Very forward measurements at the LHC

(a selection of recent results from LHCf, CMS-Forward, TOTEM and CT-PPS)

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on behalf of:

CMS LHCf TOTEM

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LHCP2017

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on Large Hadron Collider Physics
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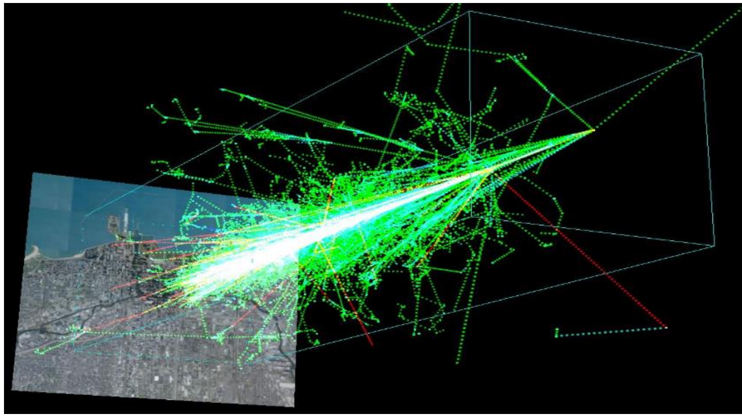
Introduction and outlook



Thanks to the exceptional coverage of many LHC experiments in the forward region, the LHC data are unique for a better understanding of many fundamental aspects of the hadron-hadron interaction, like:

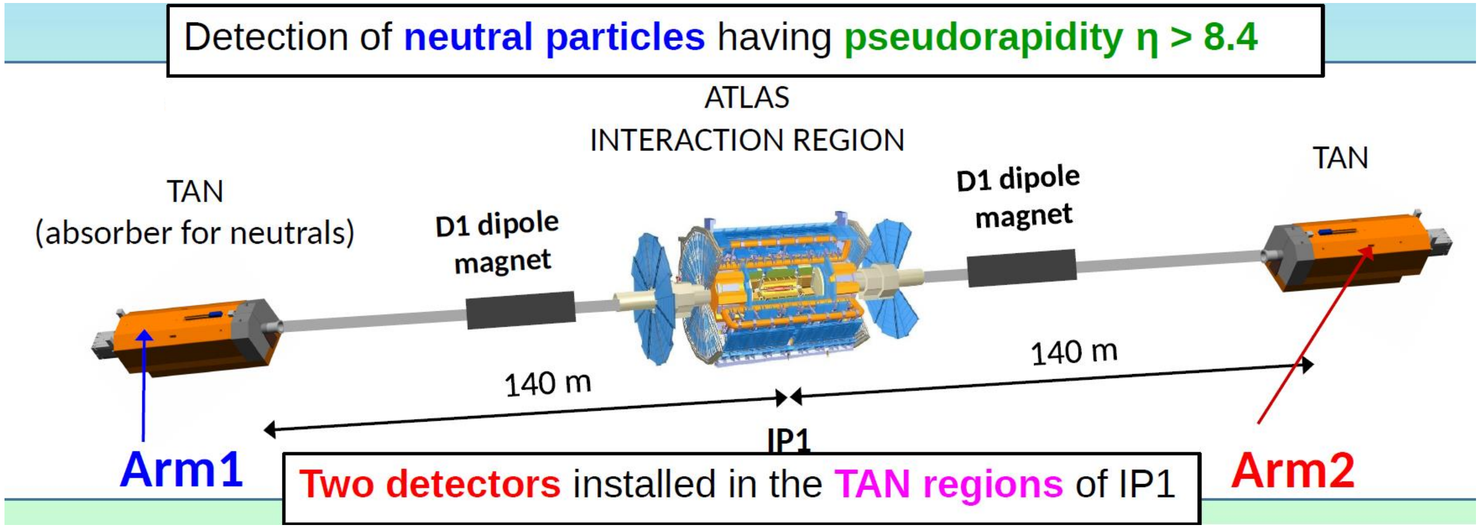
- *The dynamics of the coherent hadronic interaction (elastic/diffractive)*
- *The modelling of the high energy cosmic-ray showers*
- *The evolution of the gluon pdf at small-x*
- *The modelling of the Multiple Parton Interaction*
- *(…)*

This talk will address some recent forward physics measurements published at the LHC:

- ***Recent total, inelastic and elastic cross section measurements by TOTEM.***
- ***Proton tagging with the new proton spectrometers at high-luminosity (in particular CT-PPS).***
- ***Forward γ/n measurement with LHCf***
- ***Forward pp energy flow and p-A jets production measured by CMS-CASTOR***

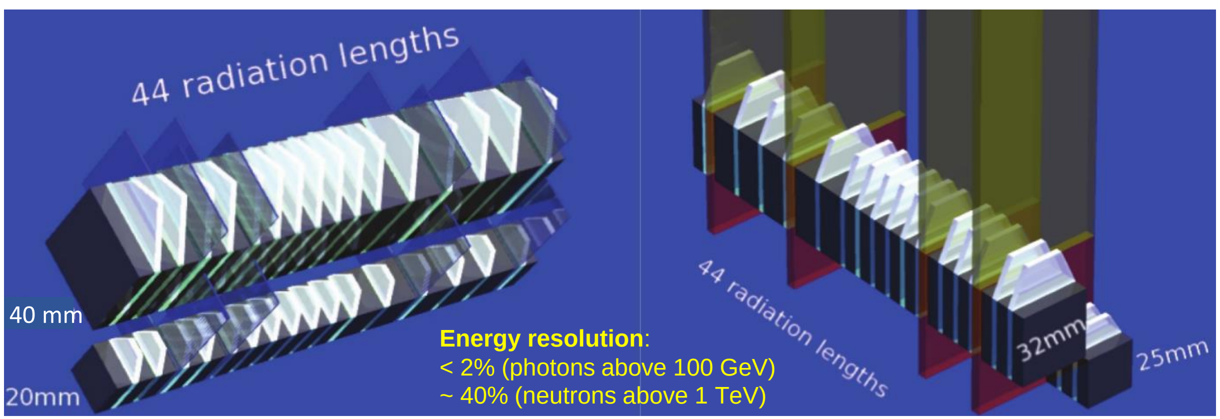
… and this is of course a non-comprehensive list !!

The LHCf experiment



Arm 1:

- **Position resolution**:
  - < 200 μm (photons)
  - < 1 mm (hadrons)
- **Imaging layers:**
  - 4 x-y GSO bars
- **1.6 λ_I, 44X_0**

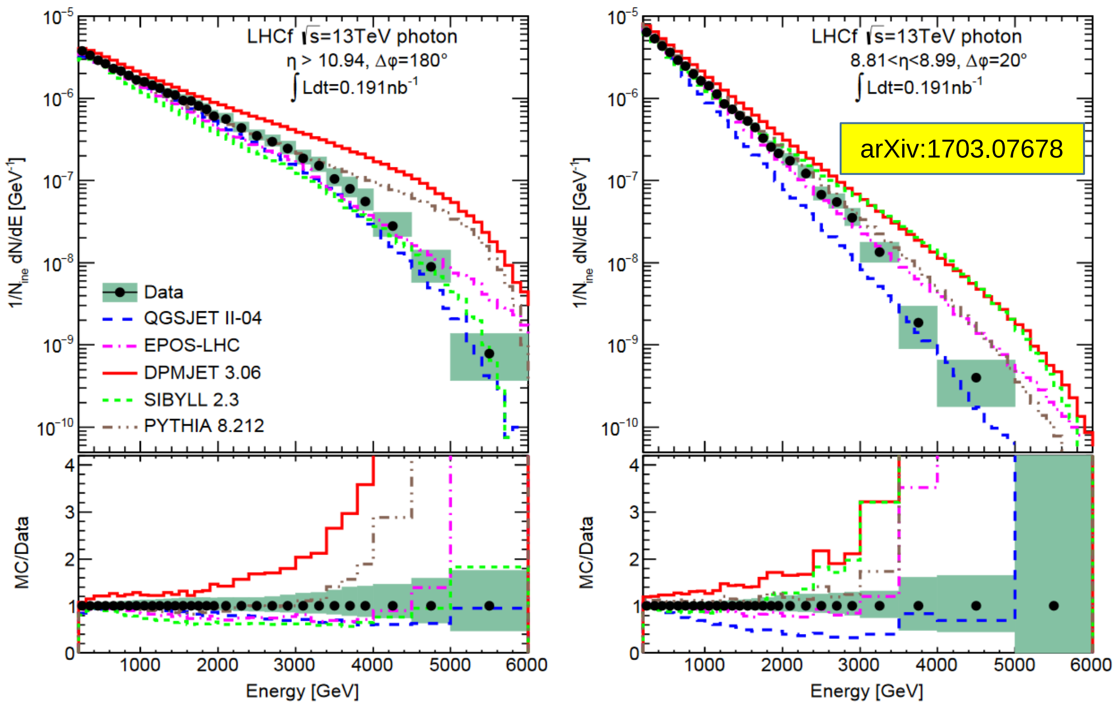


Arm 2:

- **Position resolution**:
  - < 40 μm (photons)
  - < 400 μm (hadrons)
- **Imaging layers:**
  - 4 x-y silicon microstrip
- **1.6 λ_I, 44X_0**

Recent reults from LHCf

Measurement of forward photon-energy spectra for √s = 13 TeV proton-proton collisions with the LHCf detector



- Inclusive single-photon analysis
- $\eta > 10.94$ and $8.81 < \eta < 8.99$
- $0.191\ nb^{-1}$, $\mu \sim 1\%$
- Photon PID, multi-hit rejection, beam background correction
- Spectrum Unfolding

> ➢ *Although none of the models agrees perfectly with the data, EPOS-LHC shows the best agreement with the experimental data among the models.*
>
> ➢ *Important measurement to improve the knowledge of hadronic interaction models for HECR Physics.*

Future plans:

- Opportunity in proton-Oxygen collisions.
- The detailed studies with event-by-event information measured by ATLAS (see later) will be able to help us understand more fully the production of photons in the forward region.

