Study of central exclusive production in pp collisions at $\sqrt{s}$ = 5 and 13 TeV

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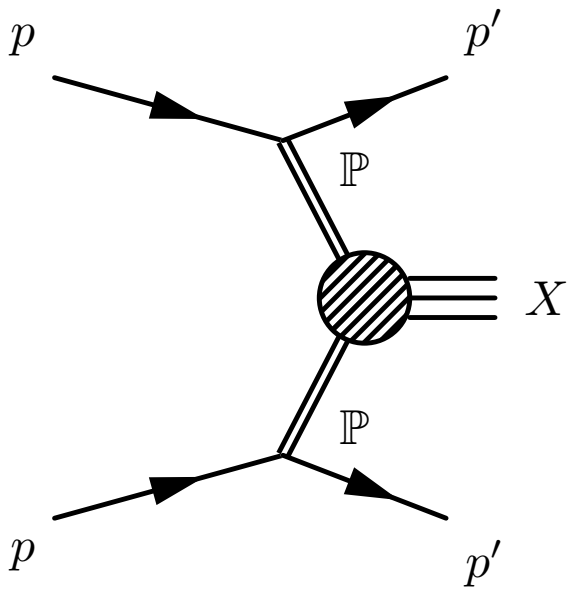
Central exclusive production (CEP)

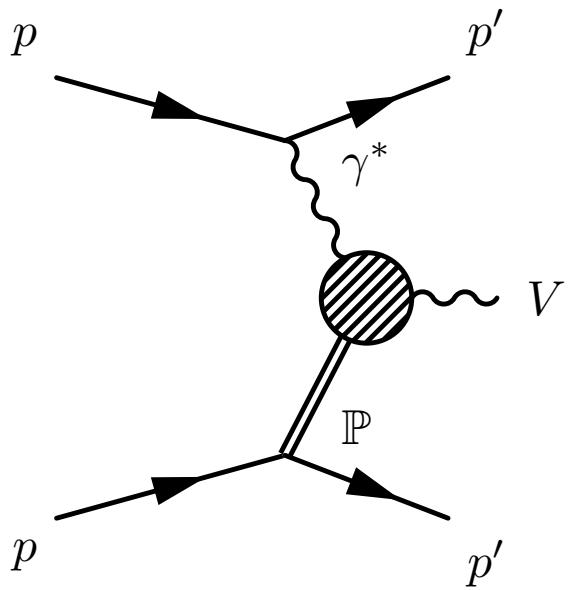
Double pomeron exchange (DPE)
$I^G(J^{PC}) = 0^+(J^{++})$, J is even

For example: $f_0(980)$, $f_2(1270)$, $f_0(1500)$, $f_0(1710)$



Vector meson photoproduction (VMP)
$I(J^{PC}) = 0, 1(1^{--})$

For example: $\rho(770)$, $\omega(782)$, $\phi(1020)$



The analysis

Aims: observe CEP processes with $\pi^+\pi^-$ final state

- Selection of CEP events
- Calculate differential cross sections
- Fit resonances in mass spectrum $\rightarrow$ cross sections of resonances
- Calculate cross section of different resonant channels

Data:

- 5 TeV pp collisions: $\sim$80 million zero bias events
- 13 TeV pp collisions: $\sim$33 million zero bias events

Analysed datasets

Run number	Date	Trigger	Number of events
13 TeV			
254989	2015. 08. 24-25	zero bias	7.9 M
255019	2015. 08. 25	zero bias	18.0 M
255029	2015. 08. 25	zero bias	9.7 M
Total			35.6 M
5 TeV			
262163	2015. 11. 19	zero bias	15.1 M
262165	2015. 11. 19	zero bias	11.7 M
262167	2015. 11. 19-20	zero bias	25.2 M
262173	2015. 11. 20	zero bias	16.9 M
262174	2015. 11. 20	zero bias	14.2 M
Total			83.2 M

Monte Carlo simulations

Inclusive generators: background events

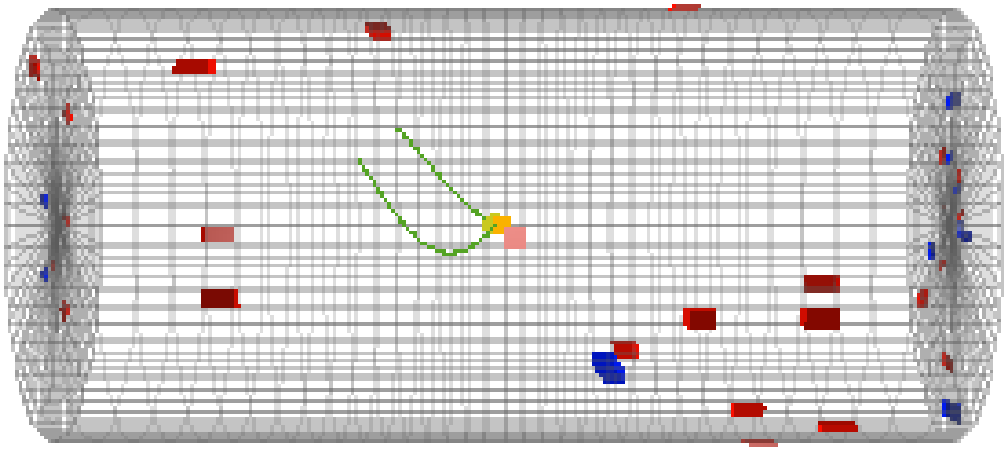
- Pythia 8 (MBR and CUETP8M1 tunes)
- EPOS
- QGSJet-II

Exclusive generators: CEP events

- STARlight: $\rho \to \pi^+\pi^-$ with vector meson photoproduction.
- Dime MC: $\pi\pi$ continuum with double pomeron exchange

Event selection

We should select central exclusive processes with two tracks:



Monte Carlo simulations

Generator	Process	$\sqrt{s}$	Number of events
Pythia 8 CUETP8M1	inclusive	13 TeV	900 000
Pythia 8 MBR	inclusive	13 TeV	900 000
EPOS	inclusive	13 TeV	900 000
QGSJet-II	inclusive	13 TeV	900 000
STARlight	$\rho \to \pi^+\pi^-$	5 TeV	10 000
STARlight	$\rho \to \pi^+\pi^-$	13 TeV	10 000
Dime MC	$\pi^+\pi^-$ continuum	5 TeV	10 000
Dime MC	$\pi^+\pi^-$ continuum	13 TeV	10 000

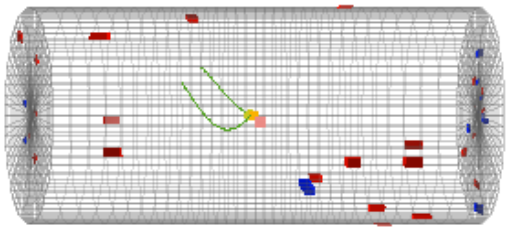
All of the samples are run through a Geant4 simulation of CMS detector.

