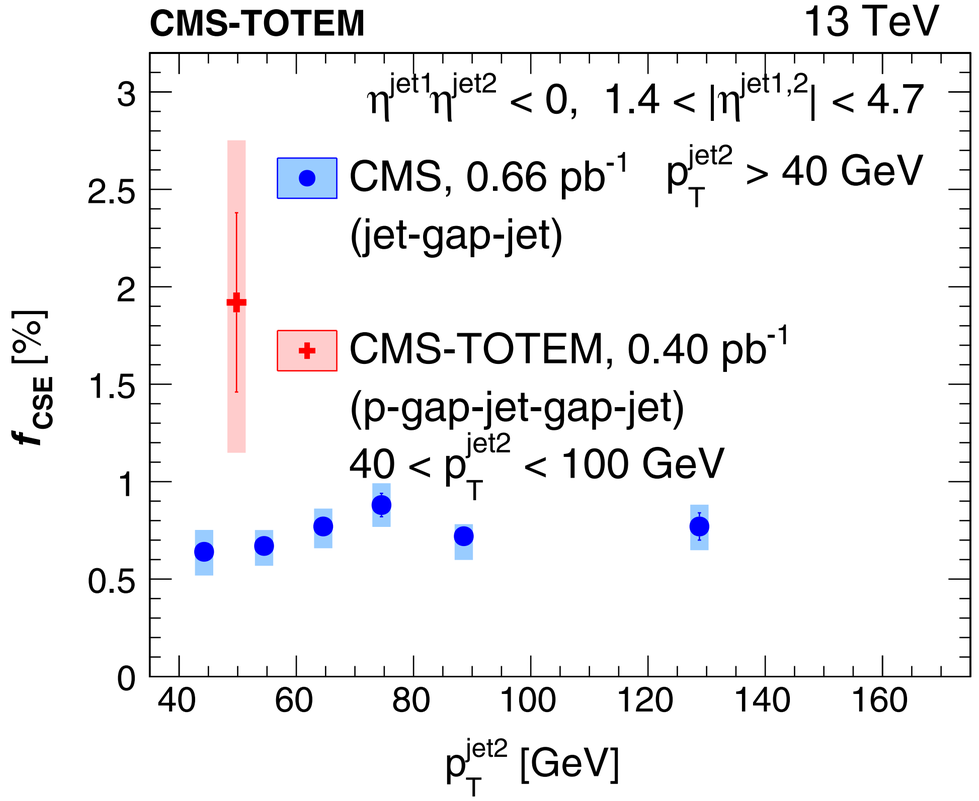
SMP-19-006

- The fraction of CSR show an increase if compared with the jet-gap-jet topology

$$f_{\mathrm{CSE}} = \left[1.92 \pm 0.46\,(\mathrm{stat})\ ^{+0.69}_{-0.62}\,(\mathrm{syst})\right]\ \%$$

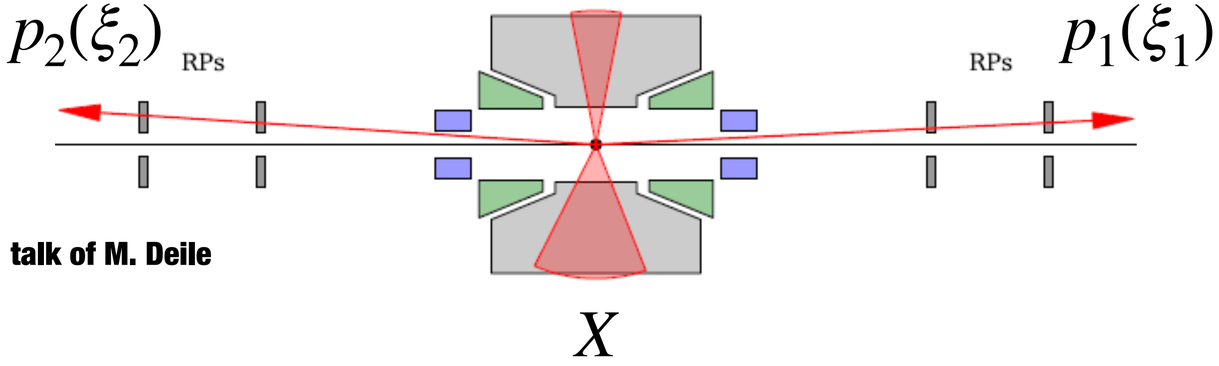
- **Larger number of events with a surviving pseudorapidity gap**

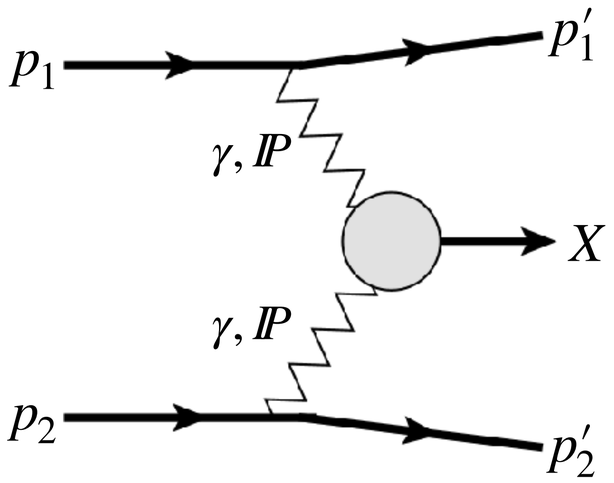




Precision Proton Spectrometer (PPS)

$$p + p \to p \oplus X \oplus p$$





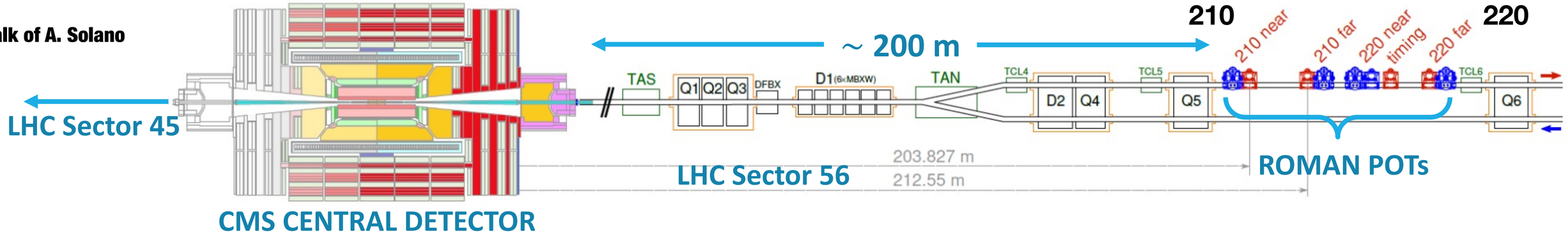
$$\xi_1 = \frac{\Delta p_1}{p}$$

$$M_X = \sqrt{\xi_1 \xi_2 s}$$

$$\xi_2 = \frac{\Delta p_2}{p}$$

$\xi = 0.02 - 0.2 \quad M_X \gtrsim 400\,\text{GeV}$

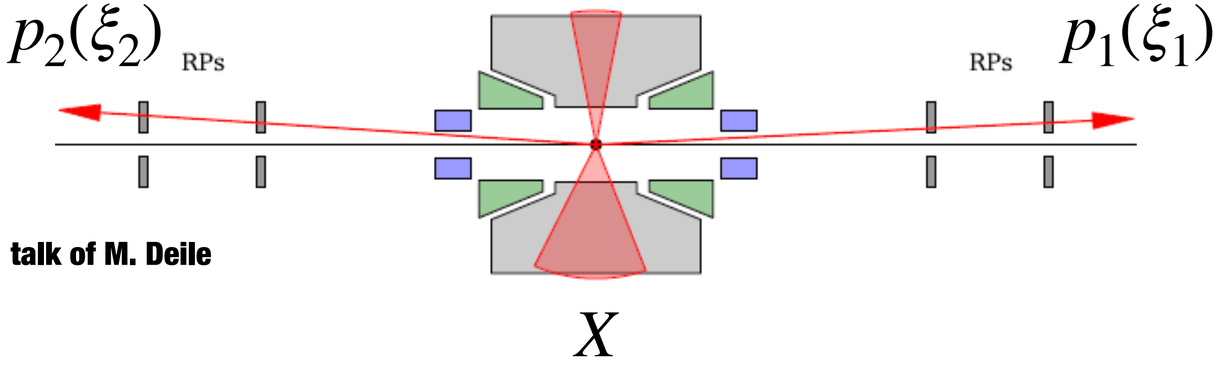
talk of A. Solano



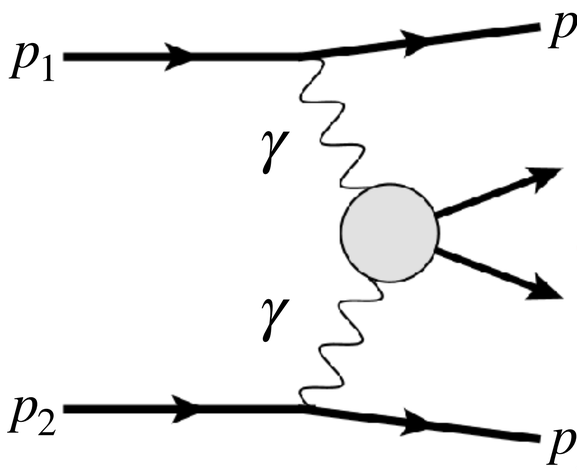
PPS is planned to operate during the High-lumi LHC CMS-NOTE-2020-008 arXiv 2103.02752

Precision Proton Spectrometer (PPS)