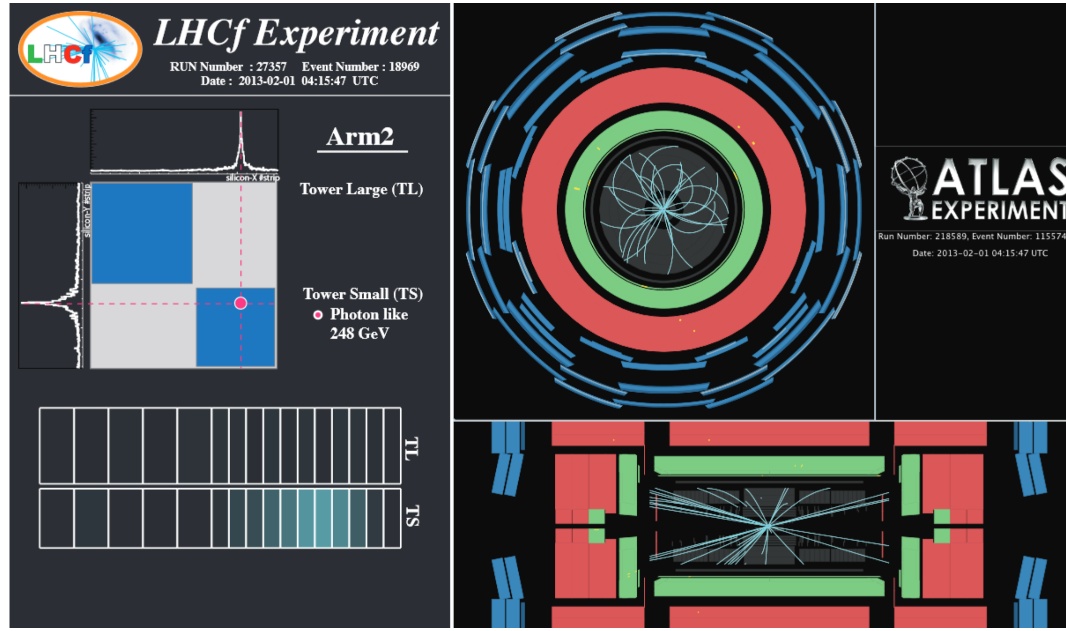
Reminder:
LHCf –ATLAS common trigger

ATL-PHYS-PUB-2015-038

ATLAS LHCf NOTE

August 26, 2015

Classification of Events in the Combined ATLAS-LHCf Data Recorded During the p+Pb Collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV



- The LHCf and ATLAS experiment demonstrated already in 2013 the capability to generate a common trigger.
- LHCf trigger signal was incorporated in the ATLAS Level-1 trigger system, events are then matched offline.
- Preliminary analysis of the combined dataset has been carried out: possibility to further improve our understanding of cosmic-ray air showers and modelling of inelastic processes at the LHC:
  - ➢ *Enhanced discrimination power by using information from ATLAS to classify the events with reconstructed particles in LHCf (diffractive/non diffractive).*

Recent reults from LHCf: neutron differential cross section at 13 TeV

Preliminary

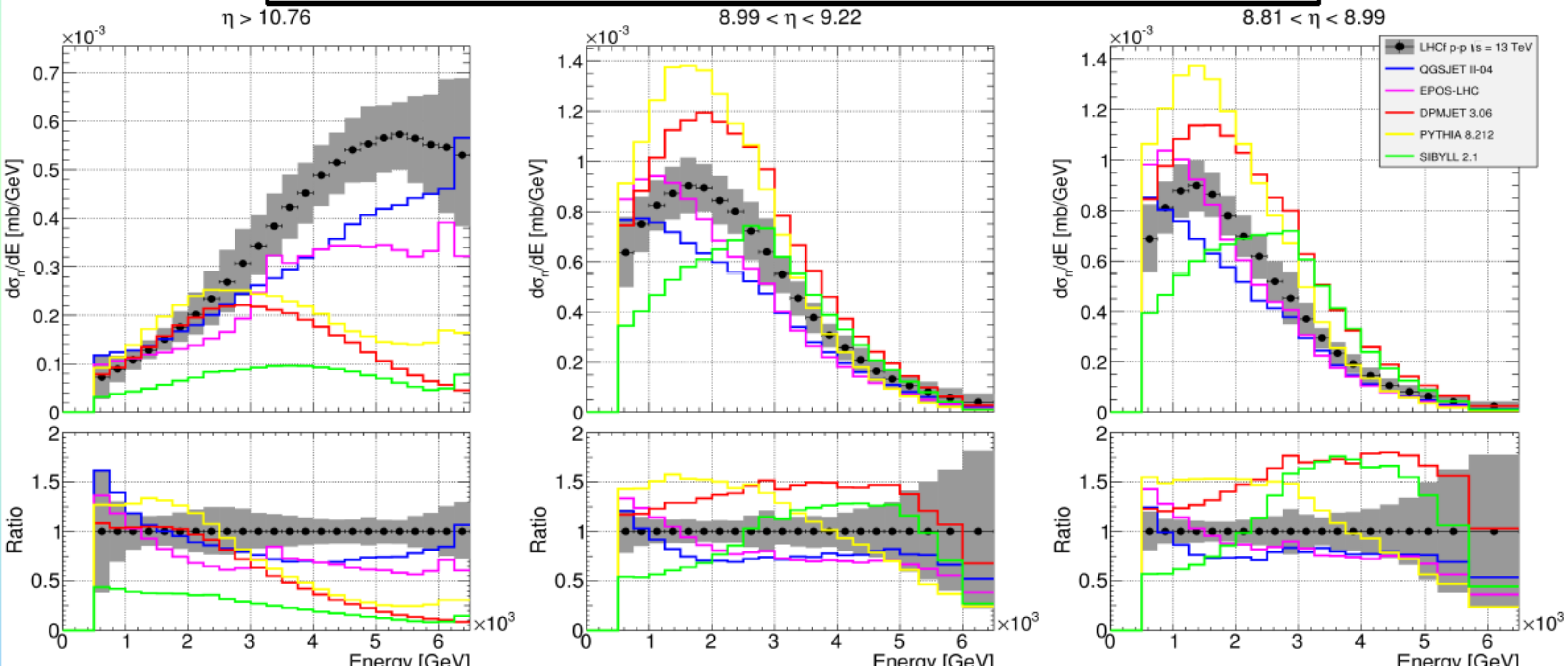
(thanks to E. Berti: PhD Thesis CERN-THESIS-2017-035)

Analysis completed in Arm2 and ongoing in Arm1

Arm2 unfolded spectra

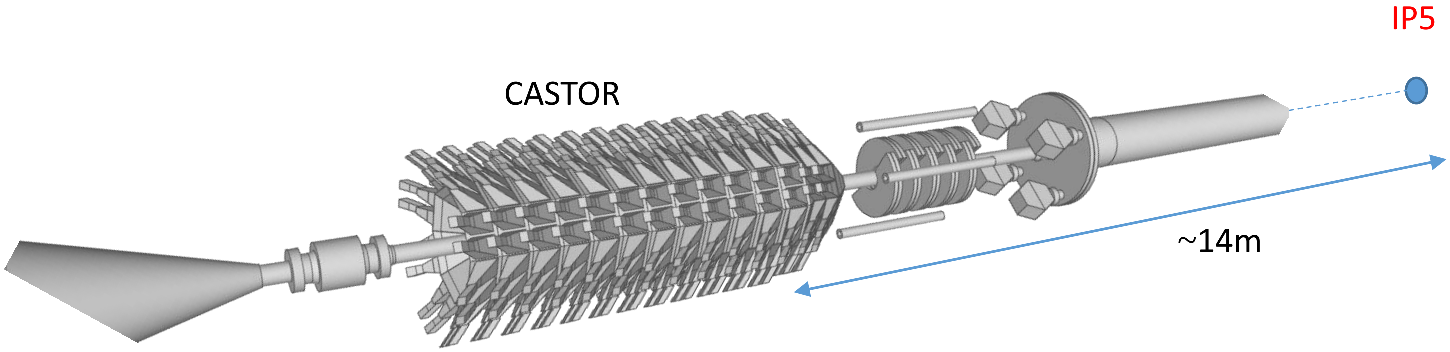
Differential neutron production cross section

$$d\sigma_n/dE = \frac{dN(\Delta\eta,\Delta E)}{E}\frac{1}{L}\times\frac{2\pi}{d\varphi},$$



Only **QGSJET II-04** qualitatively reproduces behavior of data in η > 10.76
EPOS-LHC has the best overall agreement in 8.81 < η < 9.22 despite lower yield

The Castor calorimeter



- Forward CMS detector: $-6.6 < \eta < -5.2$, about 14.37 m from the IP
- Sampling calorimeter: Quartz plates embedded in W absorbers
- 16 sectors in transverse/azimuthal plane, no segmentation in η
- 14 modules along z-axis (10.5 λ_i, 20X_0)

Selected recent results:

- CMS-FSQ-16-002: inclusive energy spectrum in the very forward direction pp collisions at 13 TeV (arXiv:1701.08695)
- CMS-PAS-FSQ-17-001: forward inclusive jet cross sections for p+Pb collisions at 5.02 TeV

(see http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html for a complete list of analyses)

Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s}$ = 13 TeV

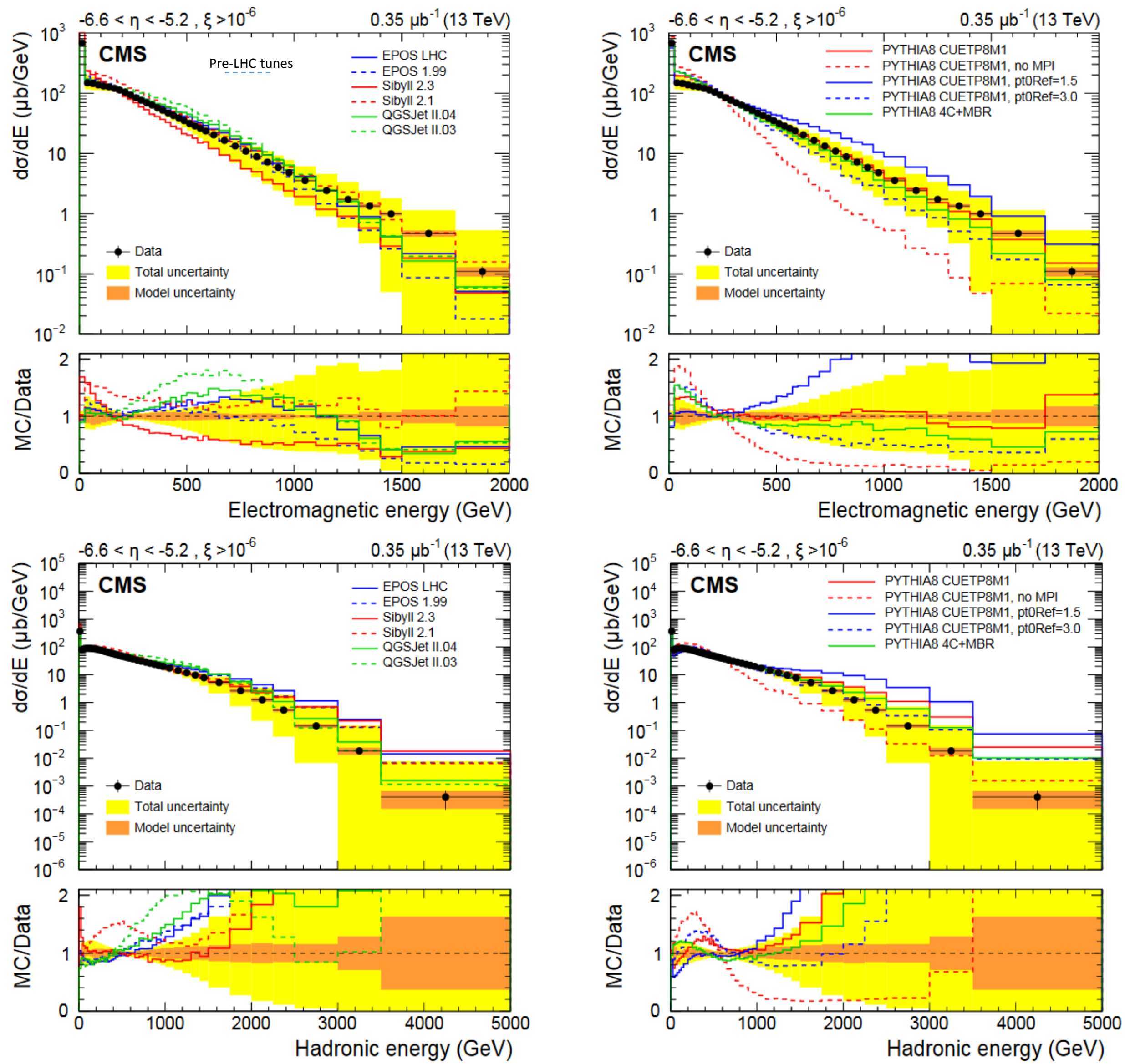
https://arxiv.org/abs/1701.08695

Event selection:

- BX trigger & HF activity (either side) & Castor E>5 GeV

Important messages:

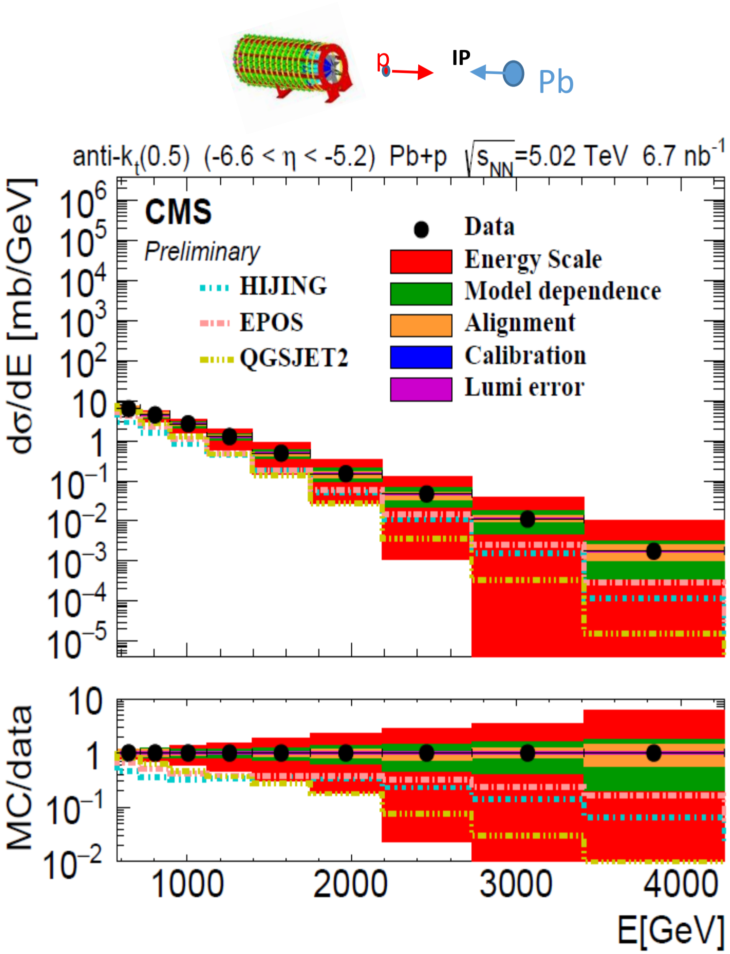
- PYTHIA8 CUETP8M1 without MPI is ruled out by the data (without MPI the spectra are much more soft).
- The shape of the spectra is significantly influenced by the MPI-related settings in PYTHIA8. The present results can therefore contribute to improvements in future Monte Carlo parameter tunes.
- Generators used in CR analyses like LHC-tuned QGSJET II and SIBYLL show better agreement. However they underestimate the μ production rate in extensive air showers: possible to improve the hadronic shower component thanks to these measurements

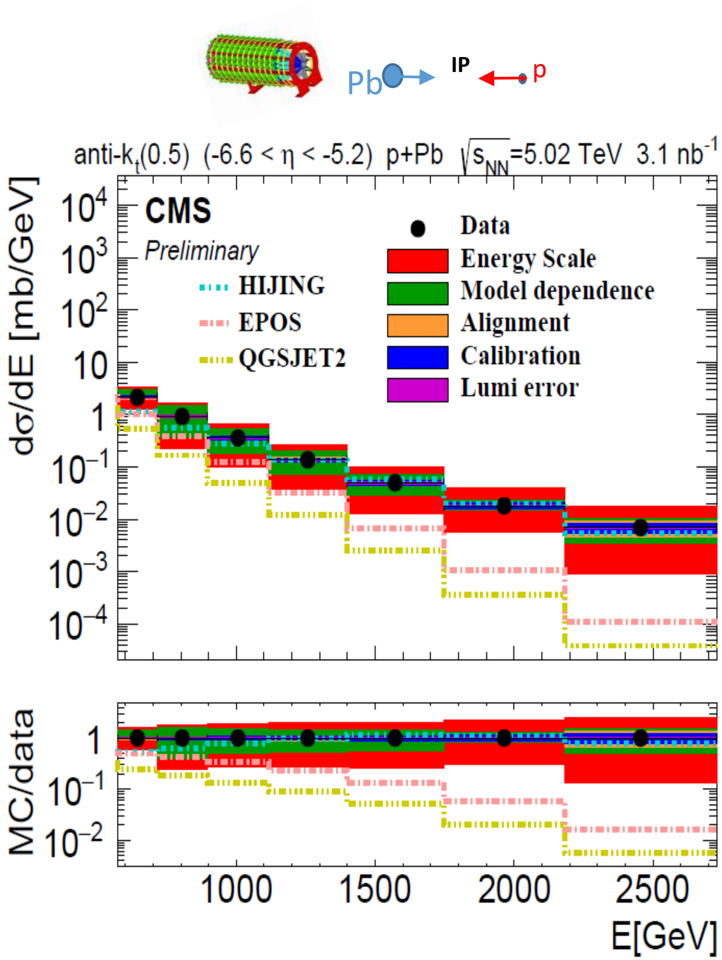


Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

Analysis representative of pPb events having:

- a particle on both sides of the HF acceptance with a minimal energy of 4 GeV
- a charged particle in the central acceptance with p_T above 0.4 GeV/c