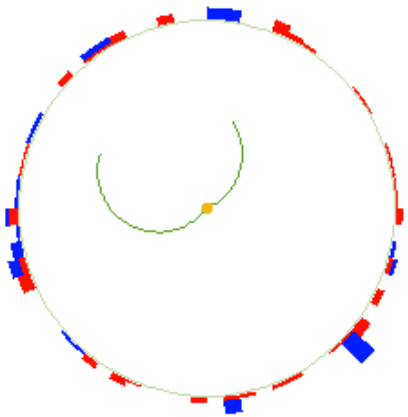
Event selection

- Track selections
  - One interaction vertex.
  - Two tracks with high-purity flag.
  - Opposite sign.
  - Kinematic constraints:

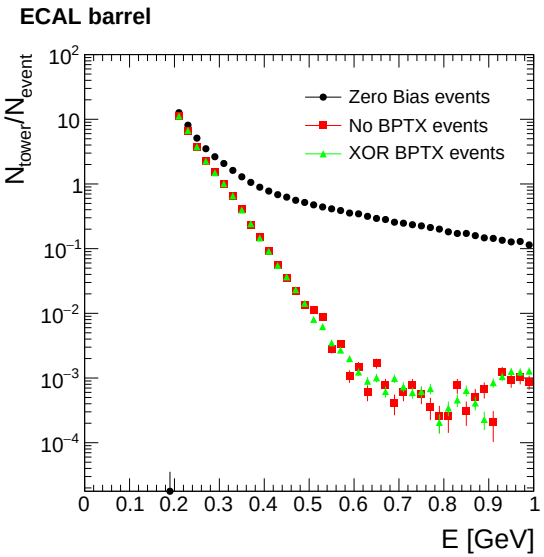
$$p_T > 0.2 \text{ GeV/c}$$
$$|\eta| < 2.4$$

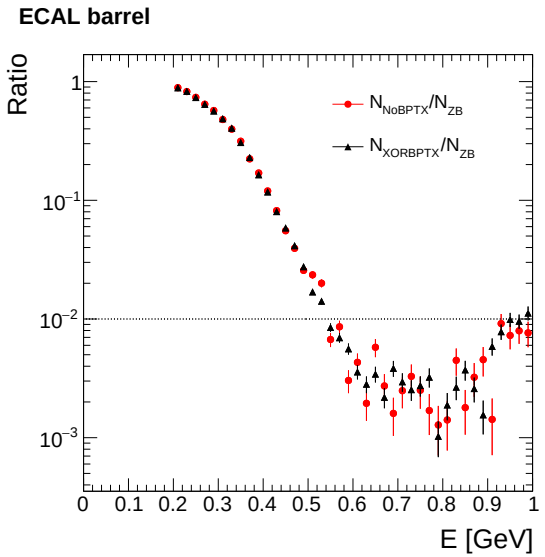
- Calorimeter selections.
  - No ECAL hit over threshold.
  - No HCAL hit over threshold.
  - No HF hit over threshold.
- Particle identification: $\pi\pi$





Calorimeter thresholds





Task: determine noise thresholds for calorimeter segments

Definition:
Noise must be below 1% of signal.

Calorimeter constituent	Threshold [GeV]
ECAL barrel	0.55
ECAL endcap	3.3
HCAL barrel	1.9
HCAL endcap	2.8
HF	4.0

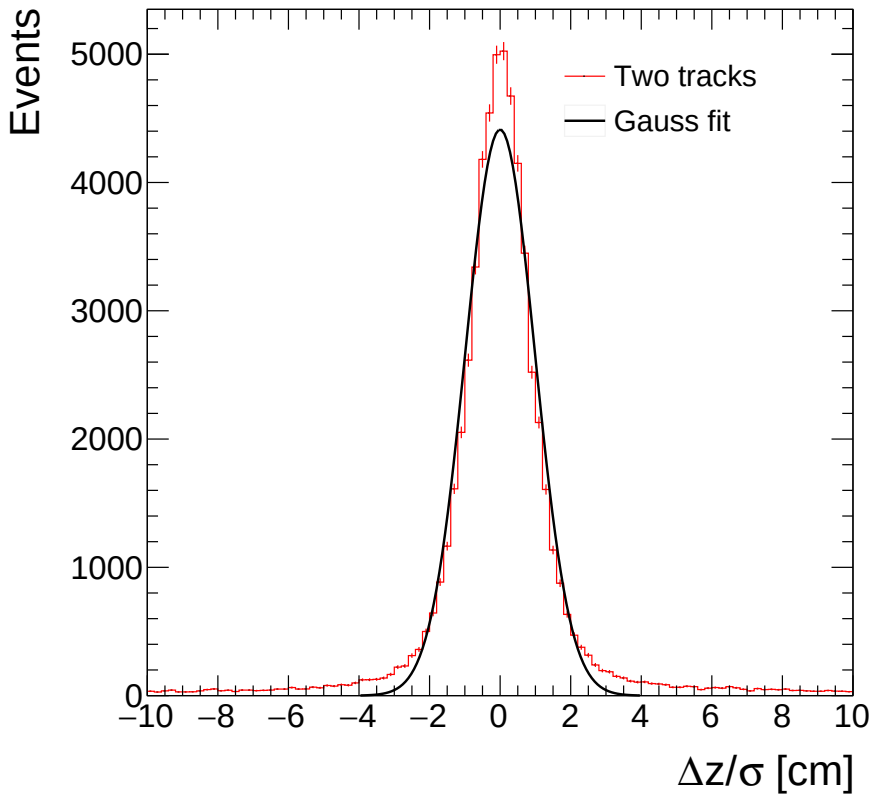
Vertexing

Efficiency of the standard CMSSW vertexing is found to be around 30 % in the case of two tracks $\rightarrow$ not designed for low multiplicity events.

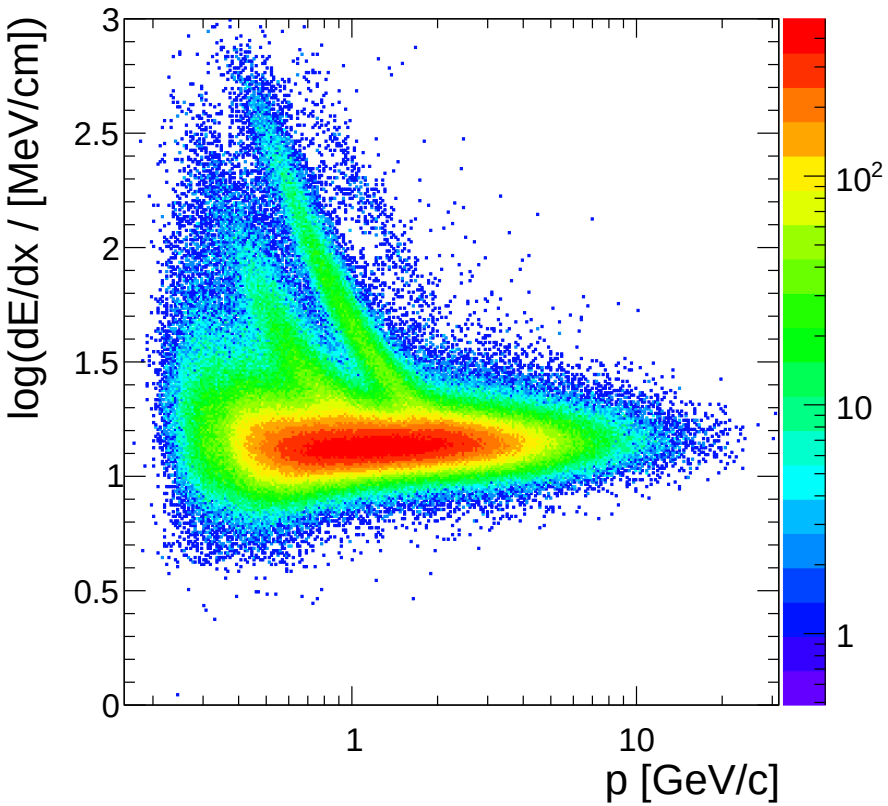
An **agglomerative clustering** algorithm is used instead:
A vertex is assigned to two tracks with longitudinal impact parameters z_1, z_2 and variance σ_1, σ_2 if

$$|z_1 - z_2| < 3\sigma,$$

where $\sigma^2 = \sigma_1^2 + \sigma_2^2$.
The efficiency of this method is about **93** %.