$$p + p \to p \oplus X \oplus p$$



talk of M. Deile



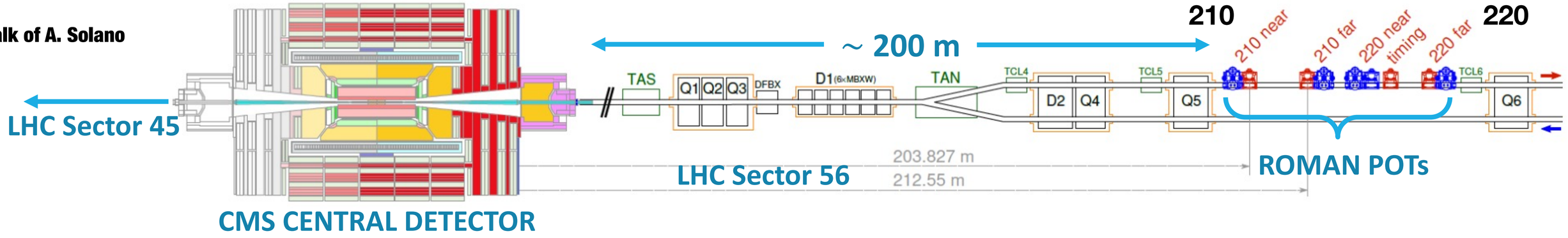
$$\xi_1 = \frac{\Delta p_1}{p}$$

$$\ell^+\ell^-, \gamma\gamma, VV, H, t\bar{t}$$

$$\xi_2 = \frac{\Delta p_2}{p}$$

$$\xi = 0.02 - 0.2 \quad M_X \gtrsim 400\,\text{GeV}$$

talk of A. Solano



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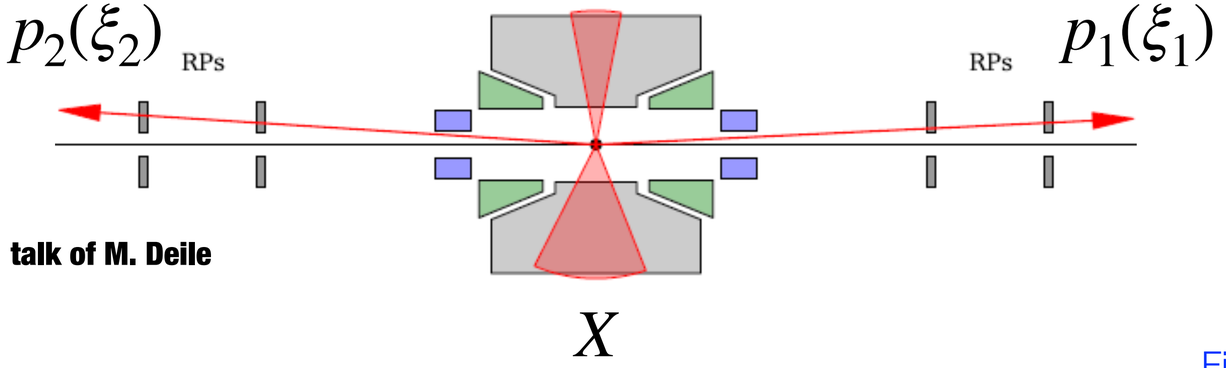
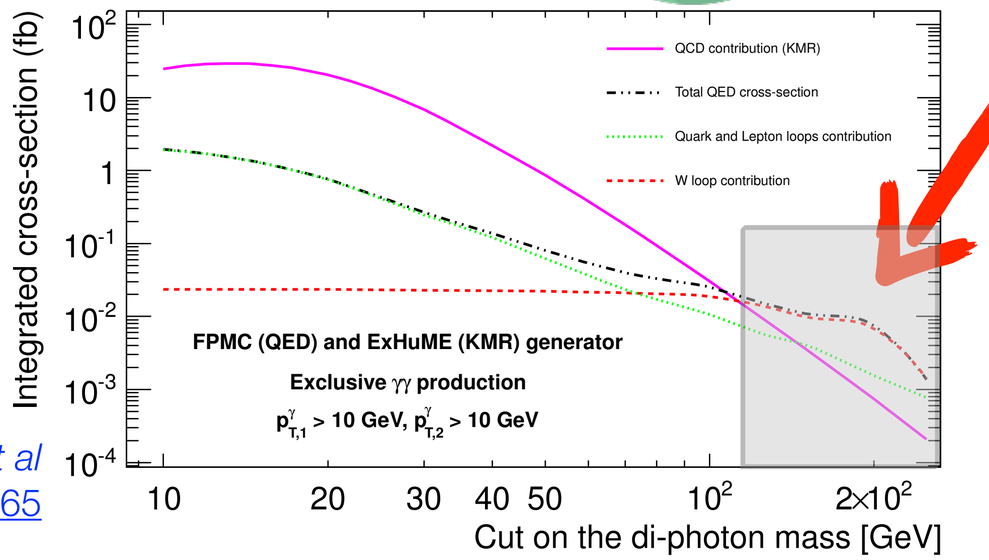


talk of M. Deile



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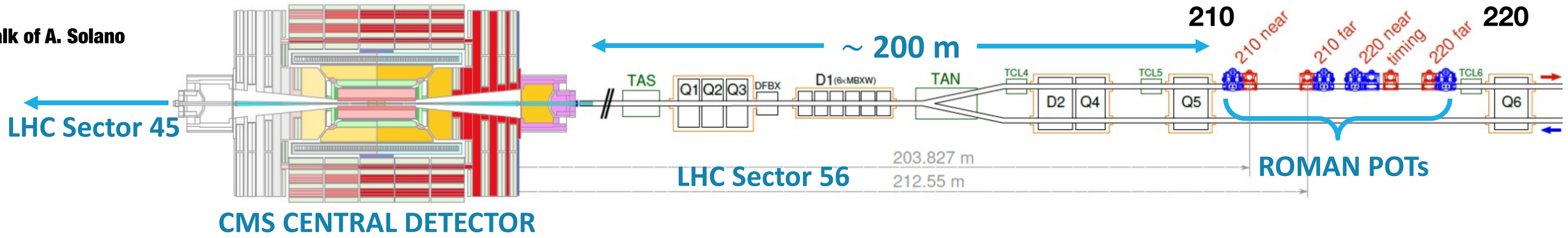
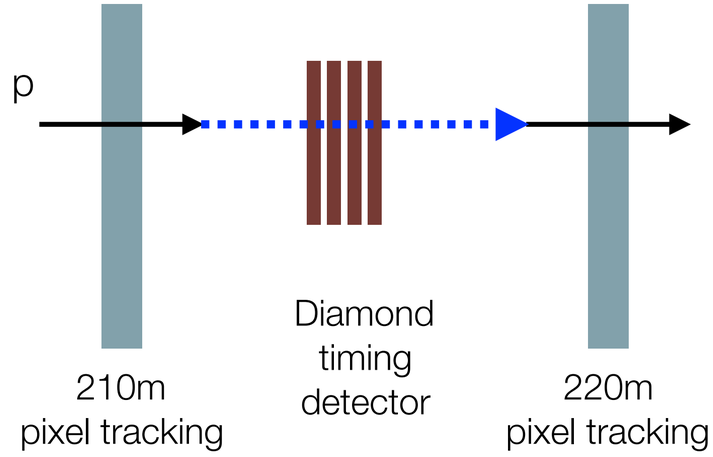
$\xi = 0.02 - 0.2 \quad M_X \gtrsim 400\,\text{GeV}$

talk of A. Solano



PPS is planned to operate during the High-lumi LHC CMS-NOTE-2020-008 arXiv 2103.02752

PPS operation during Run2



- Designed to measure intact protons with a Physics program intended for **Central Exclusive Production (CEP)**
- Roman Pots house a set of sensors for measuring intact protons coming from the interaction point in CMS:
  - **Tracking detectors**: used to determine the proton deviation from the beam in terms of ξ — **resolution 10—30 μm**
  - **Timing detectors**: measure the proton time-of-flight (ToF) and used for vertex matching — **resolution 20—30 ps**

by A. Solano

2015	2016	2017	2018
Exploratory phase	Strips + Diamonds	Strips + Pixels + Diamonds + UFSD	Pixels + Single and double diamonds
Data recorded with tracking RPs inserted	L_{INT}~15 fb^{-1}	L_{INT}~40 fb^{-1}	L_{INT}~60 fb^{-1}
	39% OF THE DATA RECORDED BY CMS	88% OF THE DATA RECORDED BY CMS	93% OF THE DATA RECORDED BY CMS

PPS total integrated luminosity so far: ~115/fb

(Semi)exclusive dilepton observation

JHEP 07 (2018) 153
PPS-17-001

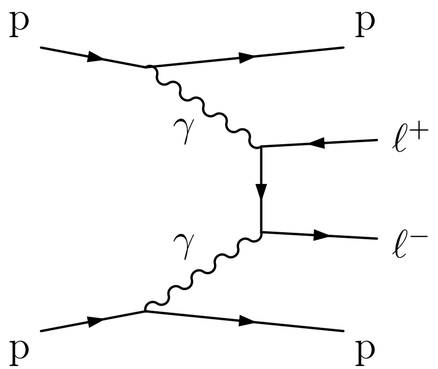
- 2016 data of PPS of **9.4/fb** (CMS 15.6/fb)

$$p_T^{\ell} > 50\,\text{GeV}$$

$$a = 1 - |\Delta\phi(\ell^+\ell^-)|/\pi)$$

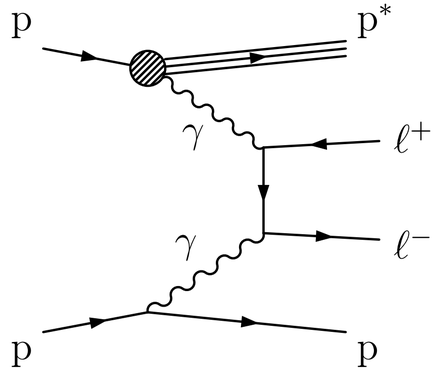
$$a(e^+e^-) < 0.006 \qquad a(\mu^+\mu^-) < 0.009$$

$$m(\ell^+\ell^-) > 110\,\text{GeV}$$



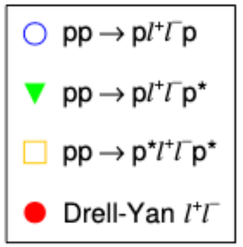
$pp \to p\ell^+\ell^-p$

$|\mathcal{S}|^2 = 0.89$

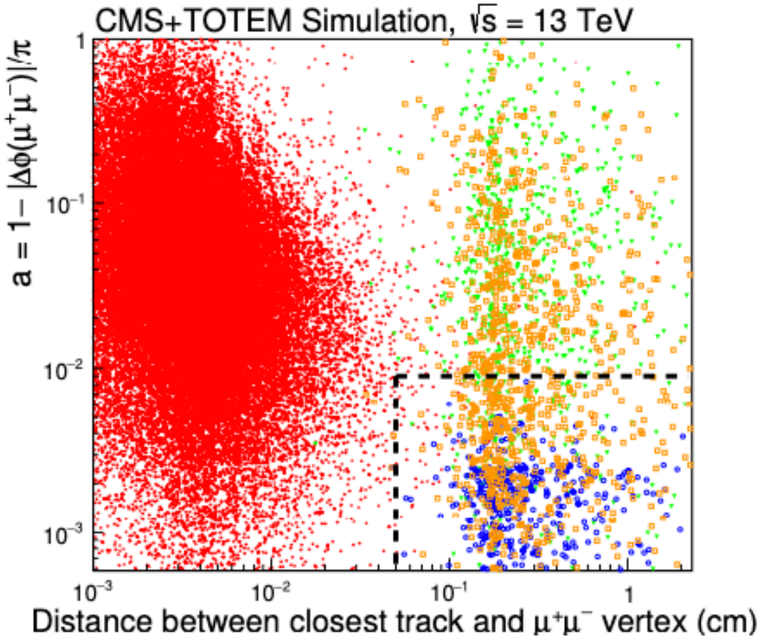


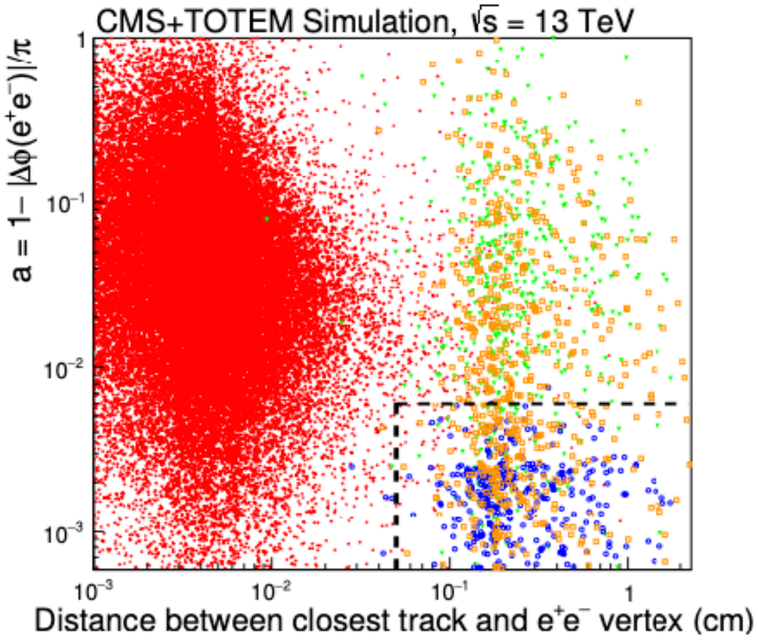
$pp \to p\ell^+\ell^-p^*$

$|\mathcal{S}|^2 = 0.76$



2016





Matching CMS and PPS

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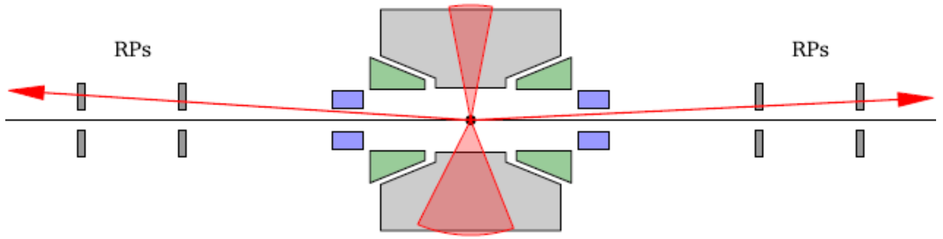
PPS-17-001