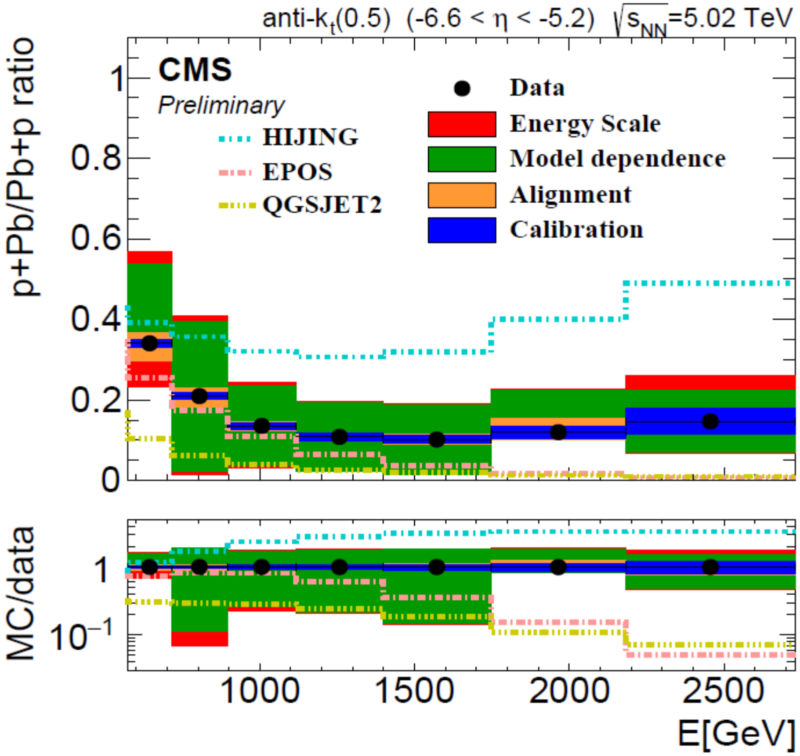


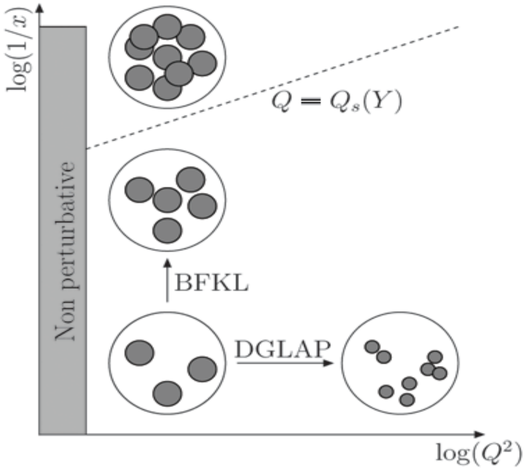


Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

p-Pb collisions are ideal to search for signature of non-DGLAP parton evolution scheme.

- These effects are expected to be important at gluon small-x and high density.
- In ions, gluon densities are larger than protons, moreover the x carried by the parton can be very small for this measurement since $x = \frac{p_T \cdot e^{-|\eta|}}{\sqrt{s}}$ and $P_{T\,min}$= 4 GeV.



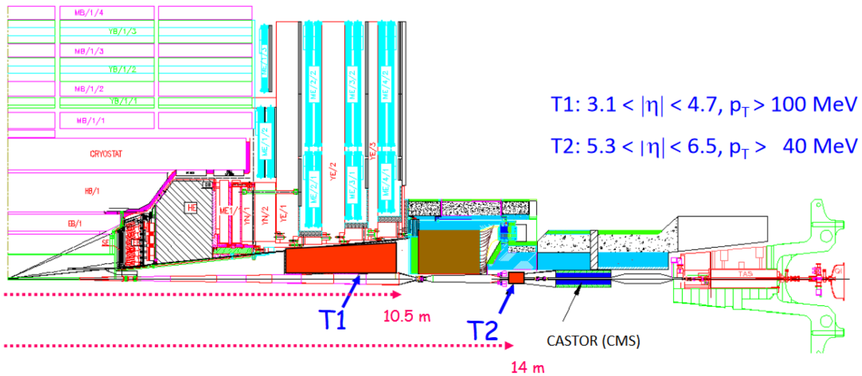


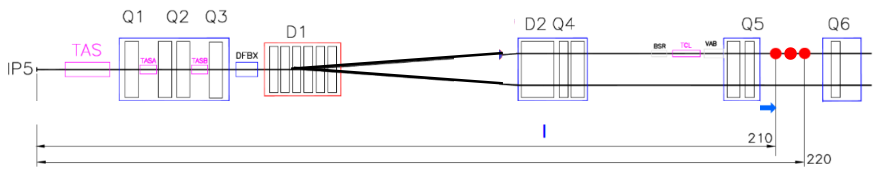
Important messages:

None of the models investigated are capable of describing all the spectra.

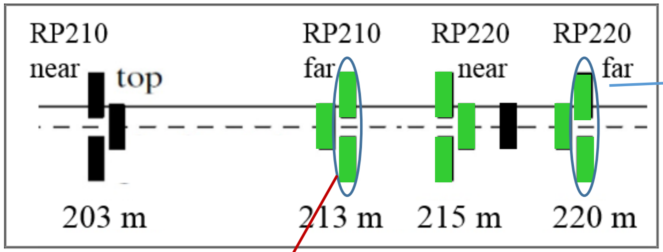
- The p+Pb spectrum is well described by HIJING
- The Pb+p spectra, is underestimated at lower energy while the models are consistent with the data for E>1.2 TeV
- The spectrum of the p+Pb/Pb+p ratio is more precise as the dominating uncertainty (energy scale) cancel out. All the models investigated don't describe this distribution
- *Future:* Analyses ongoing on single inclusive jet spectra in pp at (7, 13 TeV) and in pA (5 TeV). Planned to start analysis on jet-gap-jet and fw-central correlations

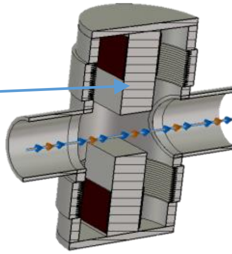
The Totem experiment



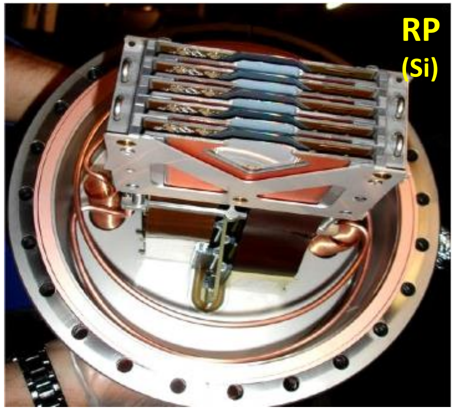


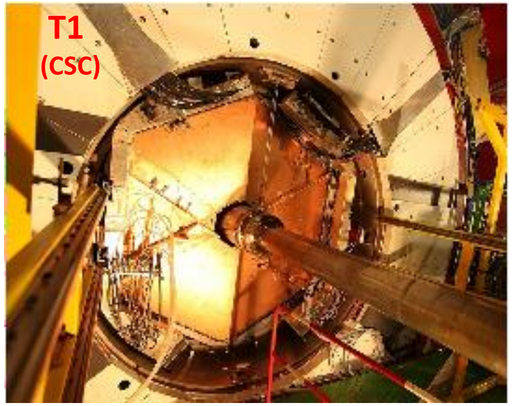
Improved RP system for LHC-Run2 measurements (3 station/side):

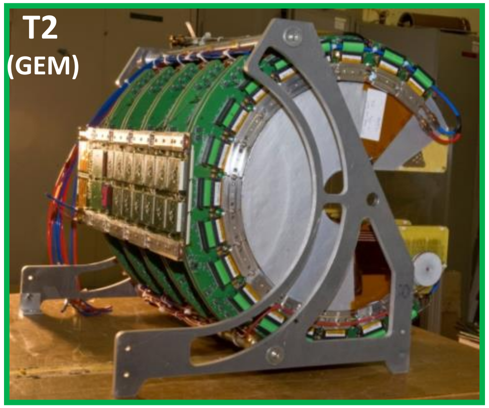




This RP is rotated by about 8 deg to increase multi-track capability







Recent reults from TOTEM

σ_{tot}, σ_{inel}, σ_{el} vs $\sqrt{s}$

with the luminosity independent method: $\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$

TOTEM @ $\sqrt{s}$ = 2.76 TeV

(ρ = 0.145):

σ_{tot} = 84.7 ± 3.3 mb

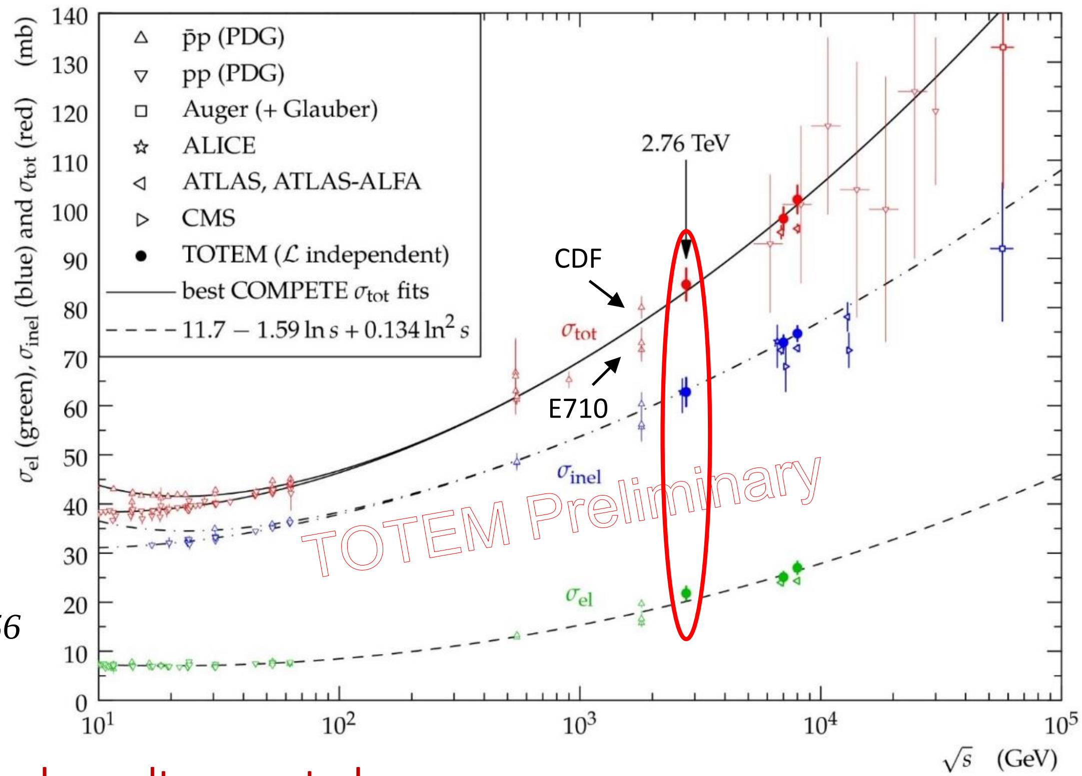
σ_{inel} = 62.8 ± 2.9 mb

σ_{el} = 21.8 ± 1.4 mb

ALICE @ $\sqrt{s}$ = 2.76 TeV:

$\sigma_{inel} = 62.8^{+2.4}_{-4.0} \pm 1.2$ mb

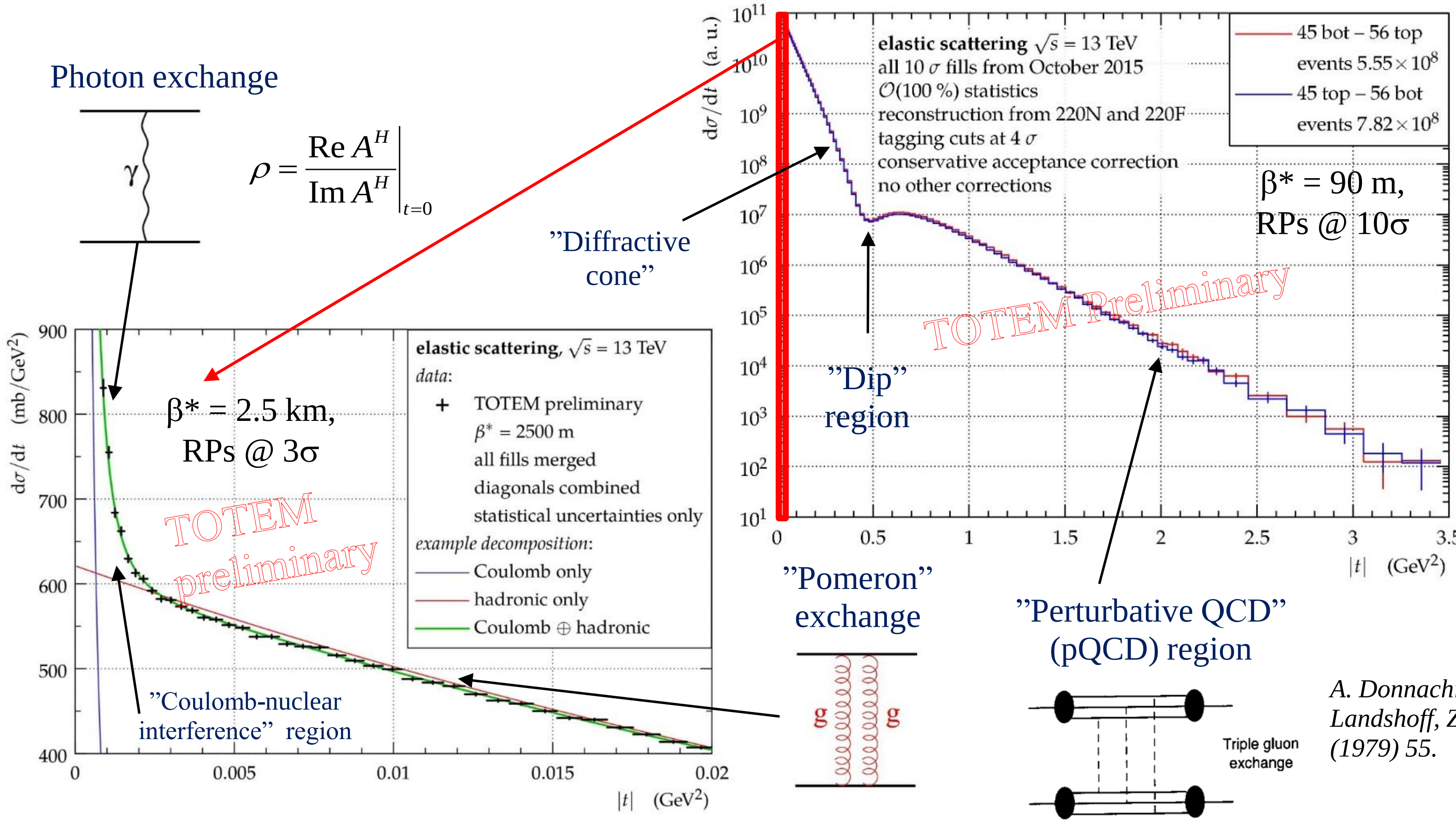
ALICE coll., EPJC 73 (2013) 2456



... 13 TeV analysis well advanced, results expected soon

Recent reults from TOTEM

Elastic pp scattering @ √s =13 TeV



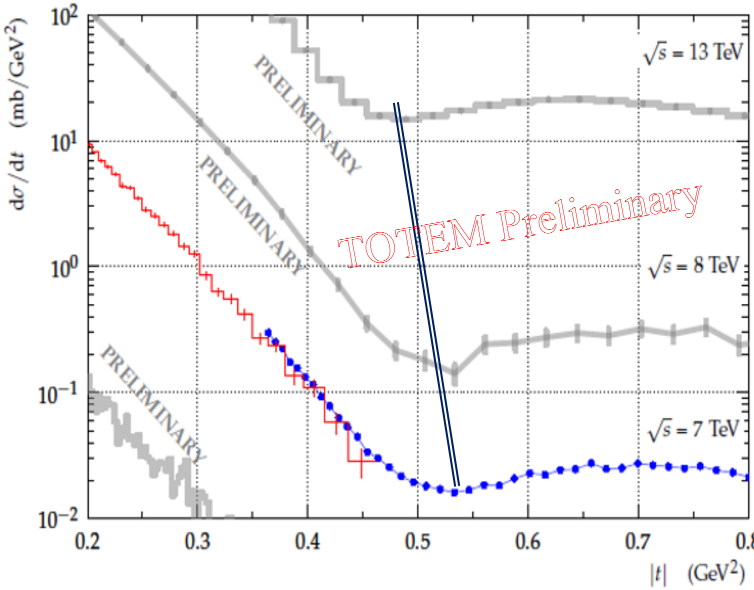
A. Donnachie and P. V. Landshoff, Z. Phys. C 2 (1979) 55.

Recent reults from TOTEM

Non exponentiality of the elastic scattering t-distribution and parameters trend

$$\frac{d\sigma}{dt} = A \cdot \exp(-Bt) \Rightarrow \frac{d\sigma}{dt} = A \cdot \exp(b_1 t + b_2 t^2 + b_3 t^3)$$

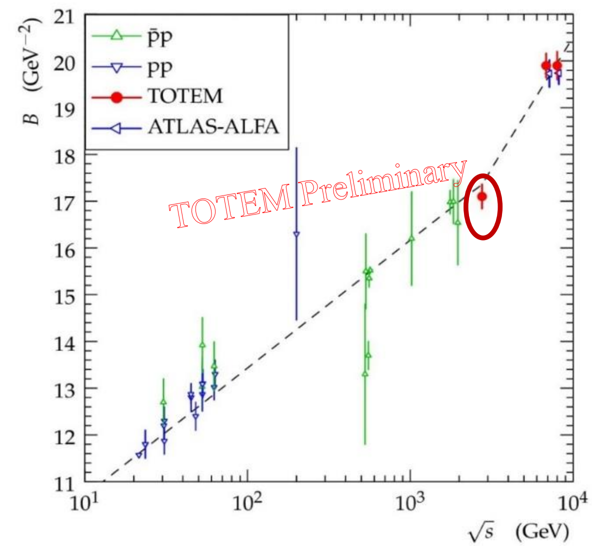
|t|-value of dip position decreases with increasing $\sqrt{s}$



TOTEM measurement @ √s = 2.76 TeV:

B = 17.10 ± 0.26 GeV^{-2} ($d\sigma_{el}/dt \propto e^{-B|t|}$)

Diffractive slope parameter $B = \frac{d}{dt} ln(\frac{d\sigma}{dt}|_{t=0})$ increase with $\sqrt{s}$



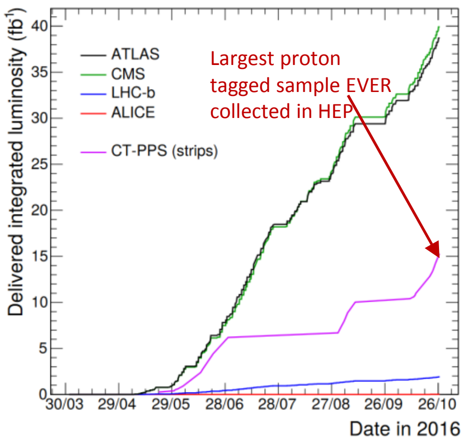
B ∝ ln√s → ln√s² @ LHC

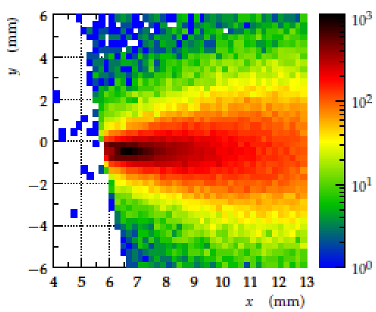
Larger impact from contribution of multi-Pomeron exchanges:
A. Donnachie, P.V. Landshoff arXiv1112.2485, PRD 85 (2012) 094024

Deviation from pure exponential under measurement at 13 TeV: *A.D. Martin, V.A. Khoze, M.G. Ryskin, JPG 42 (2015) 025003; D.A. Fagundes et al., IJMPA 31 (2016) 1645022*