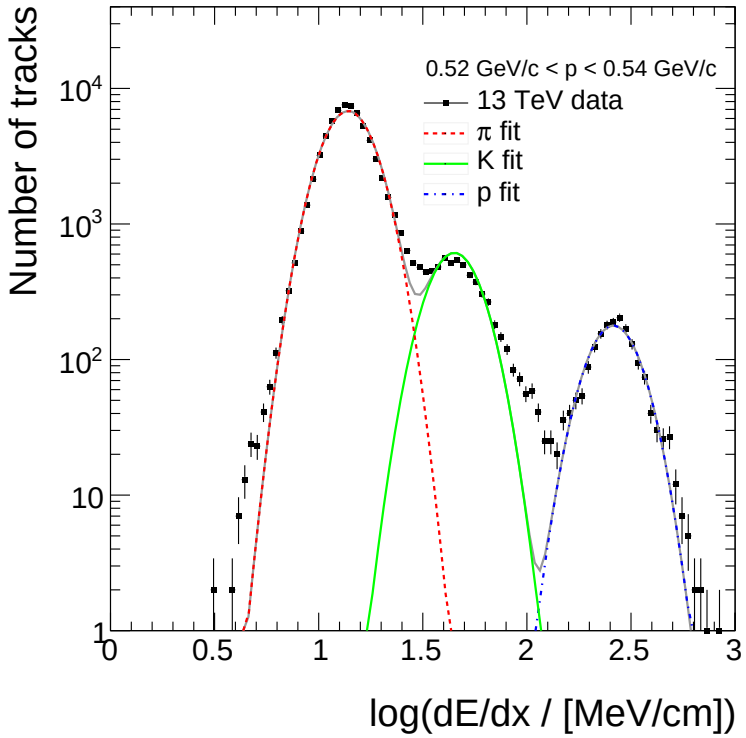
PID – Particle identification

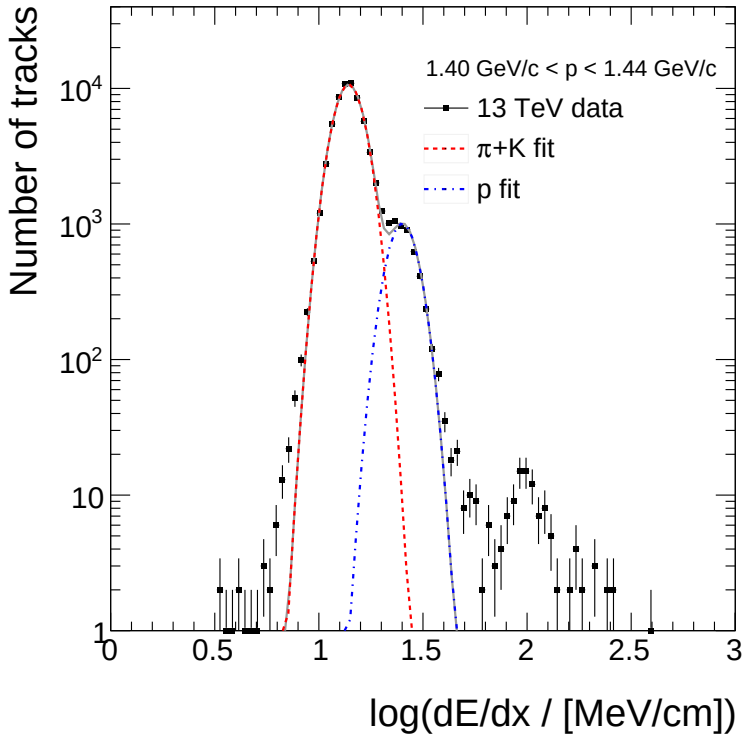


Aims:

- Identify as much π and K as possible.
- p-slices are fitted with Gaussians.
- Gaussians assumed to have same variance.

PID – Particle identification



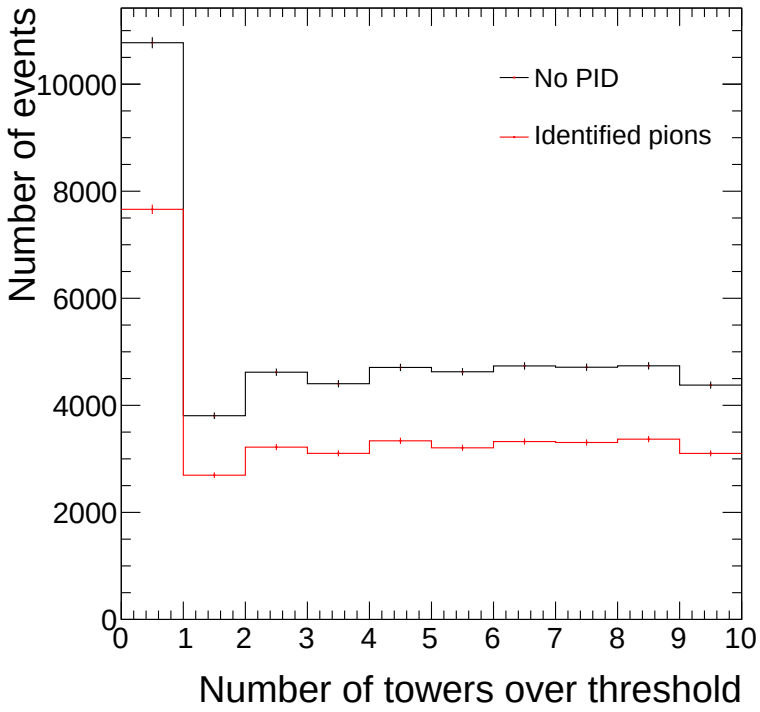


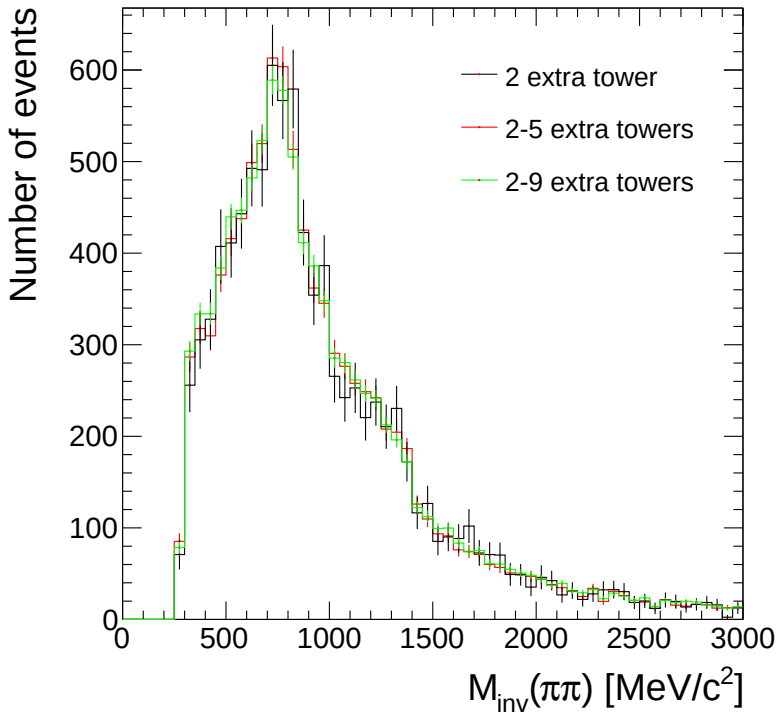
A track is considered as pion if

$$\left| \log \frac{\mathrm{d}E}{\mathrm{d}x} - \mu_\pi \right| < 3\sigma_\pi .$$

Background estimation

Using the side-band region of calorimeters: 2-5 towers over thresold. All selections are performed, except calorimeter exclusivity selections.



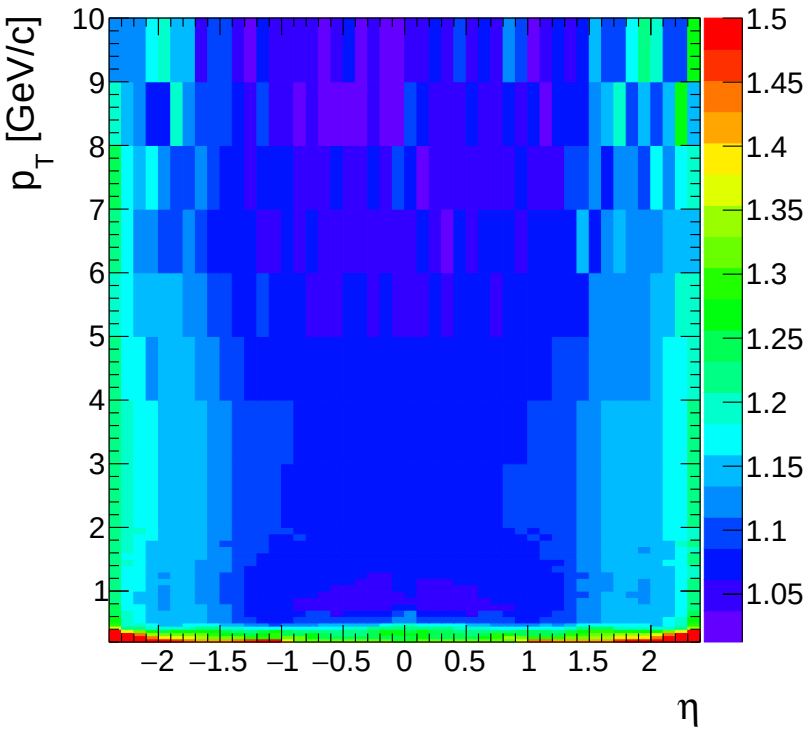


Calo tower number distribution seems flat enough for this method.