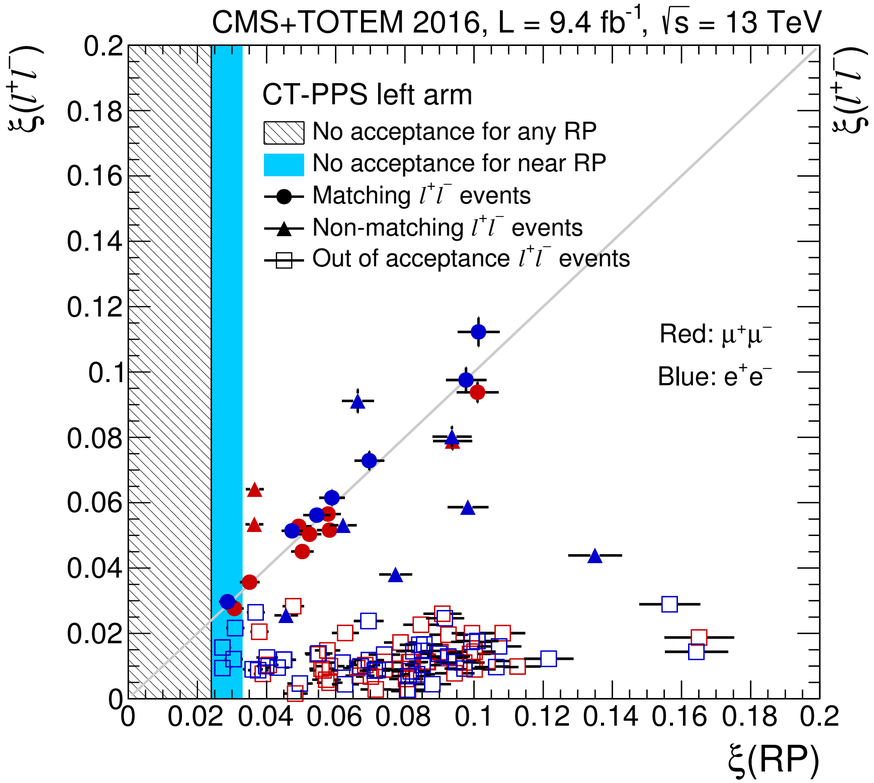
- Events with one proton observed in one of the PPS arms are related to the central system:

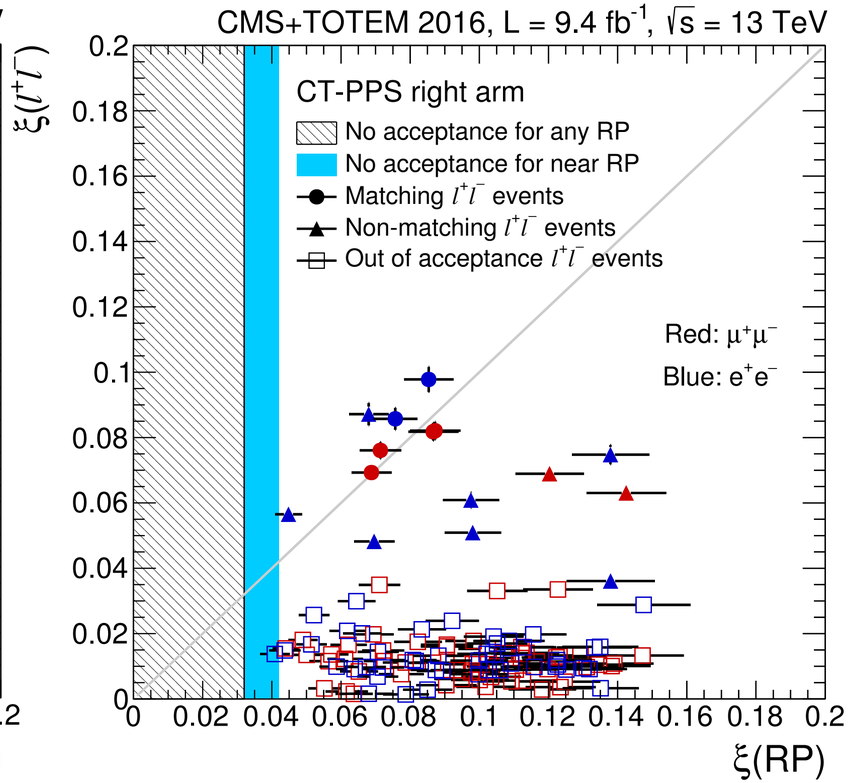
$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_T(\ell^+)e^{\pm\eta(\xi^+)} + p_T(\ell^-)e^{\pm\eta(\xi^-)}\right]$$



expression ~holds for semi-elastic

2016





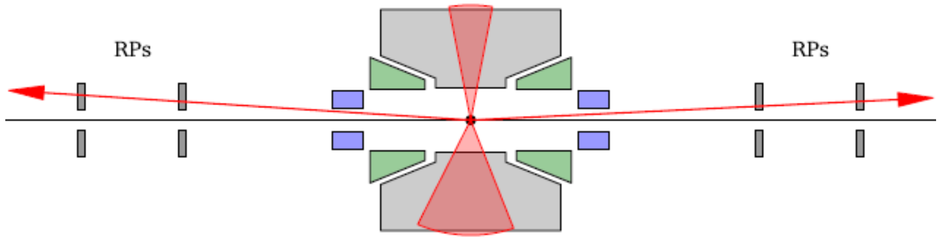
9.4/fb

Matching CMS and PPS

CMS-DP-047

- Events with one proton observed in one of the PPS arms are related to the central system:

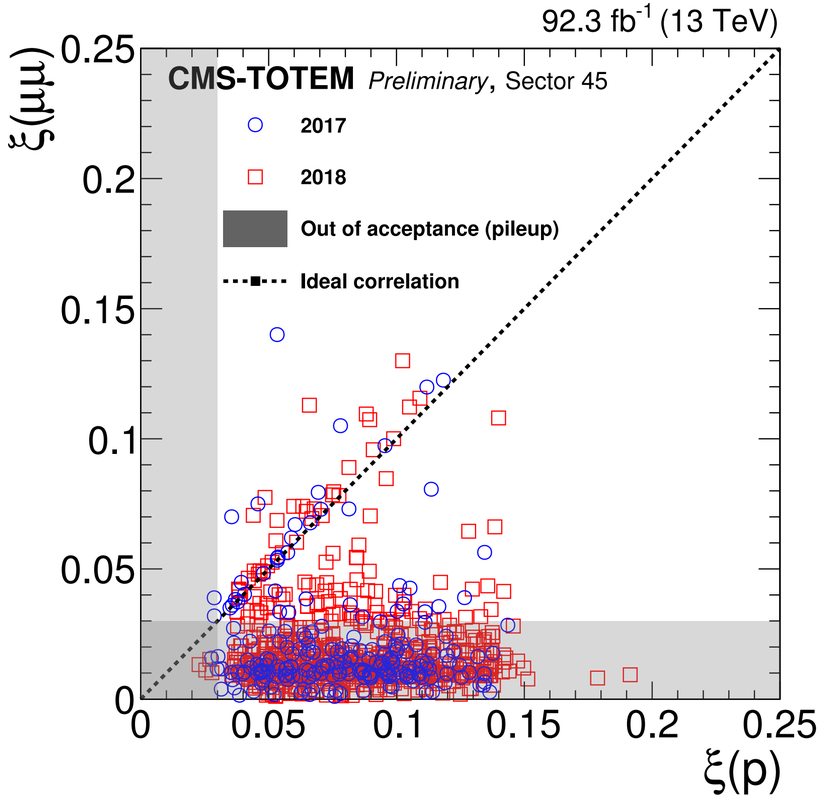
$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_T(\ell^+)e^{\pm\eta(\xi^+)} + p_T(\ell^-)e^{\pm\eta(\xi^-)}\right]$$

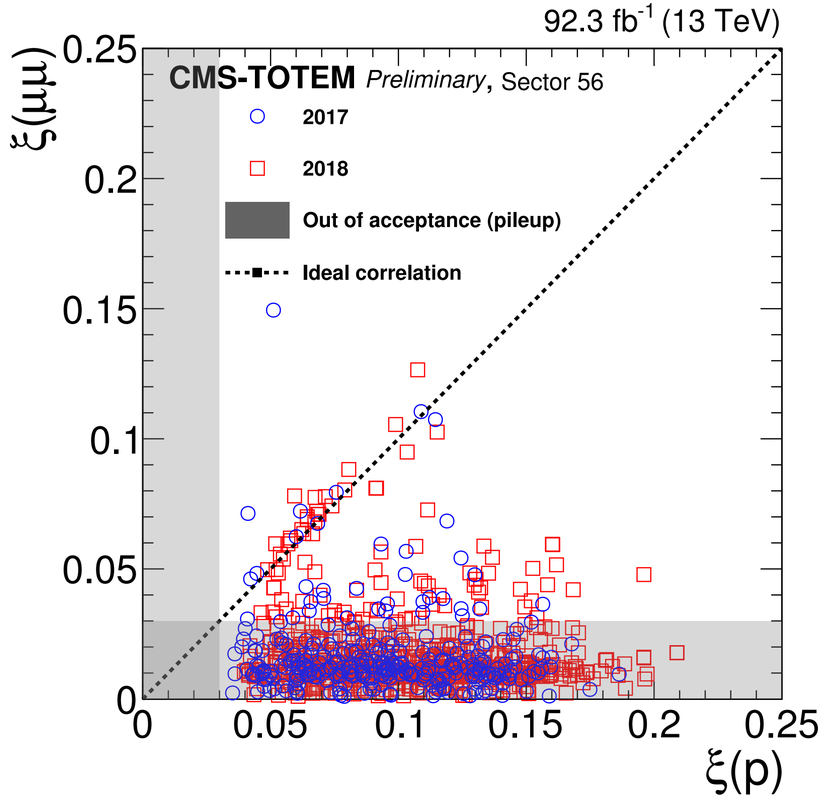


expression ~holds for semi-elastic

2017

2018





92.3/fb

(Semi)exclusive dilepton observation

JHEP 07 (2018) 153
PPS-17-001

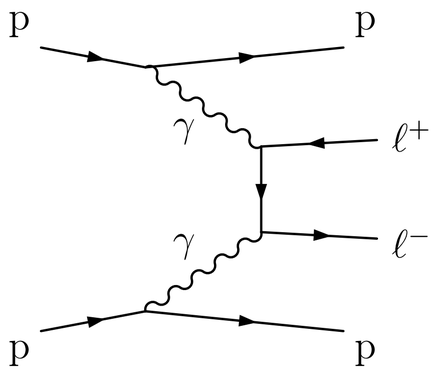
- Early **2016** data of PPS with **9.4/fb** (CMS 15.6/fb)