The CT-PPS spectrometer

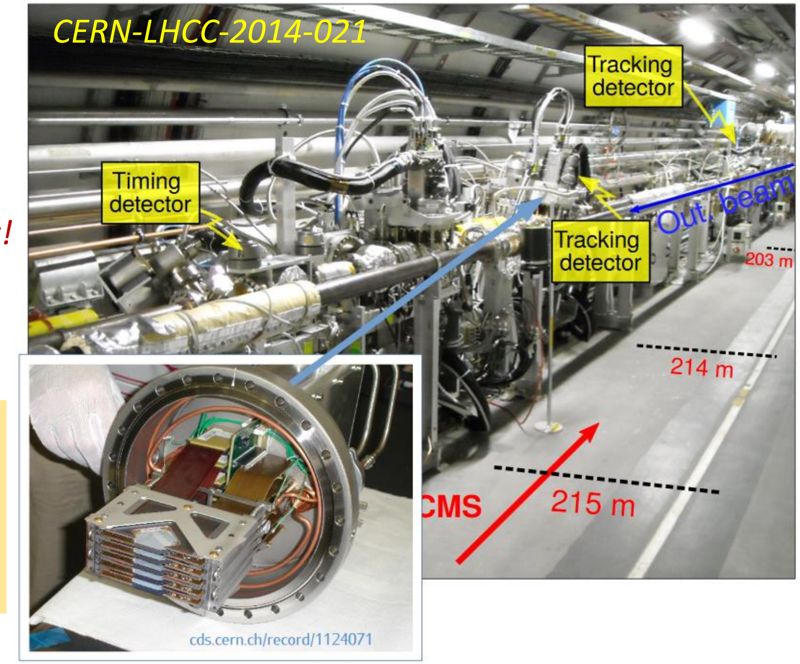
- Joint project of the CMS and TOTEM collaborations
- Tracking in 2016: TOTEM silicon strips
- Timing 2016: diamond detectors (commissioning only)
- *Tracking in 2017: TOTEM silicon strips + CT-PPS pixel detector.*
- *Timing 2017: (3 diamond + 1UFSD plane)/Arm. Clock distribution ready!*

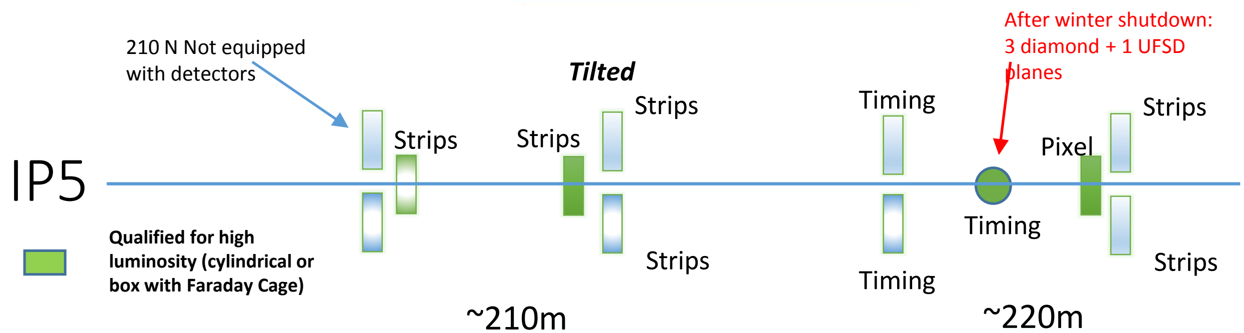




Two analyses already ongoing with the CT-PPS 2016 data:

- Search for exclusive $\gamma\gamma \rightarrow l^+l^-$
- Search for exclusive $\gamma\gamma \rightarrow \gamma\gamma$ production





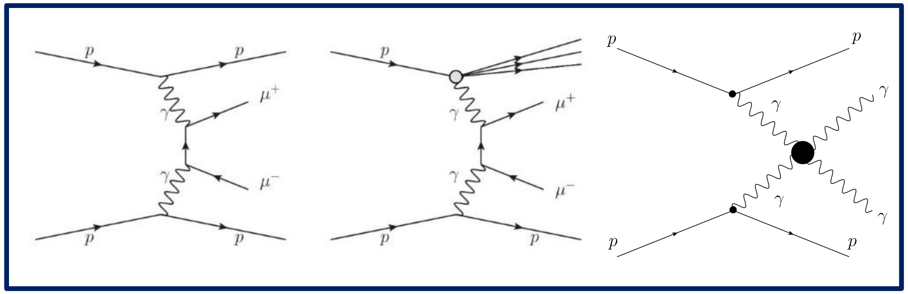
More details in my Monday talk: "Proton tagging in the forward region: prospect and performance"

CT-PPS Physics

CT-PPS Physics measurements of exclusive production:

- $\gamma\gamma$ fusion processes (including anomalous quartic gauge coupling)
- gluon-gluon fusion in color-singlet state ($J^{PC} = 0^{++}, 2^{++}$ ..)

Currently ongoing analysis (exclusive di-lepton and di-photon):



AQGC, DPE dijets and missing mass searches better with timing information

Advanced status analysis (exclusive di-lepton):

- Performed already in the past by CMS (e.g. JHEP 1307 (2013) 116, JHEP 1608 (2016) 119) and ATLAS (Phys.Rev. D94 (2016) 3.032011) without proton information (isolated back-to-back leptons)

- Proton detection in CT-PPS is fundamental to enhance the exclusive sample purity by requiring the matching between the proton momentum loss measured in the spectrometer and estimated from the leptons.
    - Evaluation of detector performance and background rejection.
    - Single dissociation process can be measured directly (not possible in the past).
    - QED process is known (calibration of survival gap probability factor)

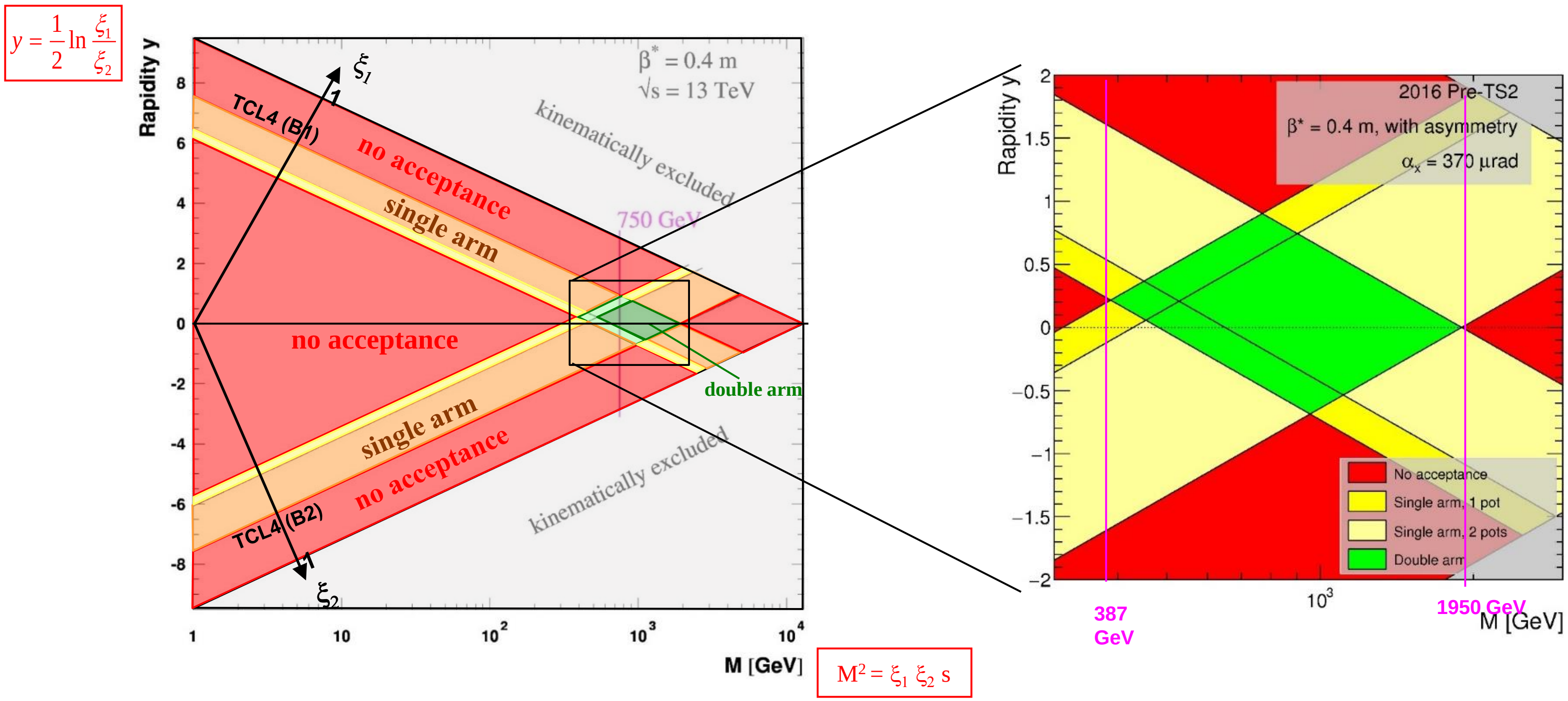
Ongoing analysis (exclusive di-photon):

- Many extensions of the SM predict a larger yield in the $\gamma\gamma \rightarrow \gamma\gamma$ scattering (example: extradimensional models).
- Previous studies suffer from small statistics (no proton tagging → small pile-up → small Lumi → low M → $\gamma\gamma$ productions from gluons).
- In the CT-PPS mass acceptance, the exclusive $\gamma\gamma$ process is dominated by electromagnetic production (light-by-light-scattering).
- *Possible to perform the measurement at high lumi thanks to the mass-rapidity matching between CT-PPS and CMS central detector.*
- Planned analysis: WW(AQGC), ZZ, Zγ, DPE and SD di-jet.