Corrections

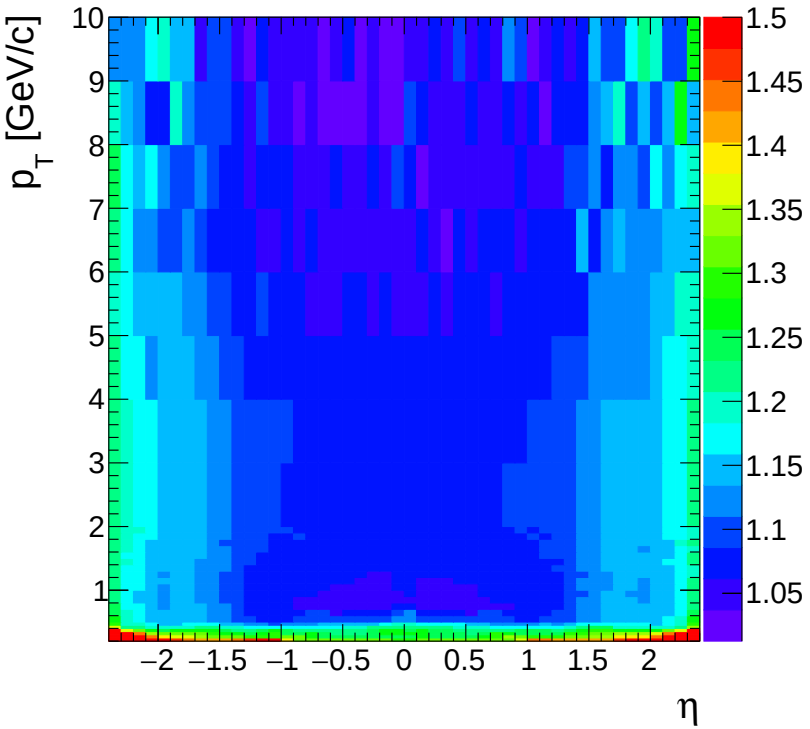
1. Tracking correction
2. Multiple reconstruction correction
3. Vertexing correction
4. Pile-up correction
5. Noise correction

Tracking correction (single track)

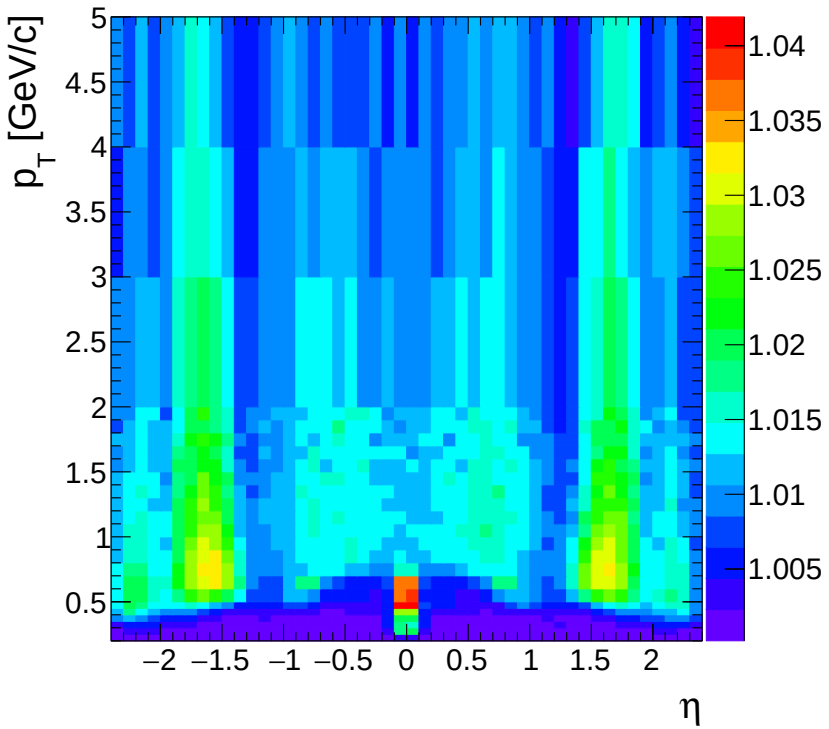


Tracking and multiple reconstruction correction

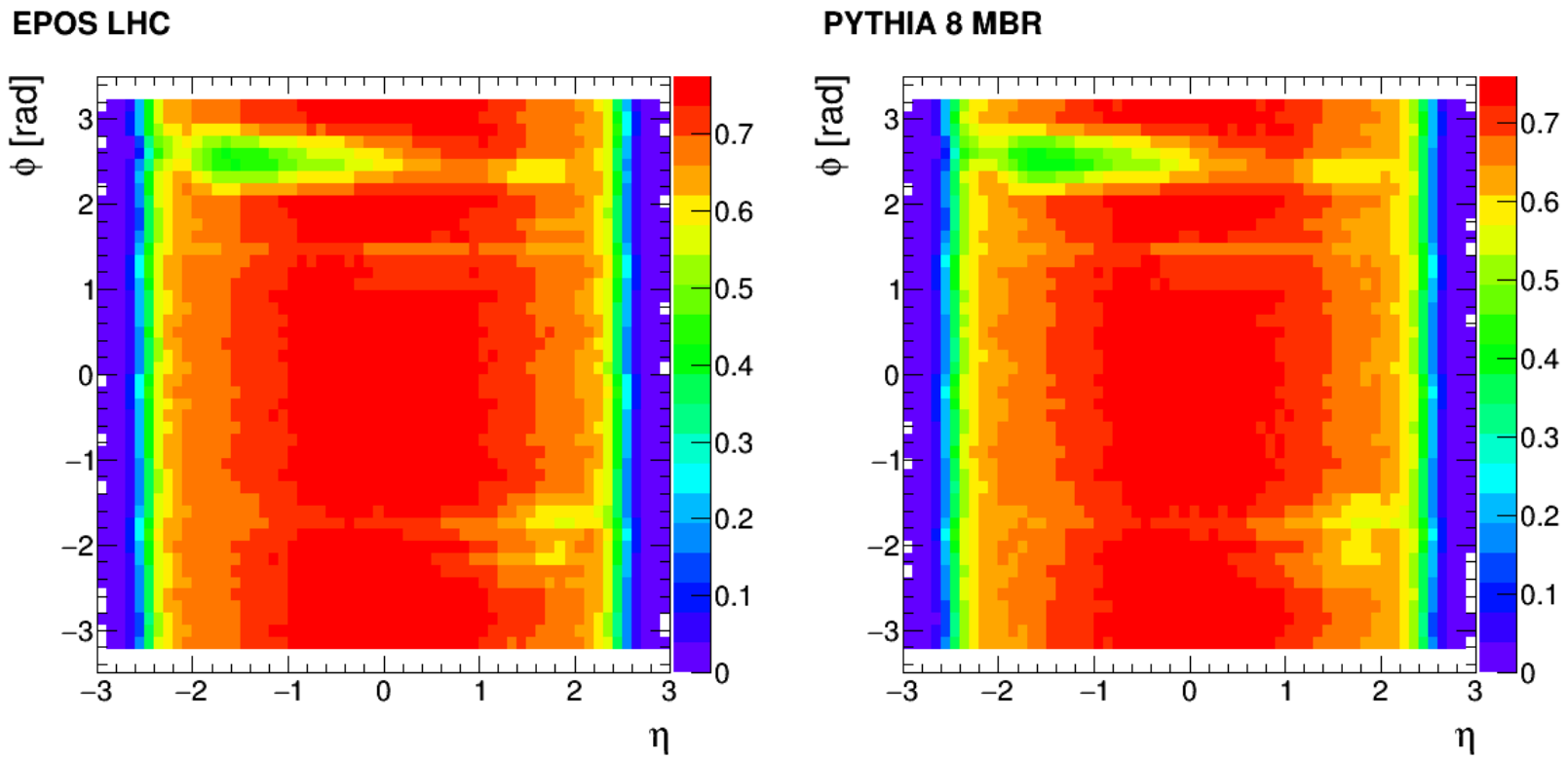
Tracking correction



Multiple reconstruction correction



Asymmetry in ϕ



A pixel detector element was out of order.