$$p_T^{\ell} > 50\,\text{GeV}$$

$$a = 1 - |\Delta\phi(\ell^+\ell^-)|/\pi)$$

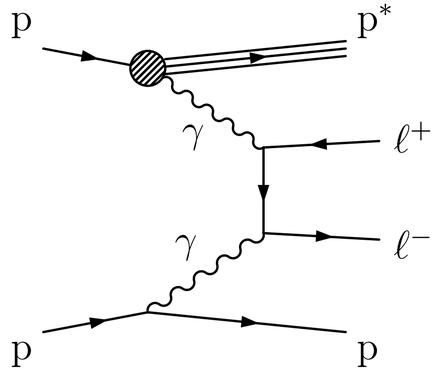
$$a(e^+e^-) < 0.006 \qquad a(\mu^+\mu^-) < 0.009$$

$$m(\ell^+\ell^-) > 110\,\text{GeV}$$



$pp \to p\ell^+\ell^-p$

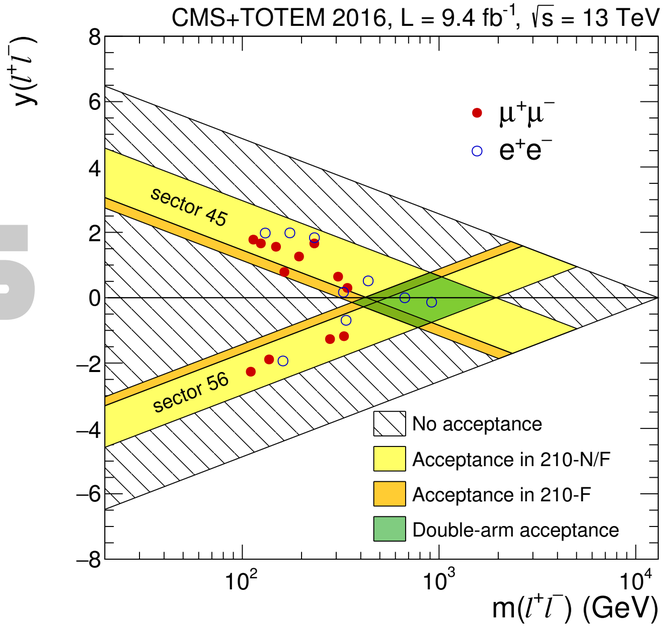
$|\mathcal{S}|^2 = 0.89$



$pp \to p\ell^+\ell^-p^*$

$|\mathcal{S}|^2 = 0.76$

2016



- Overall selection with **one** proton reconstructed in either arm of PPS above 110 GeV:

$12\,\text{events}\ \gamma\gamma \to \mu^+\mu^-$ $8\,\text{events}\ \gamma\gamma \to e^+e^-$

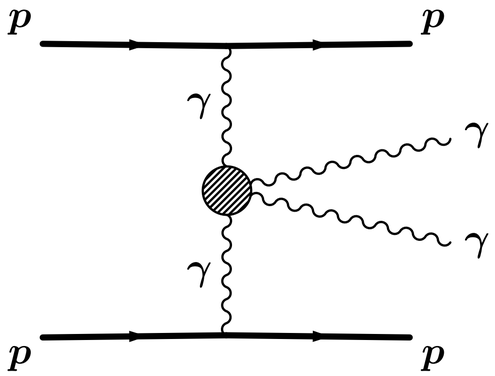
13 events with a track in both near/far RPs

two independent ξ measurements agree within 4%

Exclusive diphoton production

EXO-18-014 (Submitted to PRL)
arXiv:2110.05916

- PPS **2016** data with **9.4/fb** (CMS 15.6/fb)



$$p_T^{\gamma} > 75\,\text{GeV}$$

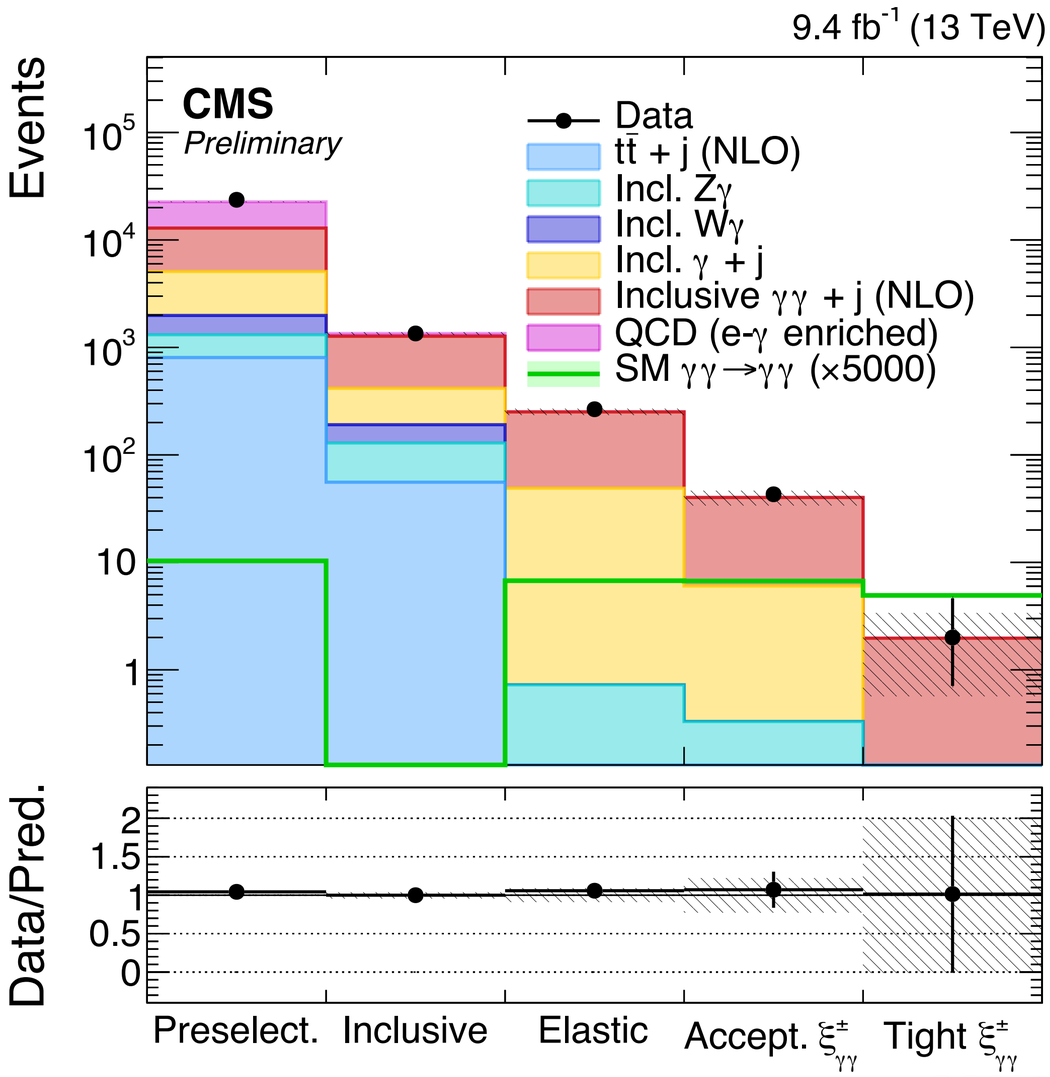
$$a(\gamma\gamma) < 0.005$$

$$m(\gamma\gamma) > 350\,\text{GeV}$$

$$\xi^{\pm}_{\gamma\gamma} = \frac{1}{\sqrt{s}}\left(p_T^{\gamma_1} e^{\pm\eta^{\gamma_1}} + p_T^{\gamma_2} e^{\pm\eta^{\gamma_2}}\right)$$

$$m_{pp} = \sqrt{\xi^{+}\xi^{-}s} \qquad y_{pp} = \frac{1}{2}\log\left(\frac{\xi^{+}}{\xi^{-}}\right)$$

- A **tighter** ξ proton selection is applied for a reconstruction efficiency above 90%

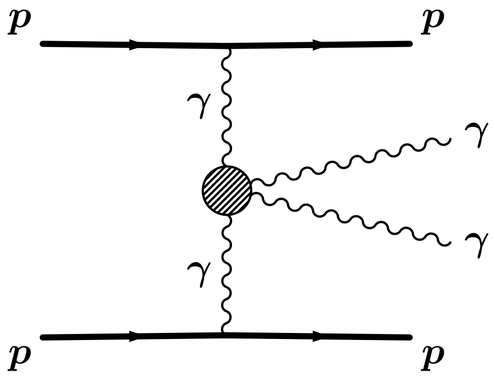


>90% eff

Exclusive diphoton production

EXO-18-014 (Submitted to PRL)
arXiv:2110.05916

- PPS **2016** data with **9.4/fb** (CMS 15.6/fb)



$$p_T^{\gamma} > 75\,\text{GeV}$$

$$a(\gamma\gamma) < 0.005$$

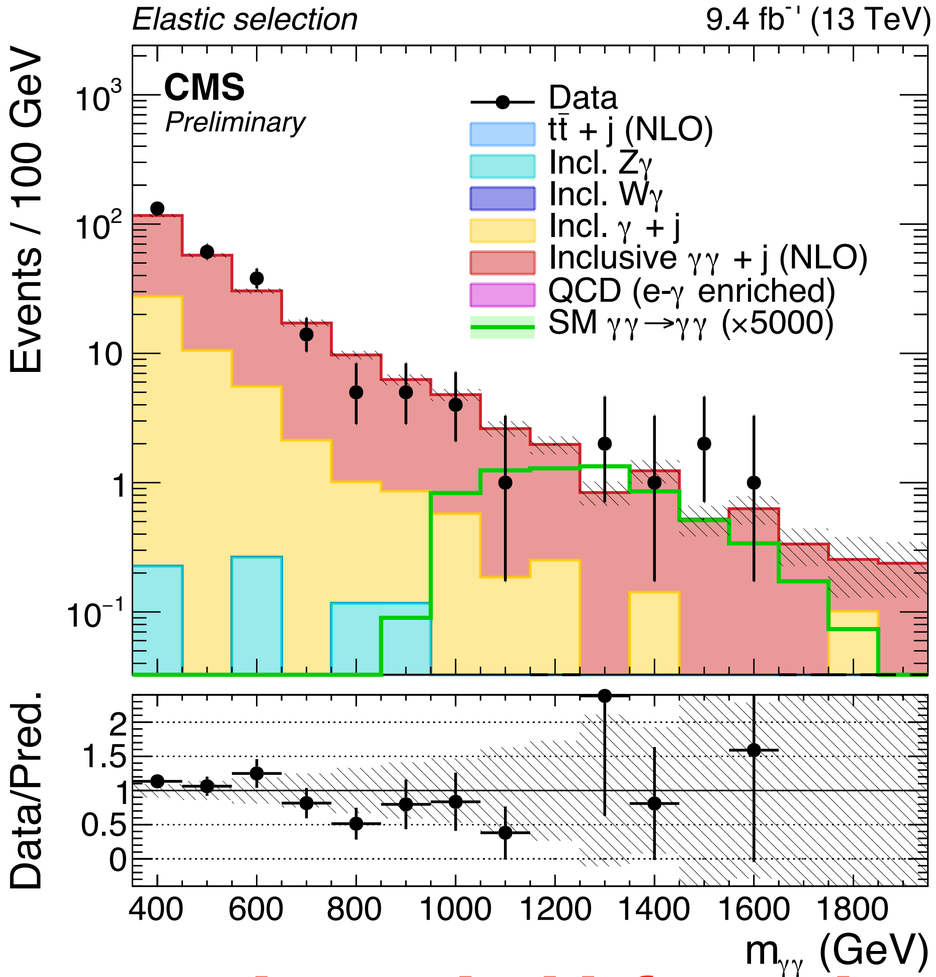
$$m(\gamma\gamma) > 350\,\text{GeV}$$

$$\xi_{\gamma\gamma}^{\pm} = \frac{1}{\sqrt{s}}\left(p_T^{\gamma_1} e^{\pm\eta^{\gamma_1}} + p_T^{\gamma_2} e^{\pm\eta^{\gamma_2}}\right)$$

$$m_{pp} = \sqrt{\xi^{+}\xi^{-}s} \qquad y_{pp} = \frac{1}{2}\log\left(\frac{\xi^{+}}{\xi^{-}}\right)$$

requirement of 2 protons

$$m_{pp} = m_{\gamma\gamma} \qquad y_{pp} = y_{\gamma\gamma}$$



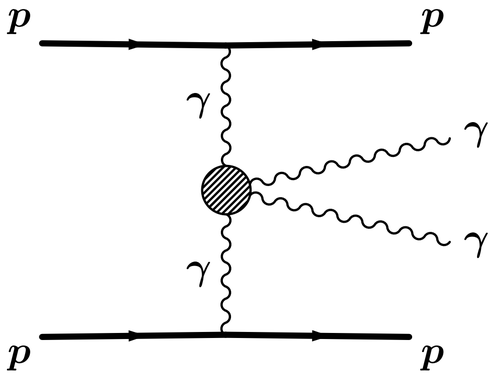
no events observed with forward protons

$$\sigma_{\text{SM}}(pp \to p\gamma\gamma p) < 4.4\,\text{fb}$$

Exclusive diphoton production

EXO-18-014 (Submitted to PRL)
arXiv:2110.05916

- PPS **2016** data with **9.4/fb** (CMS 15.6/fb)