CT-PPS results and perspective

Mass-Rapidity acceptance

2016 optics before TS2 (data-calibrated): $\beta^* = 0.4$ m, $\alpha_X = 370$ μrad, mild orbit bump, RPs @ 15σ



- Overall sensitivity with double tags to missing mass range between 385 and 1950 GeV (for low-rapidity of the central system).
- Lower mass can be reached with single-arm proton tagging

Conclusions:

- Important forward Physics results have been recently obtained by CMS, TOTEM, LHCf, and CT-PPS.

- LHCf and CMS-CASTOR measurements represent very important benchmarks for the understanding and improvement of the soft/small-x modeling of the hadron collision interaction
  - LHCf: forward γ / n yields at 13 TeV.
  - CMS-Castor: energy flow in pp and inclusive jets in pA.

- TOTEM has completed the measurement at 2.7 TeV of total, elastic, inelastic pp cross section and new elastic scattering; t-distributions were measured at 13 TeV (with important consequences on the understanding of the pp elastic scattering dynamics)

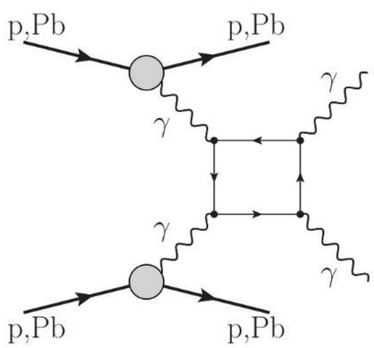
- With the LHC Run-2 we also entered the era of the high-luminosity proton spectrometers.
  - CT-PPS collected 15 fb^{-1} in 2016 and demonstrated that high luminosity proton tagging is feasible: new opportunities to study rare processes with forward protons (data analyses ongoing).
  - AFP performed single-arm commissioning measurements.
  - Both spectrometers are now ready for double-arm 4D proton reconstruction: 2017 integrated luminosity with AFP/CT-PPS = delivered luminosity to ATLAS/CMS

BACKUP

Photon-photon collisions

cross section for **AA (γγ)** $\rightarrow$ **AA X** process:

(i) Number of equivalent photons (EPA)
by integration of relevant EM form factors:



$$n(b,\omega) = \frac{Z^2\alpha_{em}}{\pi^2\omega}\left|\int \mathrm{d}q_\perp q_\perp^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp)\right|^2$$

$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$

(ii) EW **γγ** → **X** (elementary) cross section

$$\sigma^{\mathrm{EPA}}_{A_1A_2(\gamma\gamma)\to A_1A_2X} = \iint \mathrm{d}\omega_1\ \mathrm{d}\omega_2\ n_1(\omega_1)\ n_2(\omega_2)\ \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

pp collisions
+ harder spectrum (ω_{max} ~ TeV)
- large pile-up
- harder to trigger on low pT objects
+ large datasets, O(40 fb^{-1})
-> Need proton spectrometers

PbPb collisions
- softer spectrum (ω_{max} ~ 100 GeV)
+ AA (γγ) cross-sections $\propto Z^4$
+ gluonic cross-sections $\propto$ ~A^2 (lower CEP background wrt pp)
+ lower pile-up (<1%)
- smaller data set

Inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Analysis details:

Data correspond to an integrated luminosity of 0.35 fb-1
Pile-up μ=5%
Event selection: BX trigger & HF activity (2 side) & at least 1 Castor tower with E>5 GeV.
Beam halo muon for channel cross calibration.
HF spectrum used for absolute energy scale.
Unfolding technique from extract detector to particle level energy
Analysis representative for event with proton fractional E-loss ξ>10-6
Muon and neutrino not included in the computation.

Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

Source of uncertainty	Value
HF energy scale	10%
Extrapolation and model dependence	10%
CASTOR non-compensation	5%
Total	15%

Source uncertainty	p+Pb		Pb+p		p+Pb/Pb+p	
	600 GeV	2.5 TeV	600 GeV	2.5 TeV	600 GeV	2.5 TeV
Energy scale	$^{+2\%}_{-2\%}$	$^{+145\%}_{-71\%}$	$^{+6\%}_{-6\%}$	$^{+170\%}_{-82\%}$	$^{+5\%}_{-7\%}$	$^{+57\%}_{-9\%}$
Model dependence	$^{+14\%}_{-14\%}$	$^{+37\%}_{-37\%}$	$^{+13\%}_{-13\%}$	$^{+46\%}_{-46\%}$	$^{+24\%}_{-24\%}$	$^{+48\%}_{-48\%}$
Alignment	$^{+3\%}_{-3\%}$	$^{+24\%}_{-24\%}$	$^{+3\%}_{-6\%}$	$^{+49\%}_{-24\%}$	$^{+10\%}_{-6\%}$	$^{+4\%}_{-6\%}$
Jet indentification	$^{+1\%}_{-1\%}$	$^{+22\%}_{-22\%}$	$^{<1\%}_{<1\%}$	$^{<1\%}_{<1\%}$	$^{+1\%}_{-1\%}$	$^{+21\%}_{-21\%}$
Total	$^{+15\%}_{-14\%}$	$^{+153\%}_{-87\%}$	$^{+15\%}_{-16\%}$	$^{+177\%}_{-98\%}$	$^{+26\%}_{-26\%}$	$^{+77\%}_{-54\%}$

Integrated lumi for p+Pb and Pb+p runs used in this analysis is 3.13 and 6.71 nb-1

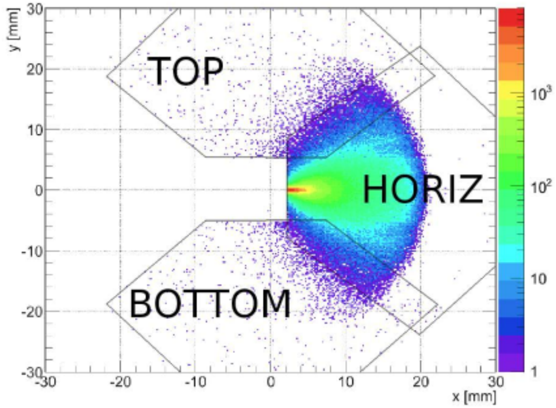
Different LHC Optics

Table 1.3: Summary of the machine parameters for the different running conditions.

Conditions	β^* [m]	N [10^{11} p]	N_b	μ (pileup)	L [$cm^{-2}s^{-1}$]	L_{int} [24h]	Physics
LOW	≥ 1000 19	0.7 0.1	2 40	0.004 0.01	10^{27} $5 \cdot 10^{28}$	0.1/nb 4.8/nb	σ_{tot}; Coulumb region Lhcf Run; Multiplicity; Energy flow; Inelastic cross section
MEDIUM	19	0.7	40	0.4	$2 \cdot 10^{30}$	0.17/pb	High cross section diffraction
	90	0.7	156–700	0.1	10^{30}–10^{31}	0.2–1/pb	σ_{tot}; low mass diffraction; Hard diffraction
	90	1.5	700	0.6	$5 \cdot 10^{31}$	4.4/pb	Glueball searches; CEP
HIGH	0.5 0.5	1.15 1.15	2800 2800	30	10^{34}	1/fb	LHCb programme Exclusive dijets, anomalous coupling

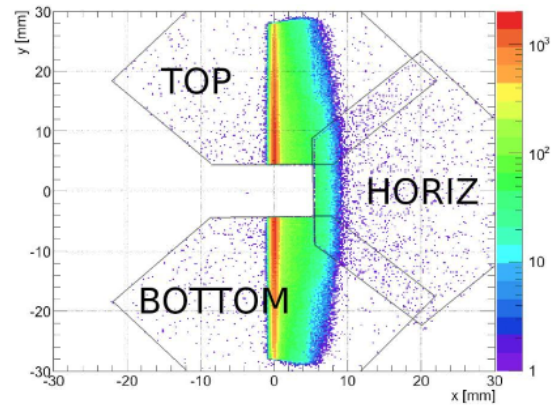
Hit maps of simulated diffractive events for 2 optics configurations

β^* = 0.55 m (low β^* = standard at LHC)



diffractive protons: mainly in **horizontal** RP
elastic protons: in vertical RP near x ~ 0
sensitivity only for large scattering angles

β^* = 90 m (developed for σ_{total} measurement)



diffractive protons: mainly in **vertical** RP
elastic protons: in narrow band at x ≈ 0,
sensitivity for small vertical scattering angles

	Transverse size of IP	Angular beam divergence	Min. reachable |t|
$\beta^* \sim 0.5$–3.5 m $\beta^* = 90$ m	$\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$ ~ 15-30 μm ~ 300μm	$\sigma(\Theta^*_{x,y}) = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$ ~ 10^{-5} μrad ~10^{-6} μrad	$\lvert t_{min} \rvert = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$ ~ 0.3–1 GeV^2 ~ 10^{-2} GeV^2

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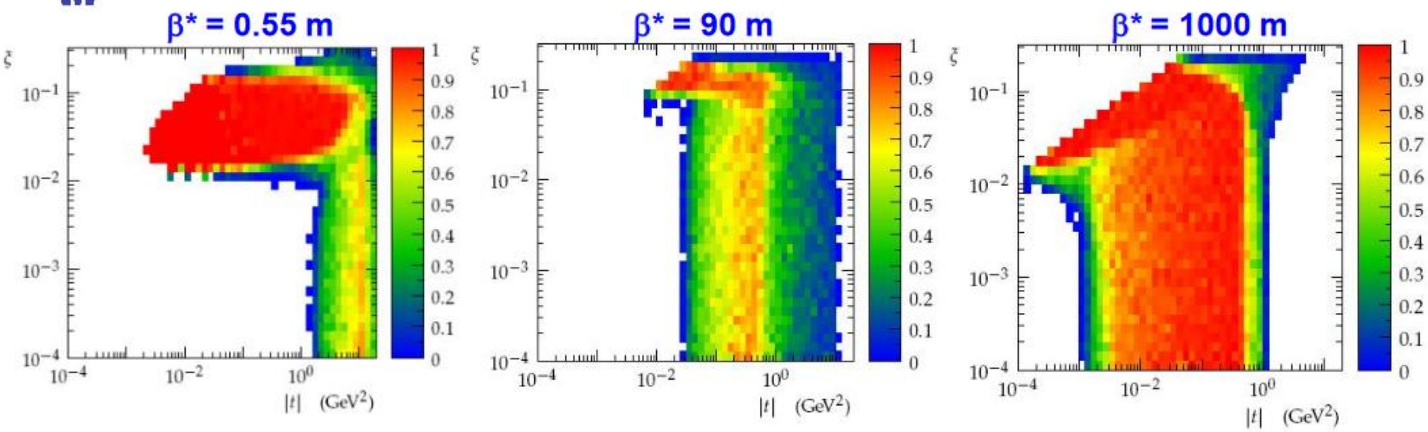
LHC Optics & proton acceptance

$t \approx -p^2\,\Theta^{*\,2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

Table 1.3: Summary of the machine parameters for the different running conditions.