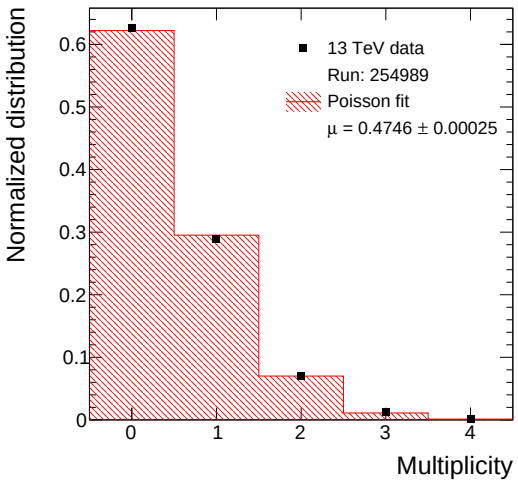
Using (p_T, η, ϕ)-dependent correction in problematic ϕ region.

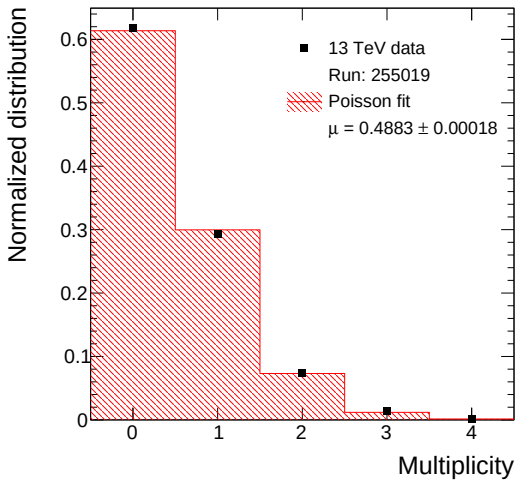
Pile-up correction

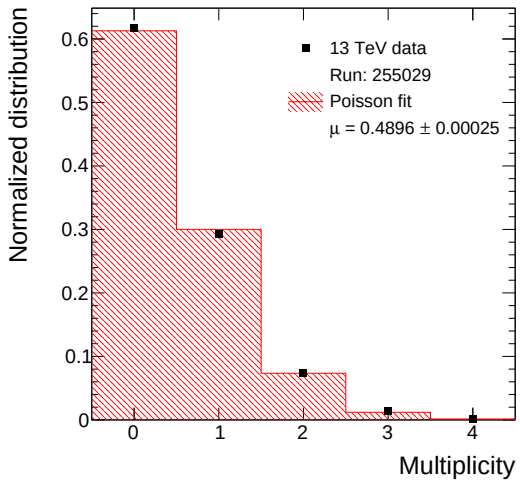
Only events with a single vertex are considered $\rightarrow$ need to correct for multi-vertex events. The appropriate factor can be derived:

$$\epsilon_{\mathrm{pu}} = \exp(\mu),$$

where μ is the expected number of vertices in a collision.







Systematic uncertainties

Source	Uncertainty
Tracking	3,9 %
Fake rate	1 %
Vertexing correction	1 %
Noise correction	1 %
Background estimation	20 %
Total	21 %
+Luminosity (from σ_{inel}, 5 TeV)	11 %
+Luminosity (from σ_{inel}, 13 TeV)	6 %
+Luminosity (BRILCALC)	2,7 %