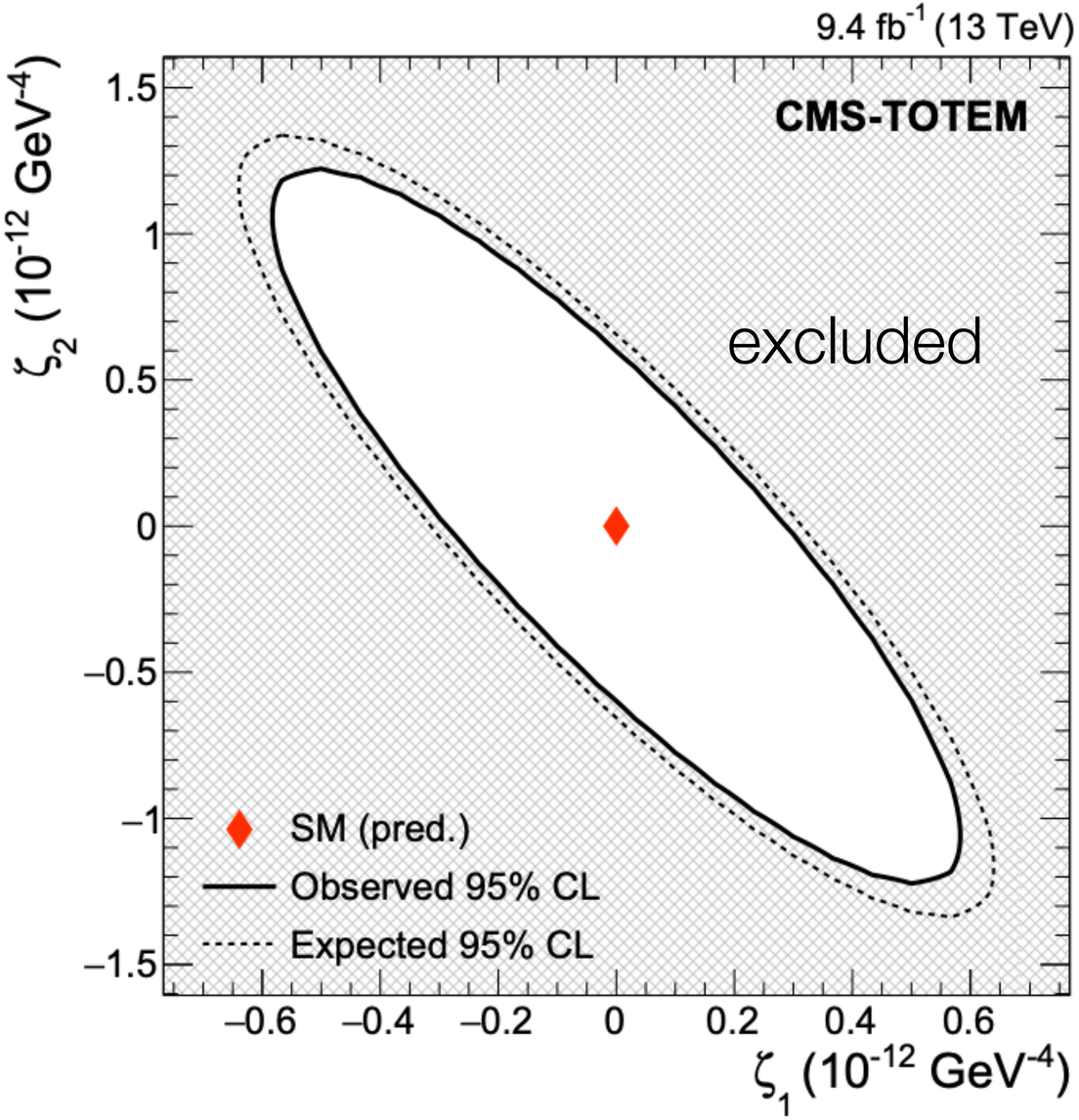
$$p_T^\gamma > 75\,\text{GeV}$$
$$a(\gamma\gamma) < 0.005$$
$$m(\gamma\gamma) > 350\,\text{GeV}$$

- Anomalous $\gamma\gamma\gamma\gamma$ gauge coupling:

$$\mathscr{L}_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

- **First** limits on **dimension-8** $\gamma\gamma\gamma\gamma$ couplings:

$$|\zeta_1| < 2.88 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_2 = 0)$$
$$|\zeta_2| < 6.02 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_1 = 0)$$



Summary

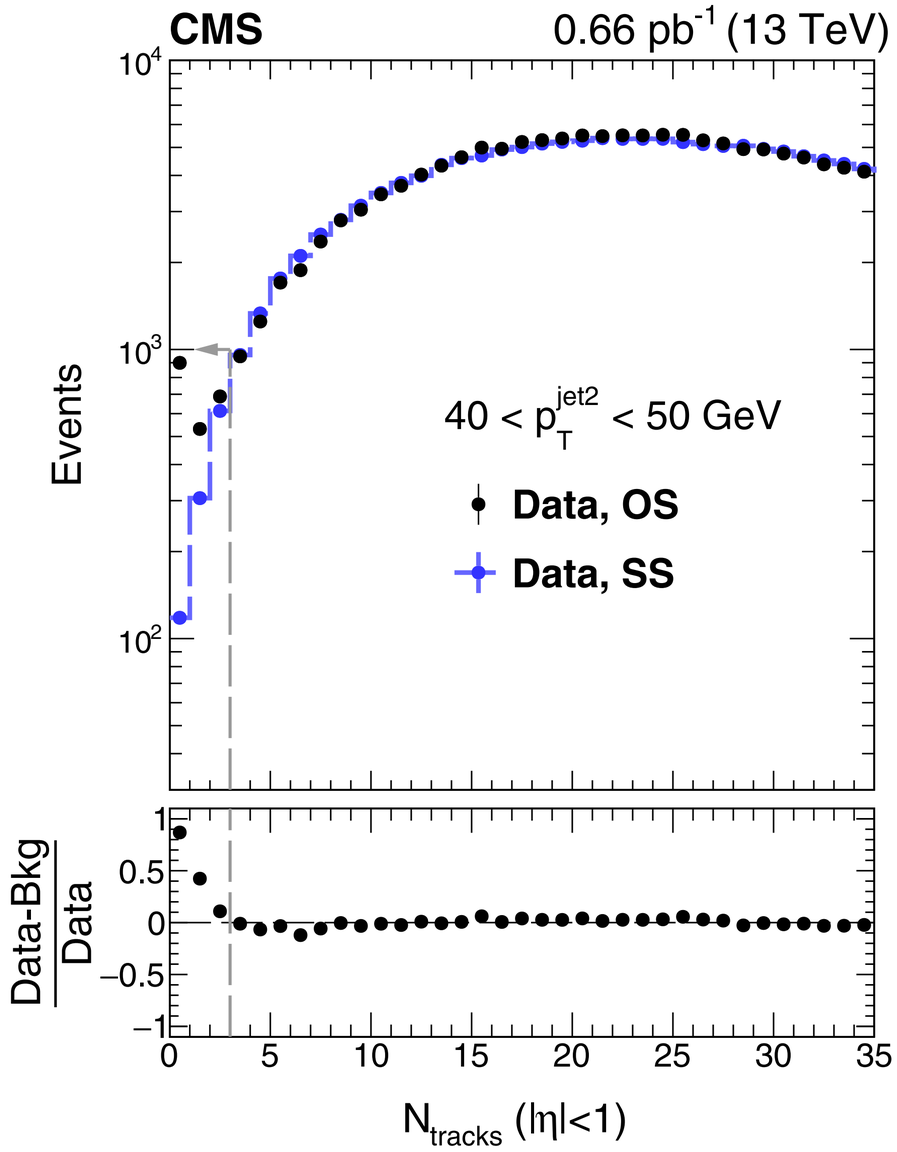
- The CMS and TOTEM Collaborations are performing **precise measurements** of QCD over the last years
  - Kinematical region to explore extensions of the SM for evidences of **New Physics**
- The Jet-Gap-Jet results provide new insight on the **BFKL dynamics** by extending the kinematical region probed at high-energies
  - **First time** jet-gep-jet events with proton tag are observed
- PPS has completed a full Run 2 data-taking period with the **first observation** of exclusive dilepton production with proton tagging
- PPS data has opened the searches at the **high-mass** region for exclusive processes
  - First search for **exclusive diphoton production** at high masses and investigation of evidences of New Physics