Conditions	β^* [m]	N [10^{11} p]	N_b	μ (pileup)	L [$cm^{-2}s^{-1}$]	L_{int} [24h]	Physics
LOW	$\geq$ 1000 19	0.7 0.1	2 40	0.004 0.01	10^{27} $5\cdot10^{28}$	0.1/nb 4.8/nb	σ_{tot}; Coulumb region Lhcf Run; Multiplicity; Energy flow; Inelastic cross section
MEDIUM	19 90 90	0.7 0.7 1.5	40 156–700 700	0.4 0.1 0.6	$2\cdot10^{30}$ 10^{30}–10^{31} $5\cdot10^{31}$	0.17/pb 0.2–1/pb 4.4/pb	High cross section diffraction σ_{tot}; low mass diffraction; Hard diffraction Glueball searches; CEP
HIGH	0.5 0.5	1.15 1.15	2800 2800	30	10^{34}	1/fb	LHCb programme Exclusive dijets, anomalous coupling



> 10^{33} cm^{-2} s^{-1} ← $\mathcal{L} \propto \dfrac{1}{\beta^*}$ → ~10^{27} cm^{-2} s^{-1}

Diffraction:
ξ > ~0.01, low cross-section processes (hard diffraction)
Elastic scattering: large |t|

Diffraction: all ξ if |t| > ~10^{-2} GeV^2, soft & semi-hard diffraction
Elastic scattering: low to mid |t|
Total Cross-Section

Elastic scattering: very low |t|, Coulomb-Nuclear Interference
Total Cross-Section

Acquired data
and published results

	Proton equivalent energy in LAB (eV)	γ	n	π^0
SPS test beam		NIM A, 671, 129 (2012) JINST 12 P03023 (2017) (upgrade)	JINST 9 P03016 (2014)	
p+p 900 GeV	4.3×10^{14}	Phys. Lett. B 715, 298 (2012)		
p+p 7 TeV	2.6×10^{16}	Phys. Lett. B 703, 128 (2011)	Phys. Lett. B 750 (2015) 360-366	Phys. Rev. D 86, 092001 (2012) + Phys. Rev. D 94 032007 (2016)
p+p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014) + Phys. Rev. D 94 032007 (2016)
p+Pb 5.02 TeV	1.4×10^{16}			
p+p 13 TeV	9.0×10^{16}	submitted to PLB	Analysis ongoing	
p+Pb 8.1 TeV	3.6×10^{16}	Data taking completed in November 2016		

Thanks to information in the central region it is possible to distinguish between diffractive and non-diffractive events

ATLAS-LHCf common data taking

Exclusive WW:

Cuts and cross sections (fb)

Selection	Cross section (fb)			
SM	exclusive WW	exclusive WW (incorrectly reconstructed)	inclusive WW	exclusive $\tau\tau$
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	0.86±0.01	N/A	2537	1.78±0.01
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	0.47±0.01	N/A	1140±3	0.087±0.003
opposite sign leptons, "tight" ID	0.33±0.01	N/A	776±2	0.060±0.002
dilepton pair $p_T > 30$ GeV	0.25±0.01	N/A	534±2	0.018±0.001
protons in both PPS arms (ToF and TRK)	0.055 (0.054)±0.002	0.044 (0.085)±0.003	11 (22)±0.3	0.004±0.001
no overlapping hits in ToF + vertex matching	0.033 (0.030)±0.002	0.022 (0.043)±0.002	8 (16)±0.2	0.003 (0.002)±0.001
ToF difference, $\Delta t = (t_1 - t_2)$	0.033 (0.029)±0.002	0.011 (0.024)±0.001	0.9 (3.3)±0.1	0.003 (0.002)±0.001
$N_{\text{tracks}} < 10$	0.028 (0.025)±0.002	0.009 (0.020)±0.001	0.03 (0.14)±0.01	0.002±0.001

aQGC	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}\text{GeV}^{-2}$ ($a_C^W = 0$)	$a_C^W/\Lambda^2 = 5 \times 10^{-6}\text{GeV}^{-2}$ ($a_0^W = 0$)
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	3.10±0.14	1.53±0.07
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	2.33±0.08	1.00±0.04
opposite sign leptons, "tight" ID	1.82±0.08	0.78±0.03
dilepton pair $p_T > 30$ GeV	1.69±0.07	0.68±0.03
protons in both PPS arms (ToF and TRK)	0.52 (0.50)±0.04	0.18 (0.17)±0.02
no overlapping hits in ToF detectors	0.35 (0.32)±0.03	0.12 (0.11)±0.01
ToF difference, $\Delta t = (t_1 - t_2)$	0.35 (0.32)±0.03	0.12 (0.11)±0.01
$N_{\text{tracks}} < 10$	0.27 (0.24)±0.03	0.11 (0.10)±0.01

Auger determination of the ”muon problem”

PRL117,192001 (2016)

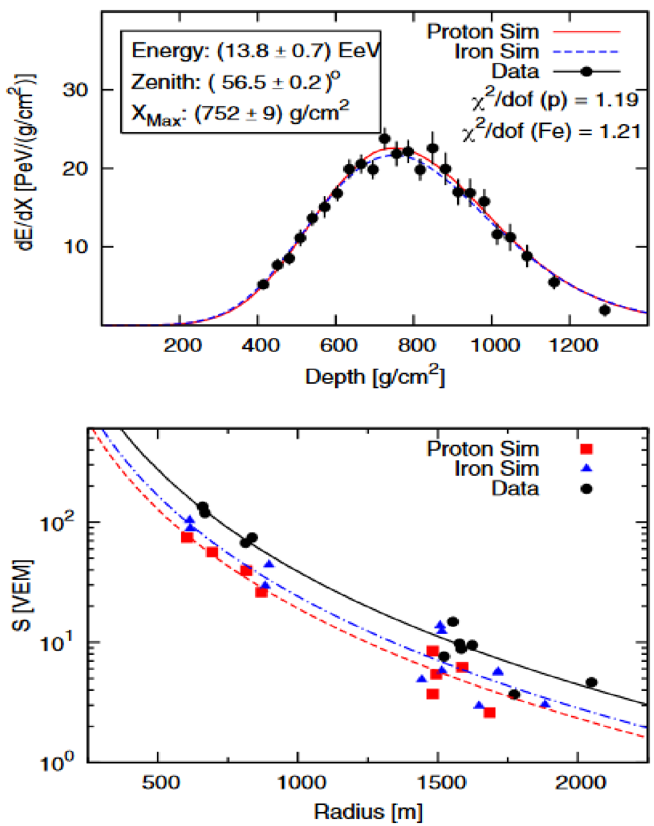


FIG. 1. Top: The measured longitudinal profile of an illustrative air shower with its matching simulated showers, using QGSJet-II-04 for proton (red solid) and iron (blue dashed) primaries. Bottom: The observed and simulated ground signals for the same event (p: red squares, dashed-line, Fe: blue triangles, dot-dash line) in units of vertical equivalent muons; curves are the lateral distribution function (LDF) fit to the signal.

σ_{inel} by ATLAS at 13 TeV

PRL117,182002 (2016)

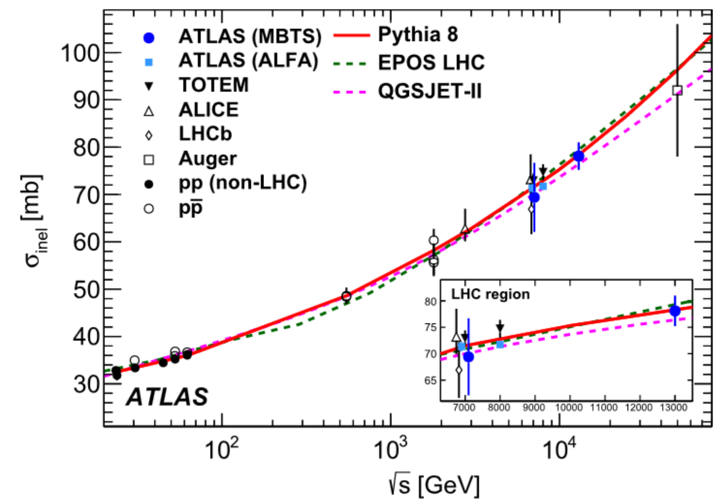


FIG. 3. The inelastic proton-proton cross section versus $\sqrt{s}$. Measurements from other hadron collider experiments [6,7,9,14,15] and the Pierre Auger experiment [16] are also shown. Some LHC data points have been slightly shifted in the horizontal position for display purposes. The data are compared to the PYTHIA8, EPOS LHC and QGSJET-II MC generator predictions. The uncertainty in the ATLAS ALFA measurement is smaller than the marker size.