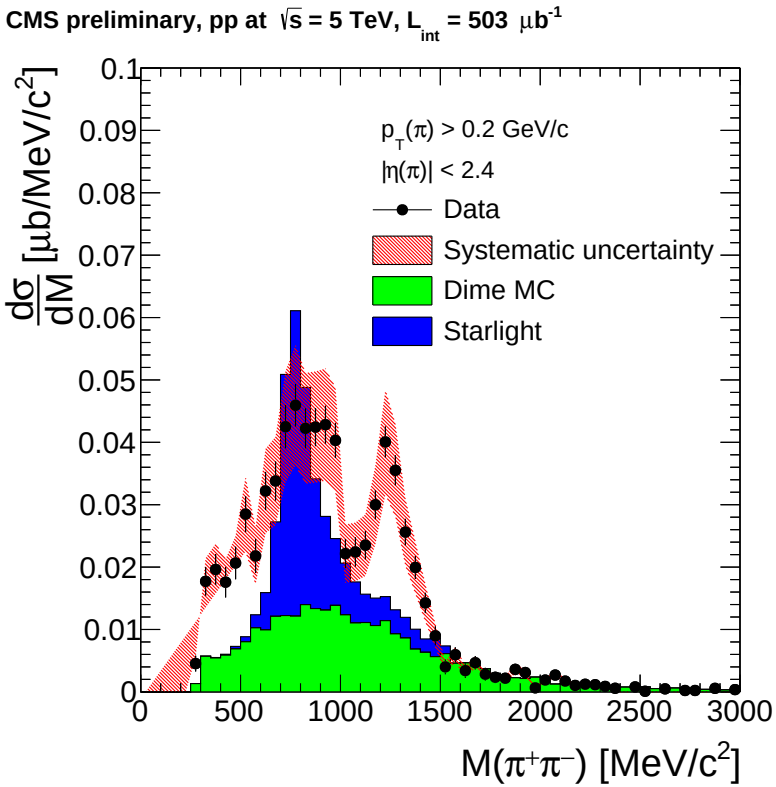
Tracking: *CMS-TRK-10-002 PAS*

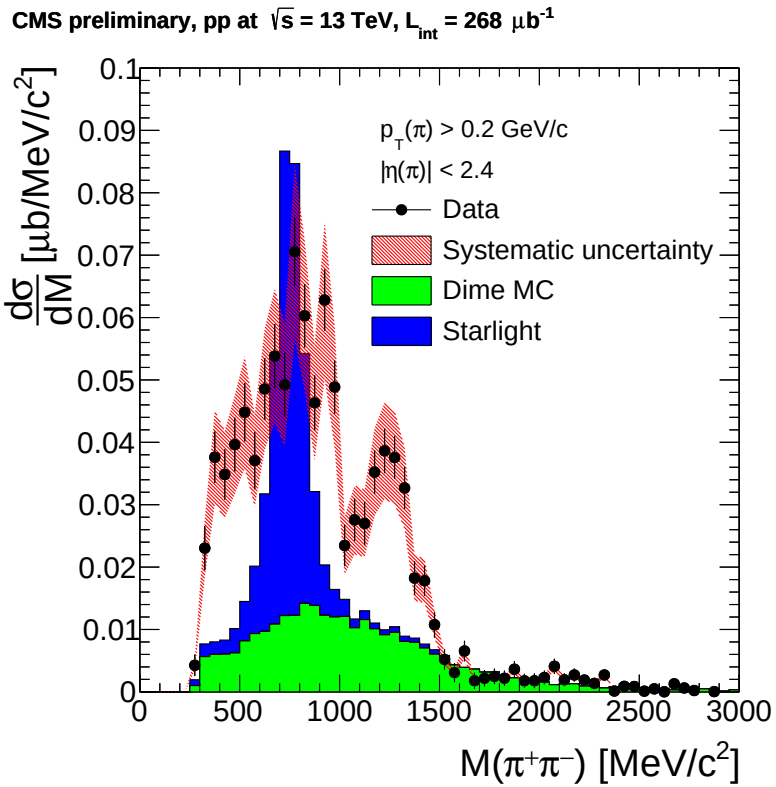
Fake rate: from inclusive Monte Carlo

Vertexing and noise correction: from exclusive Monte Carlo

Background estimation: from same sign sample

Differential cross sections – mass

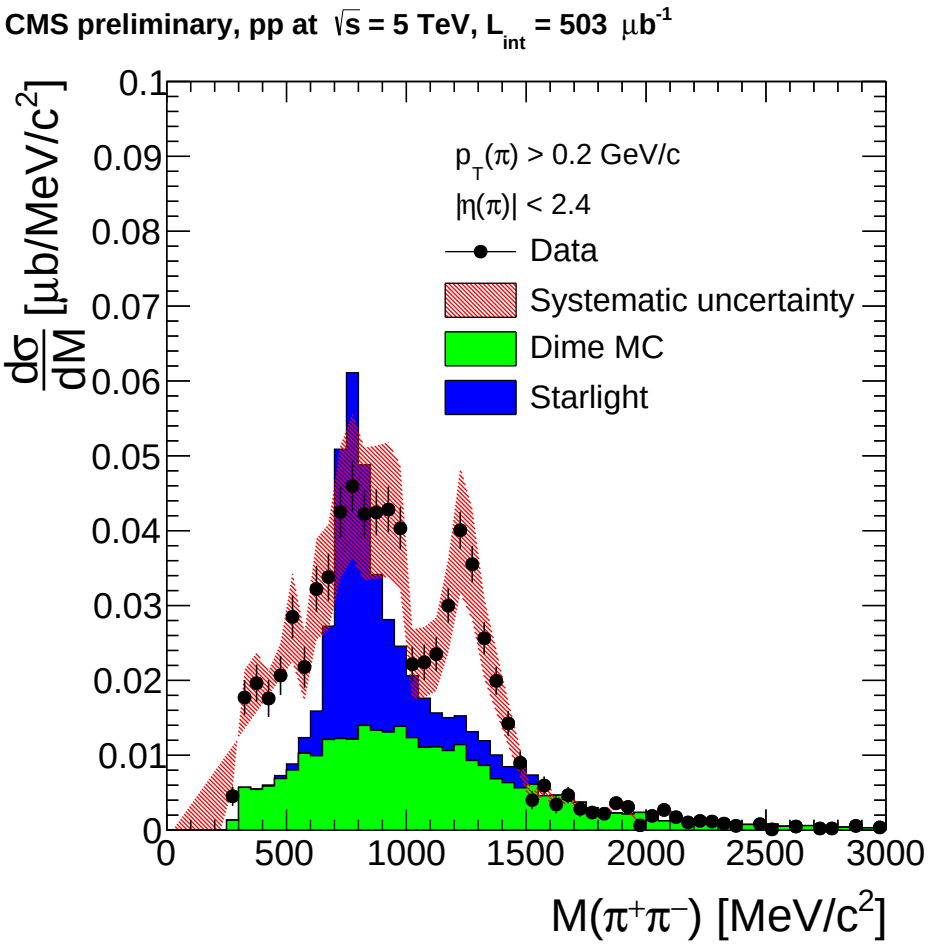




MC generators:

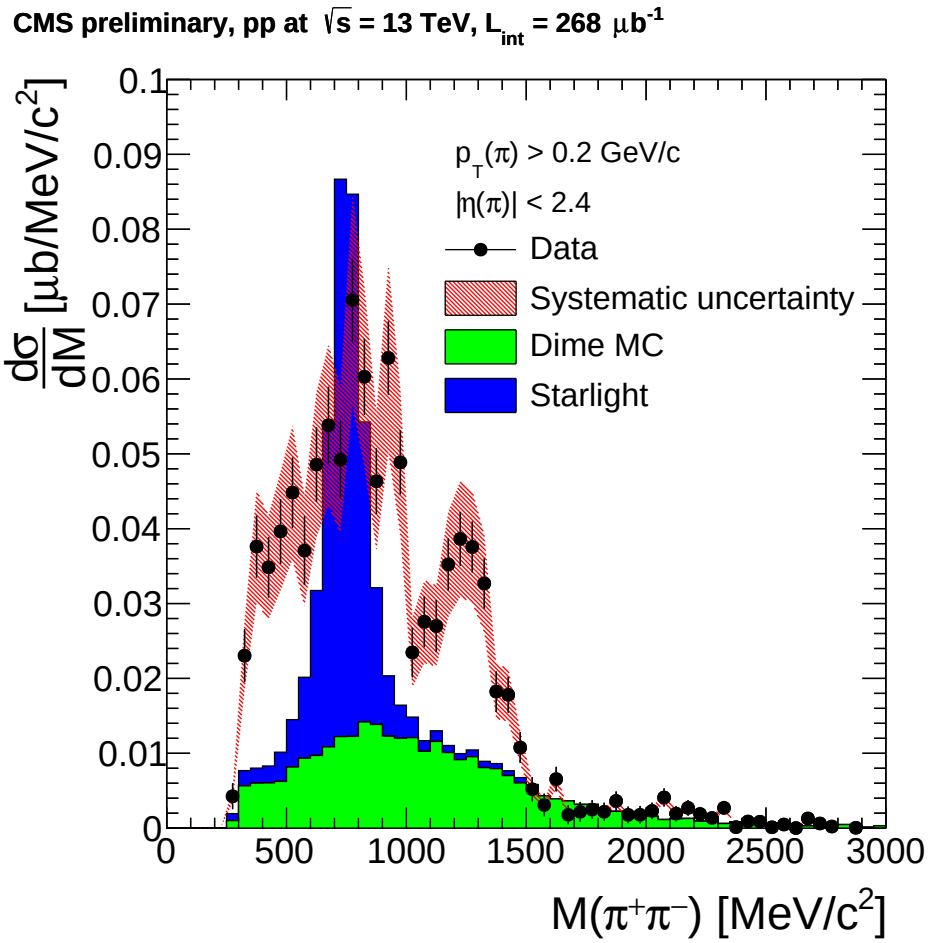
- Starlight: exclusive ρ production through VMP
- Dime: continuum $\pi\pi$ production

Differential cross sections – mass



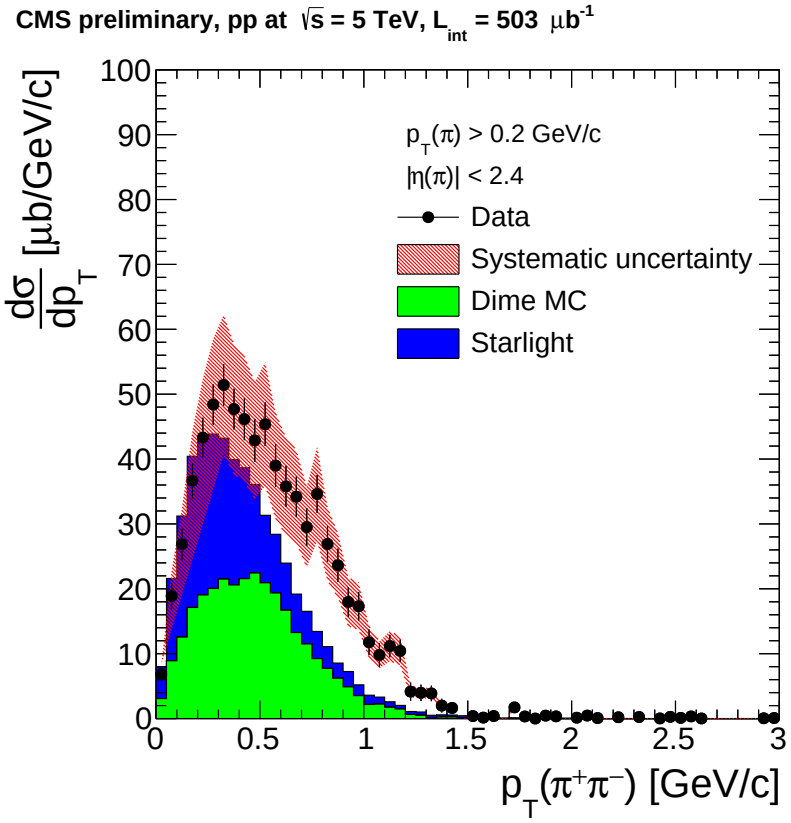
- $\rho(770)$ and $f_0(980)$ peak merged
- No MC to describe $f_0(980)$ and $f_2(1270)$
- Additional contribution to measured spectrum under 500 MeV/c^2 $\rightarrow$ probably σ resonance.