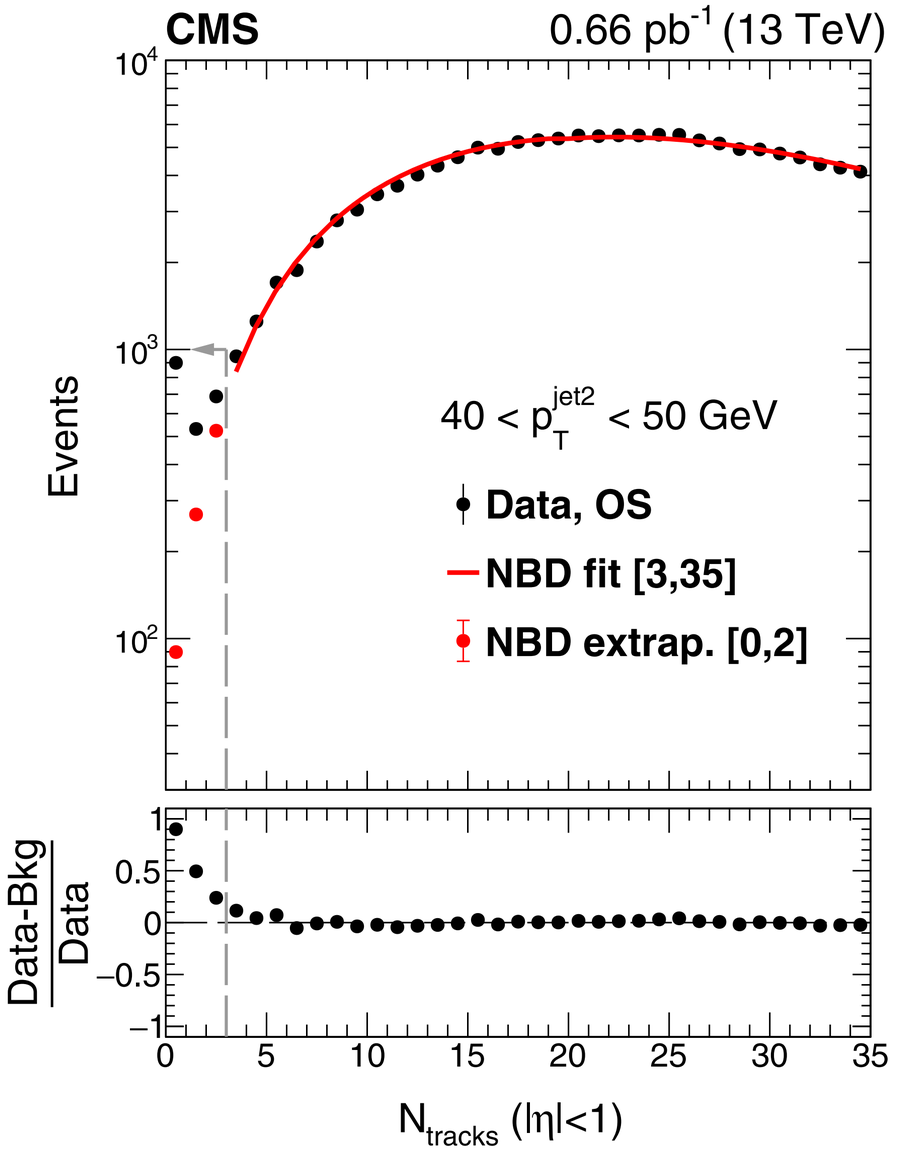
MORE RESULTS COMING SOON

BACKUP

Color-exchange background estimation

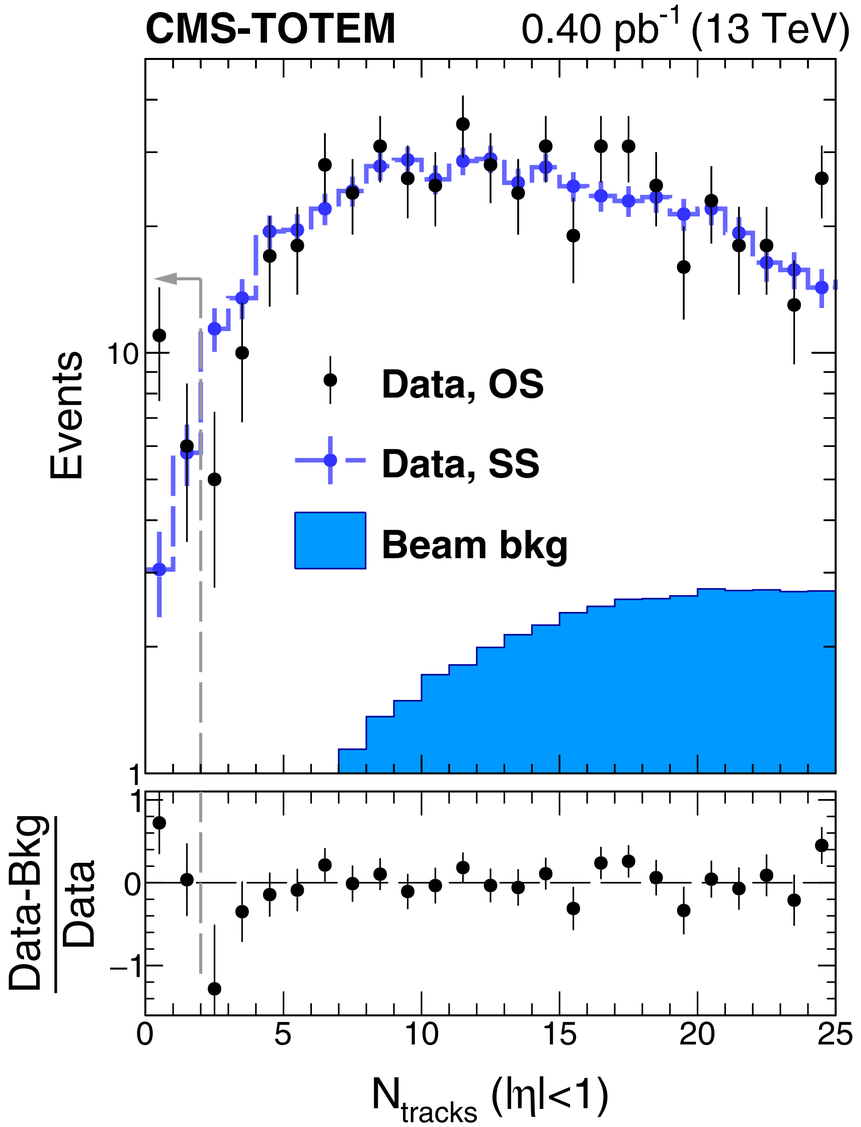
no proton tagging

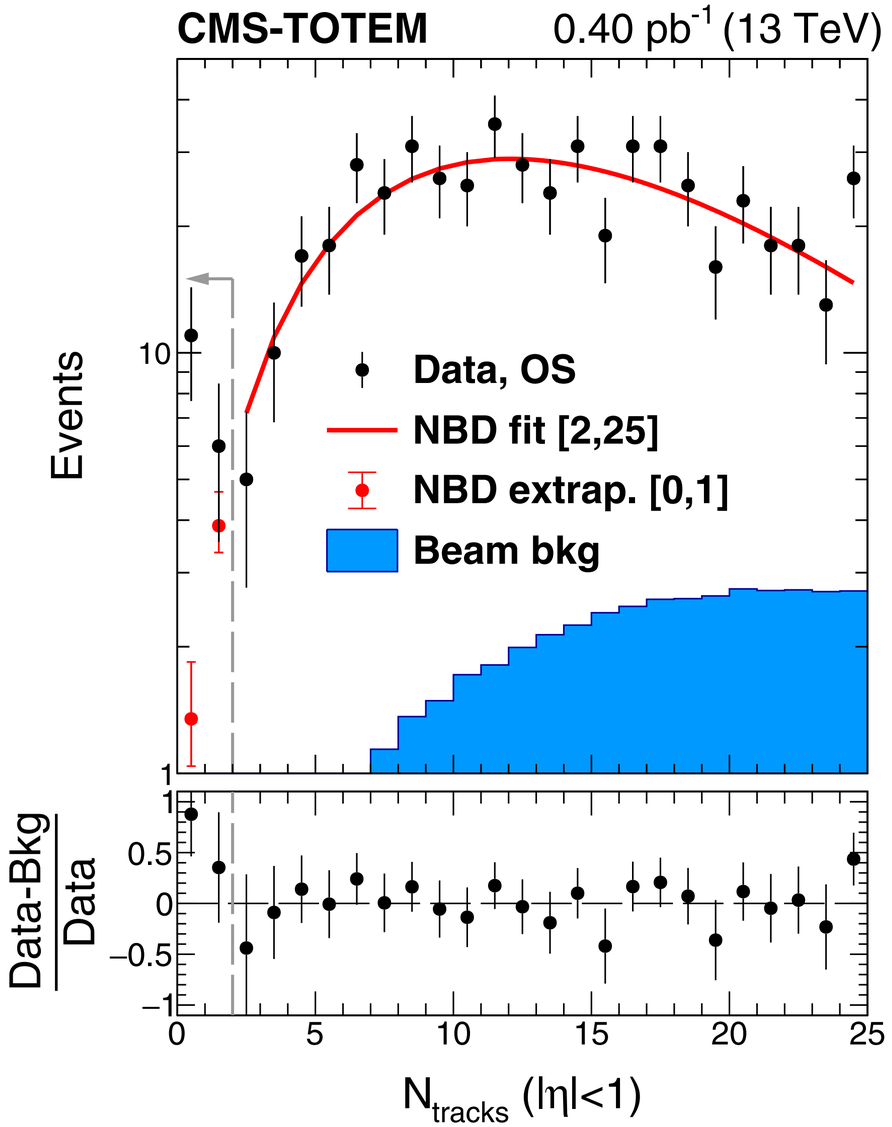




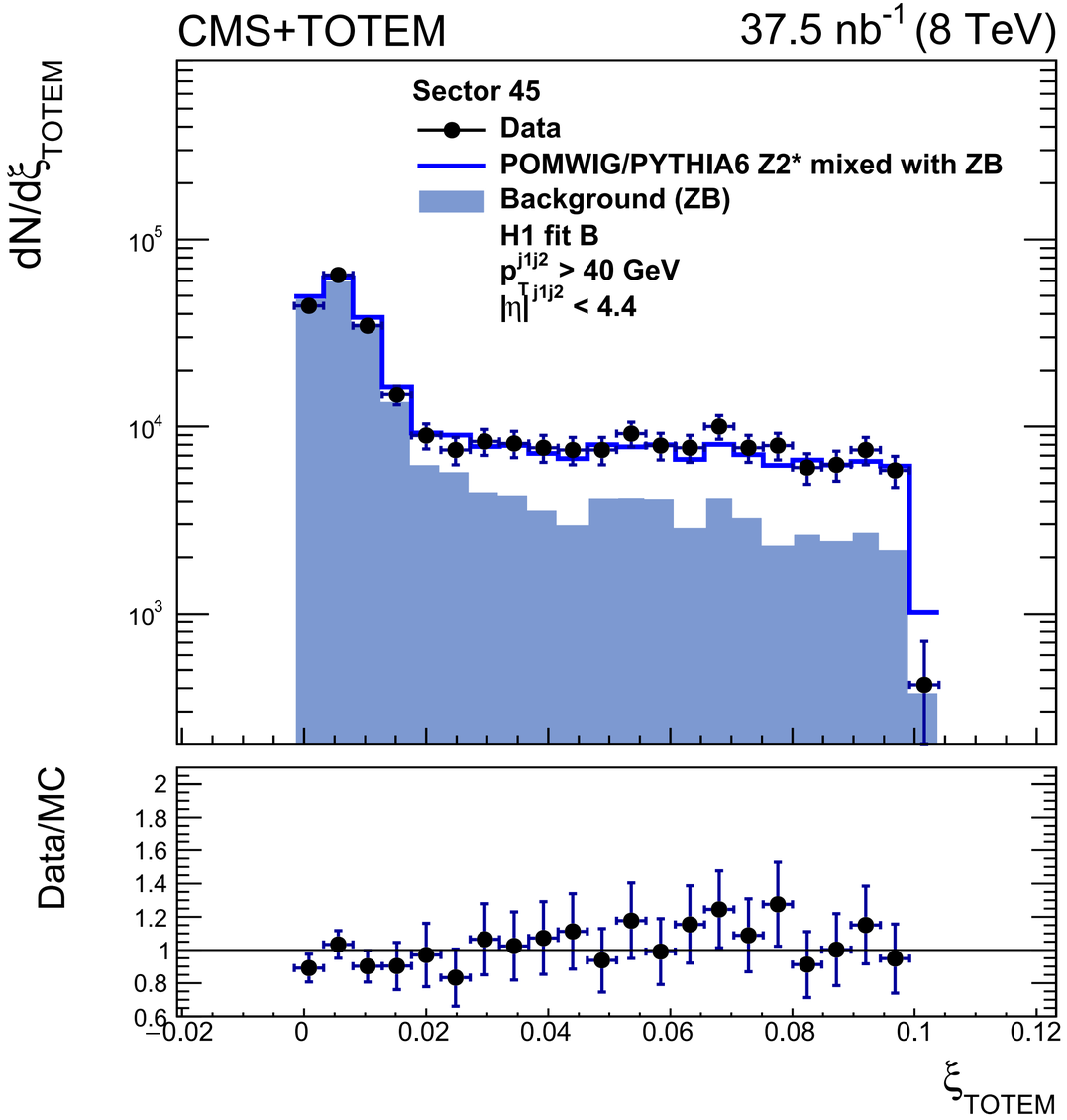
Color-exchange background estimation

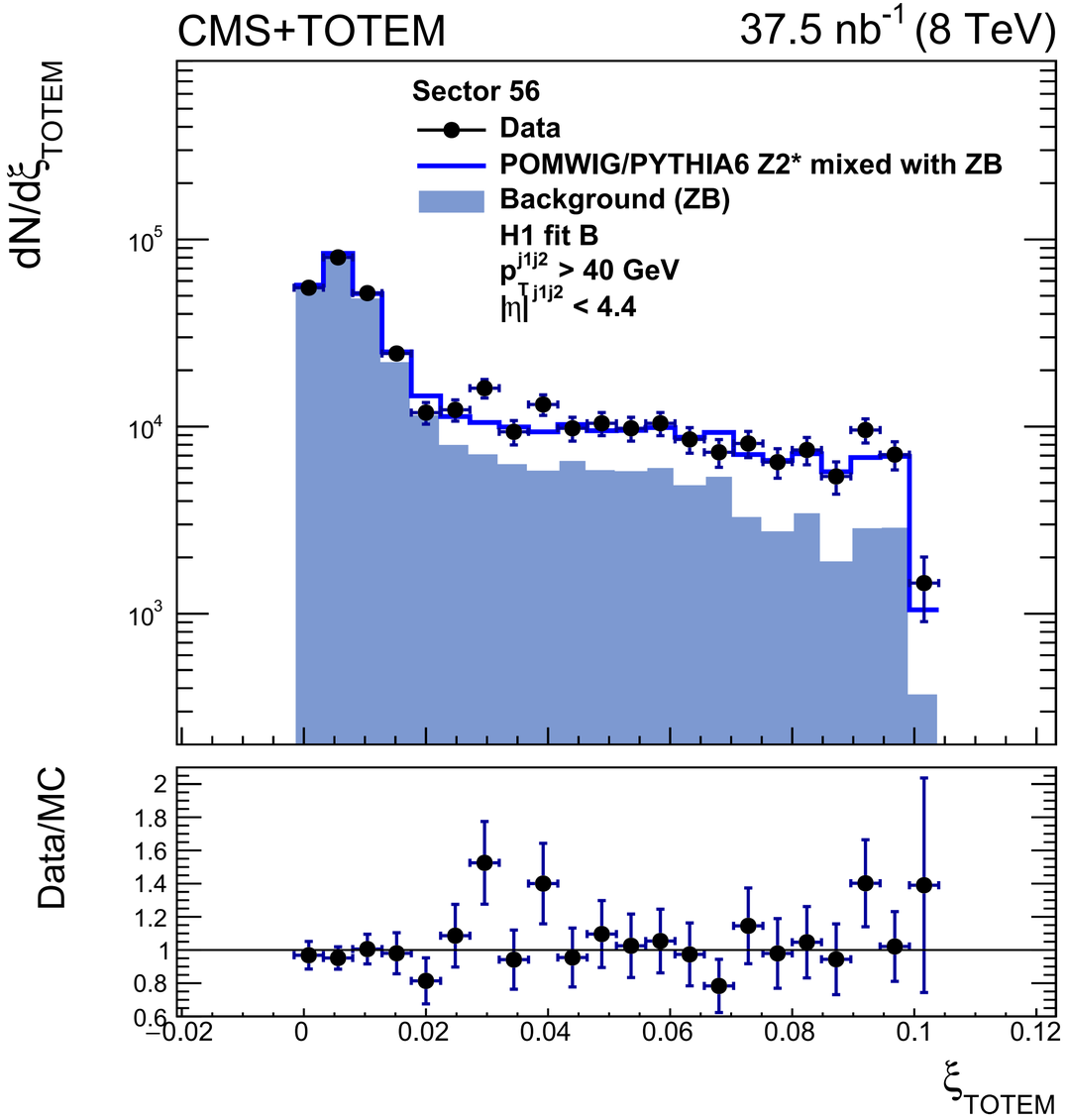
with proton tagging



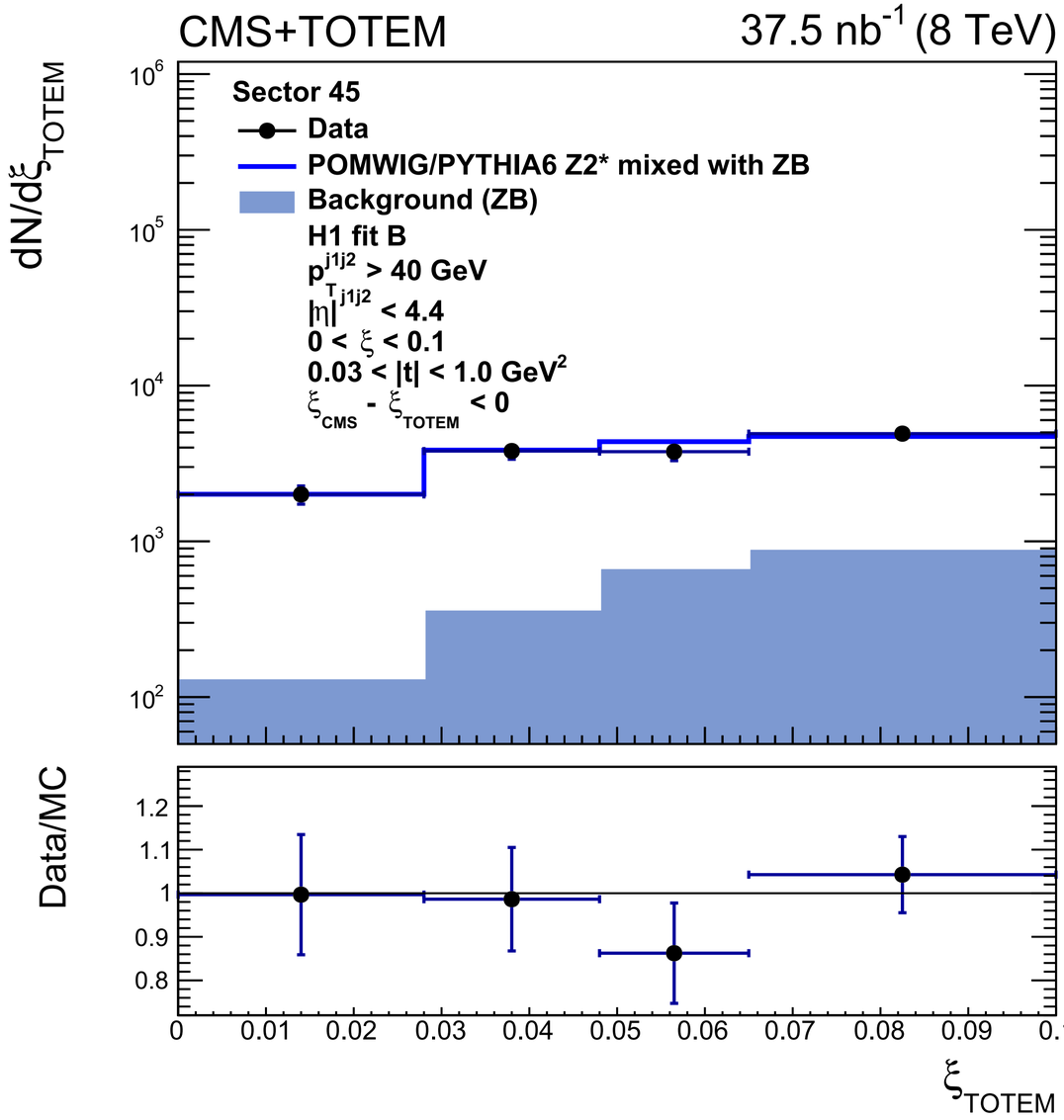


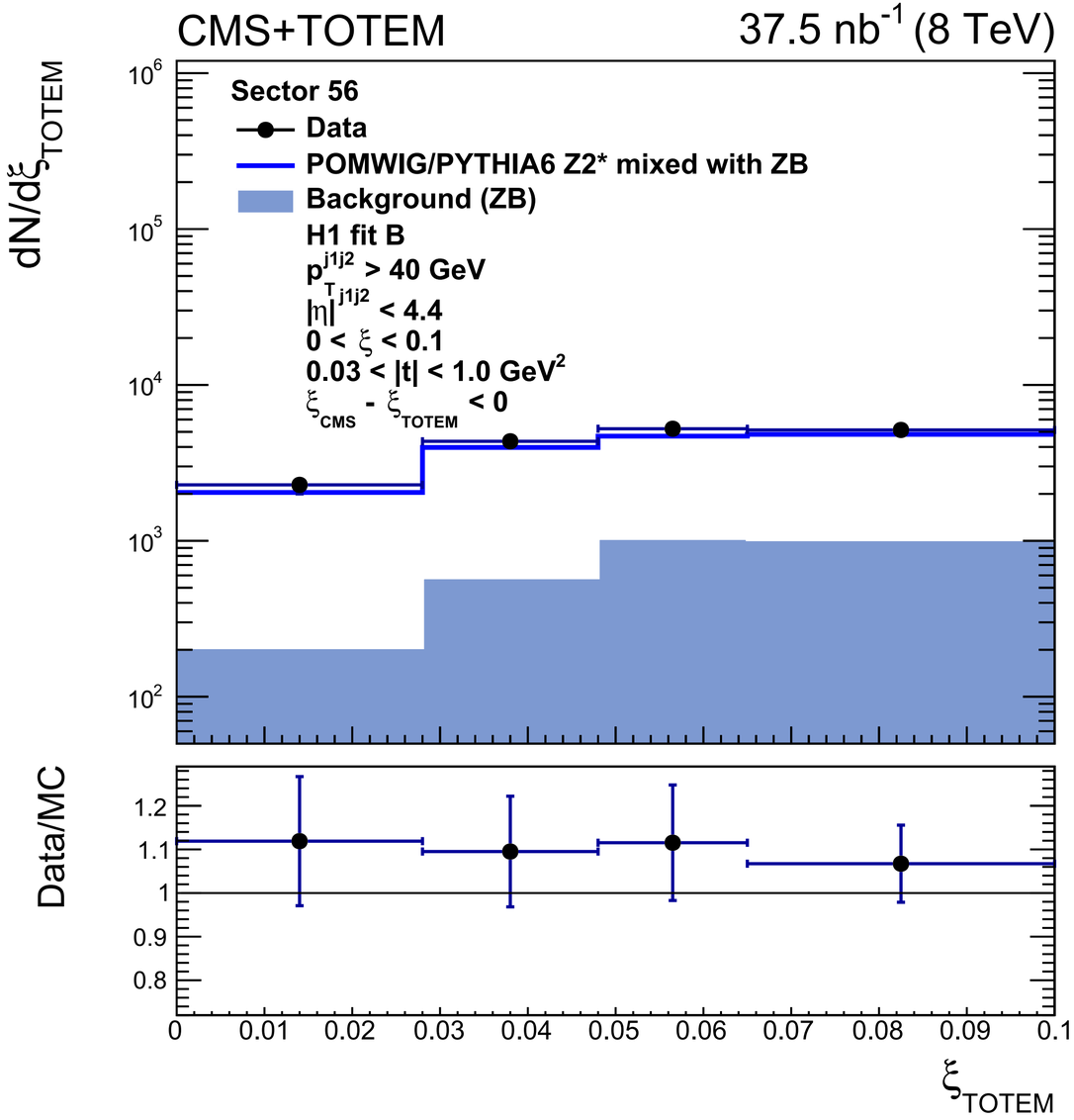
Distribution with $\xi_{CMS} - \xi_{TOTEM}$