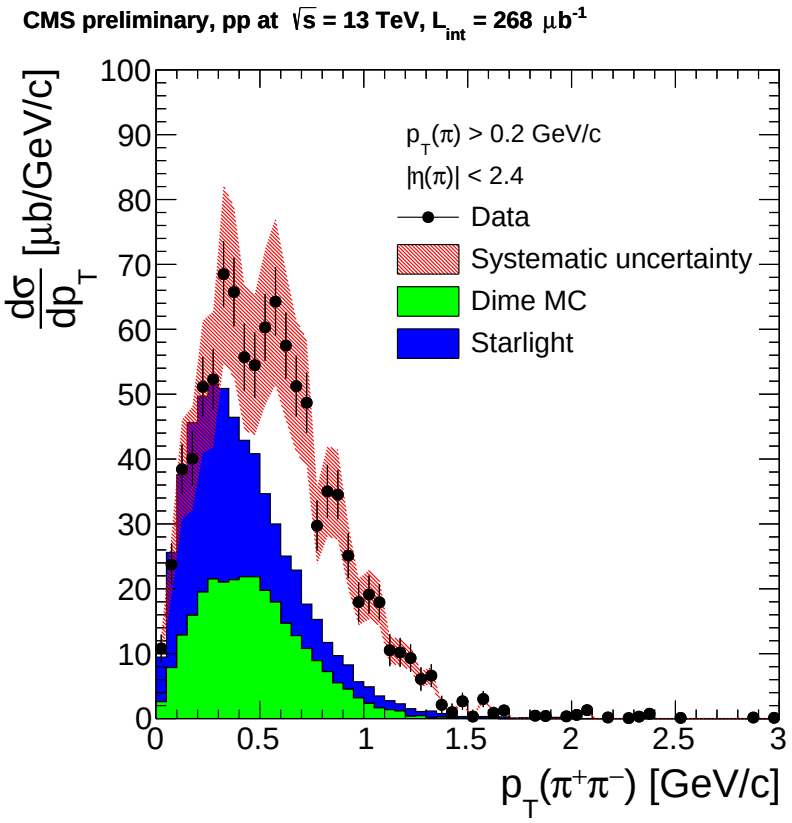
Differential cross sections – mass



- Lower $\rho(770)$ peak, than predicted from Starlight.
- No MC to describe $f_0(980)$ and $f_2(1270)$.
- Contribution below 500 MeV/c also visible.

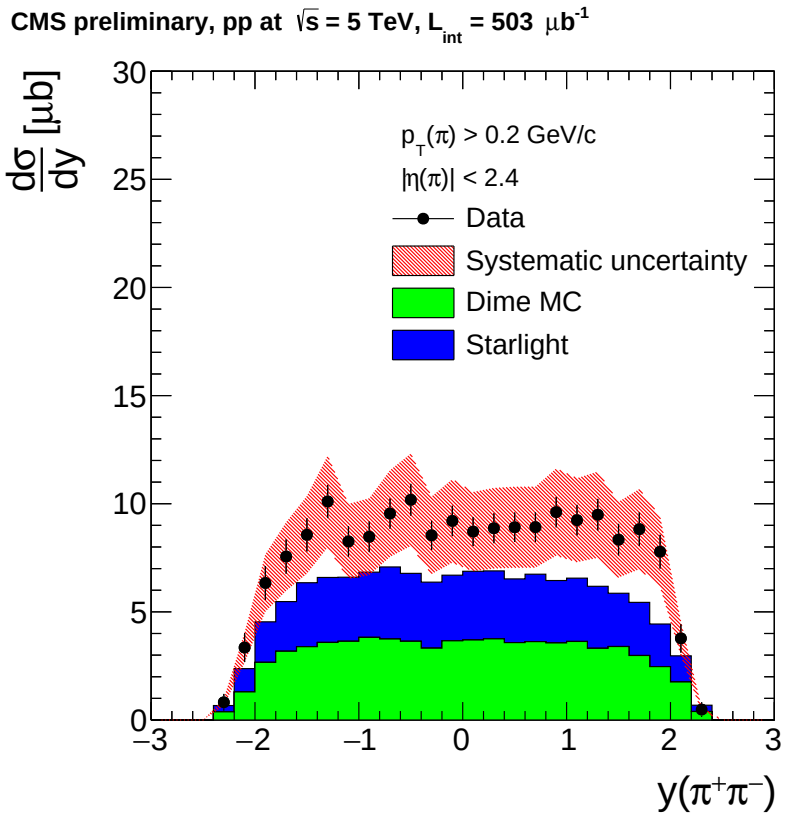
Differential cross sections – p_T

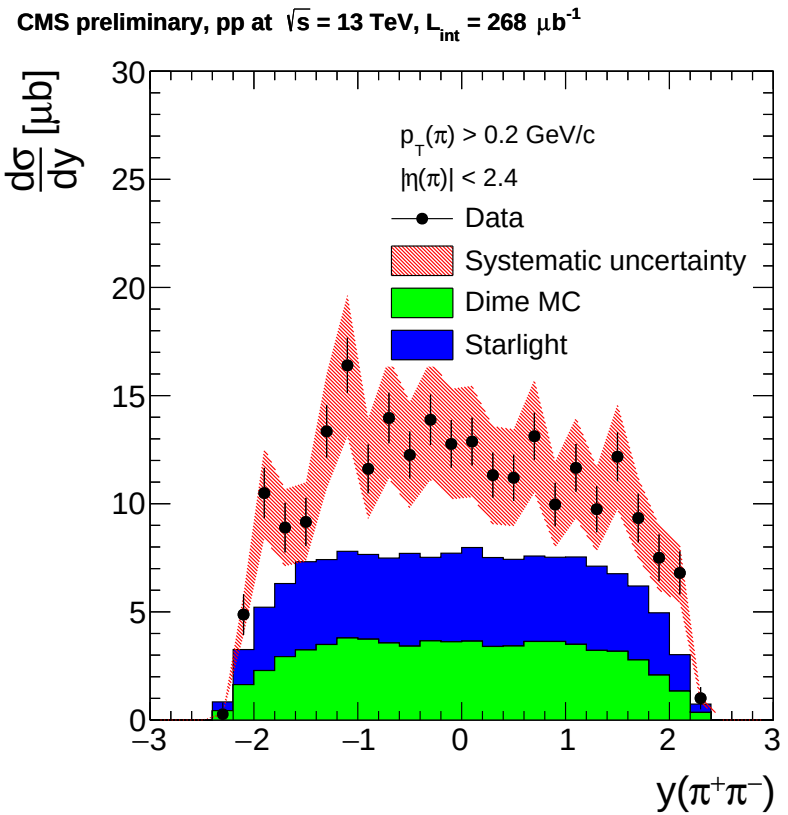




In the low p_T region data matches the predicted spectrum. The f-resonances has higher average p_T.

Differential cross sections – η





Asymmetry in 13 TeV is under investigation.

Fitting of resonance peaks

Fitting with the sum of three Breit-Wigner functions leads to incorrect results.

QM amplitude of CEP processes:

$$A_{\mathrm{CEP}} = A^{\rho}_{\mathrm{VMP}} + A^{f0}_{\mathrm{DPE}} + A^{f2}_{\mathrm{DPE}} + + A^{\pi\pi-\mathrm{continuum}}_{\mathrm{DPE}}.$$

Interference appears in $\sigma \propto |A_{\mathrm{CEP}}|^2$. According to literature the interference between the VMP and DPE sector is negligible.