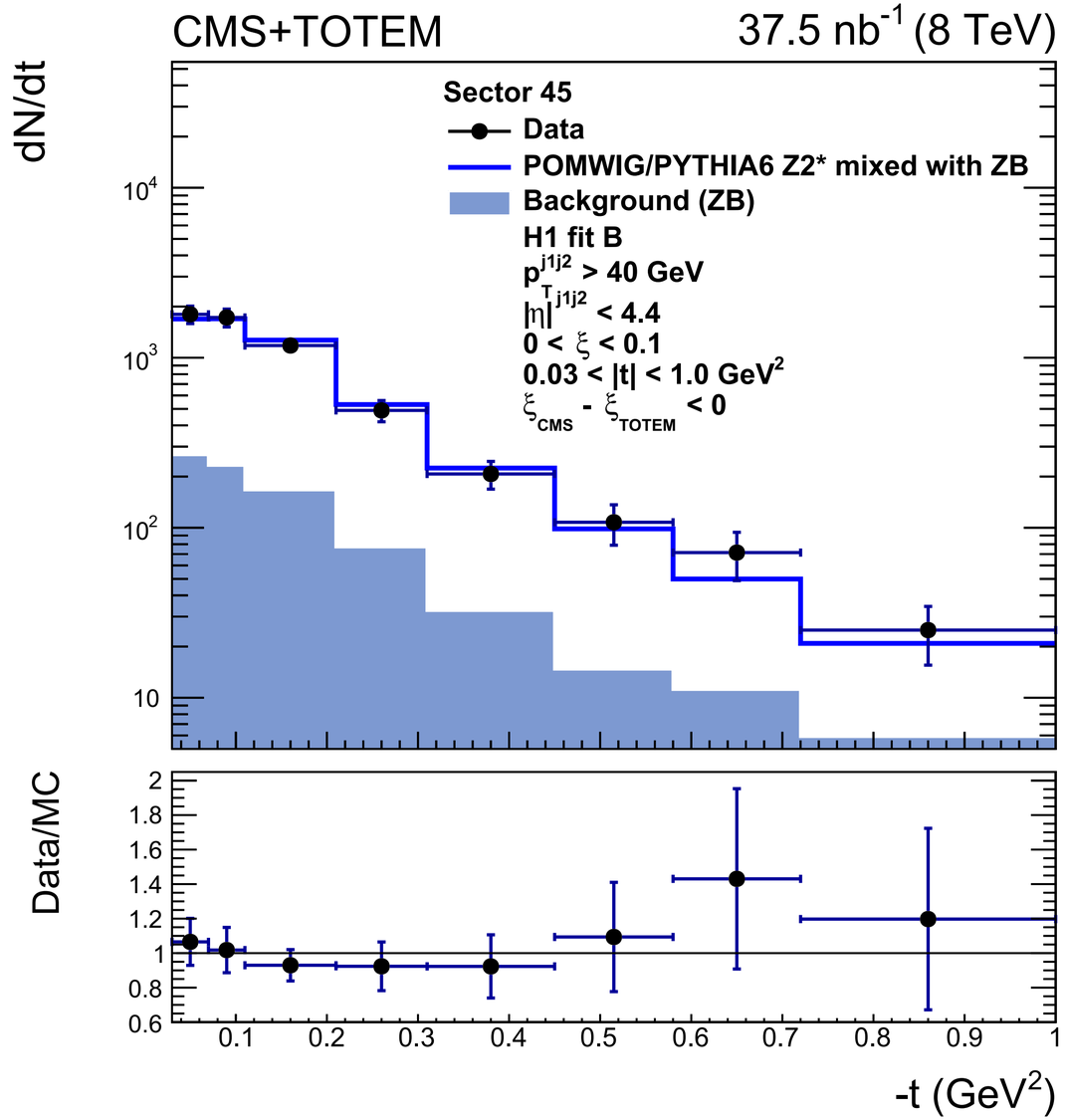


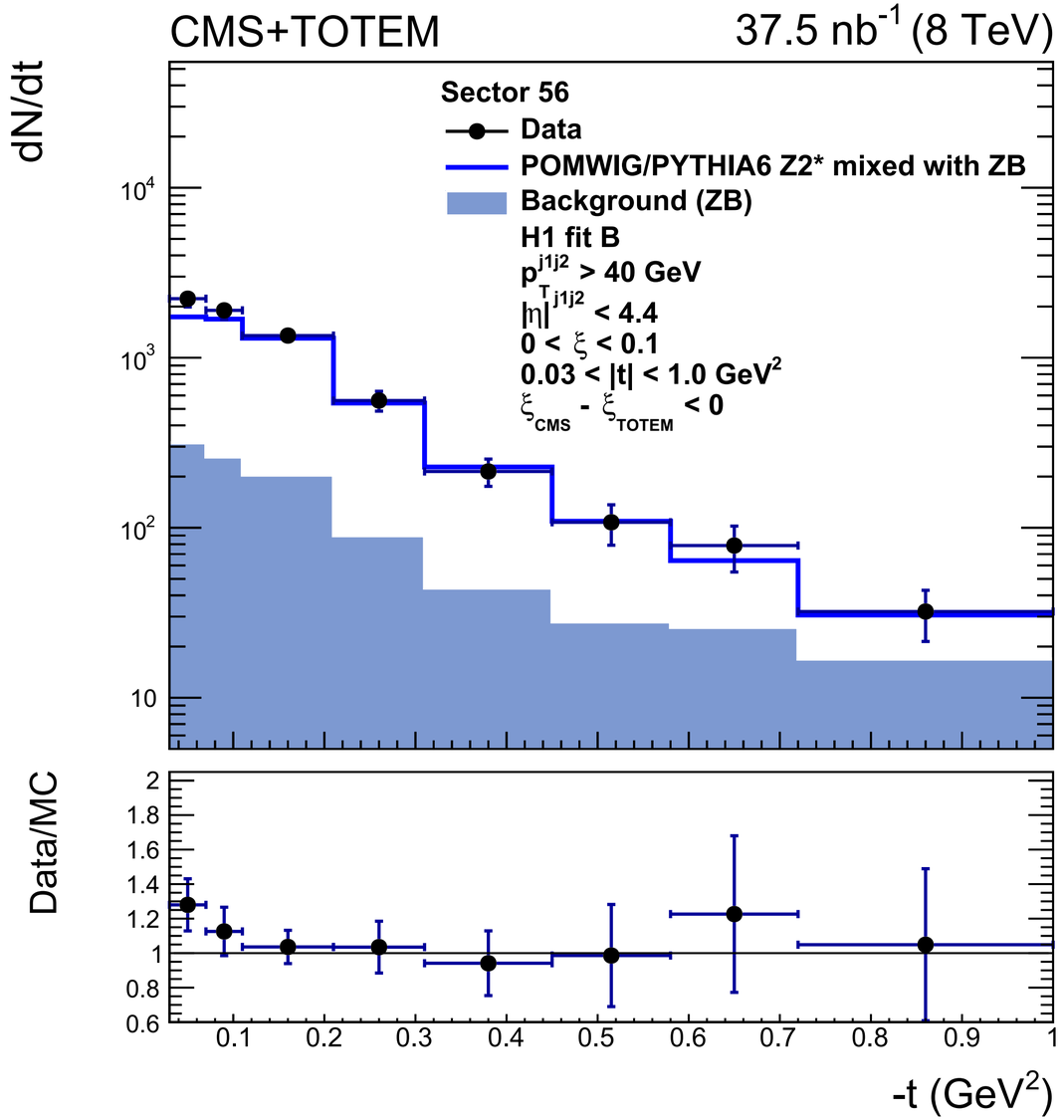
Distribution after $\xi_{CMS} - \xi_{TOTEM}$



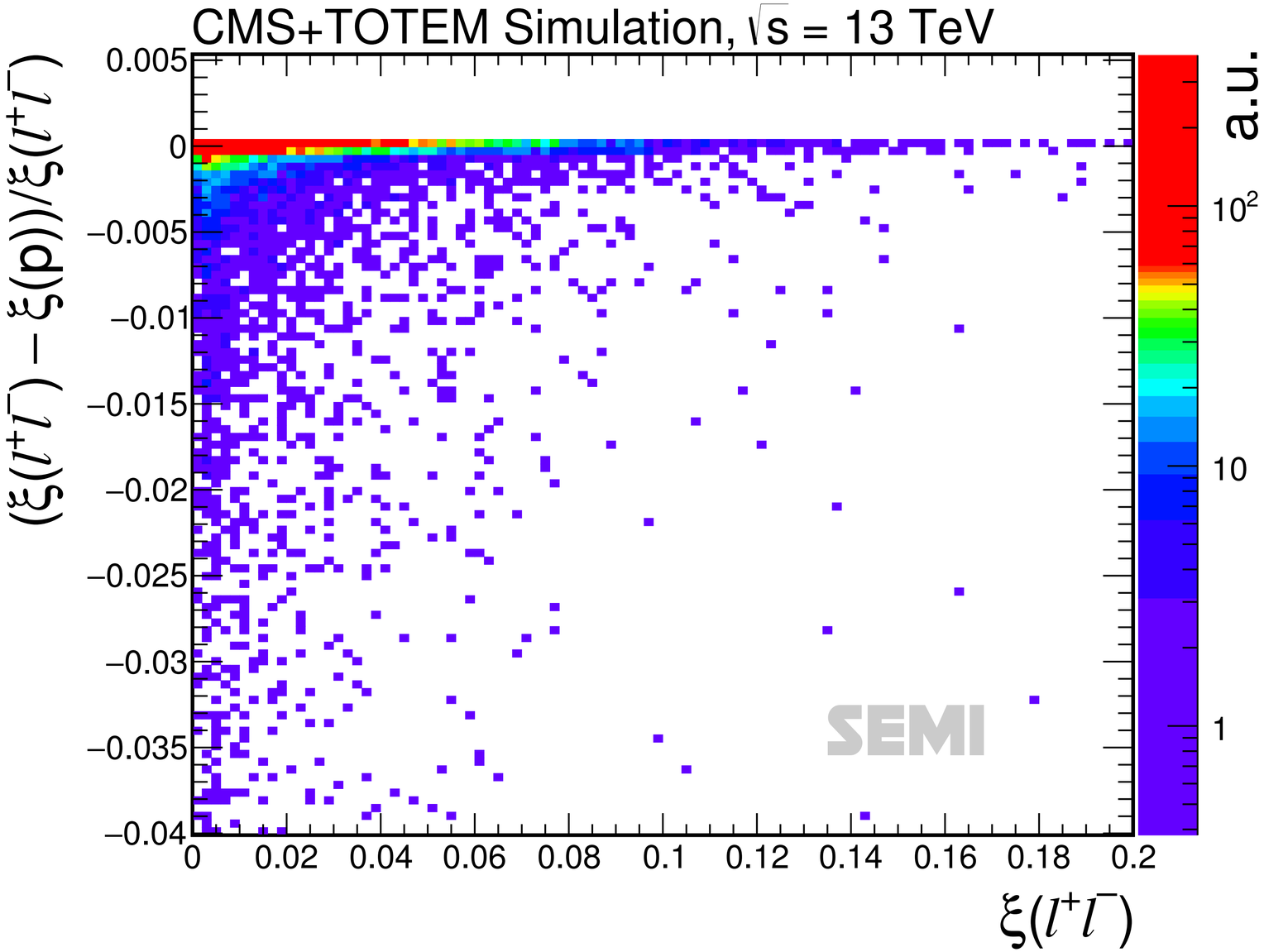


Distribution after $\xi_{CMS} - \xi_{TOTEM}$





Semi-elastic case



Ratio in terms of parton momentum fraction