Fit function:

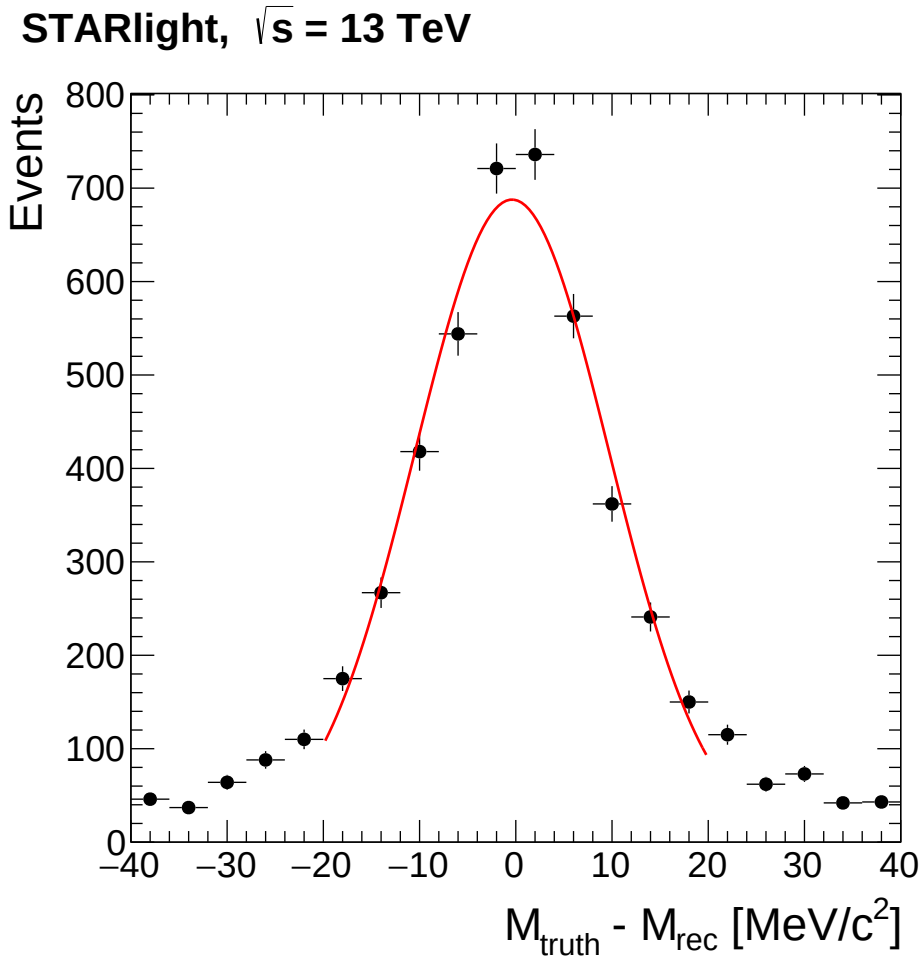
$$f(x) = |A^{\rho}_{\mathrm{RBW}}(x)|^2 + \\ + |A^{f_0}_{\mathrm{RBW}}(x)\mathrm{e}^{\mathrm{i}\phi^{f_0}x} + A^{f_2}_{\mathrm{RBW}}(x)\mathrm{e}^{\mathrm{i}\phi^{f_2}x} + B^{\mathrm{Dime}}(x)|^2.$$

Fitting of resonance peaks

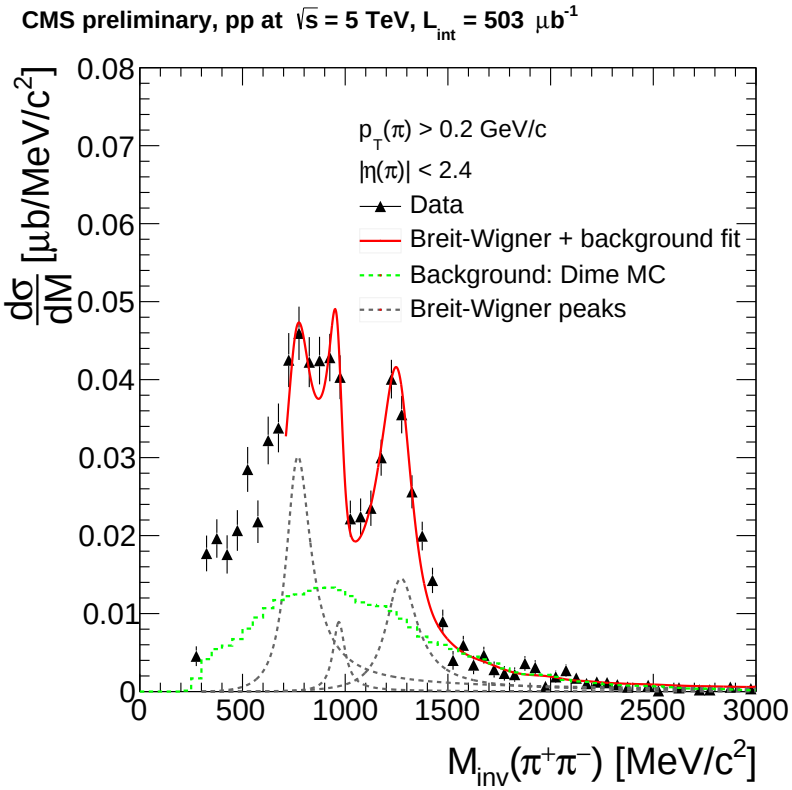
Taking mass resolution into account $\rightarrow$ convolution with Gaussian. σ variance corresponds to mass resolution. The value of σ is calculated from STARlight and Dime MC dataset.

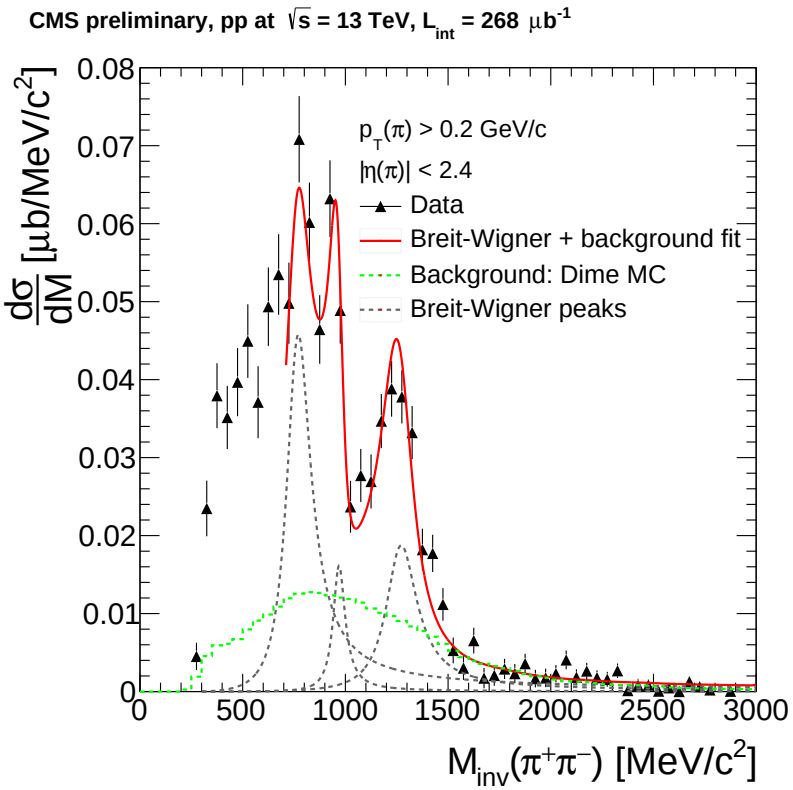
Final fitting function:

$$f^*(x) = \int G(x;\sigma) f(x' - x) dx'.$$



Fitting of resonance peaks





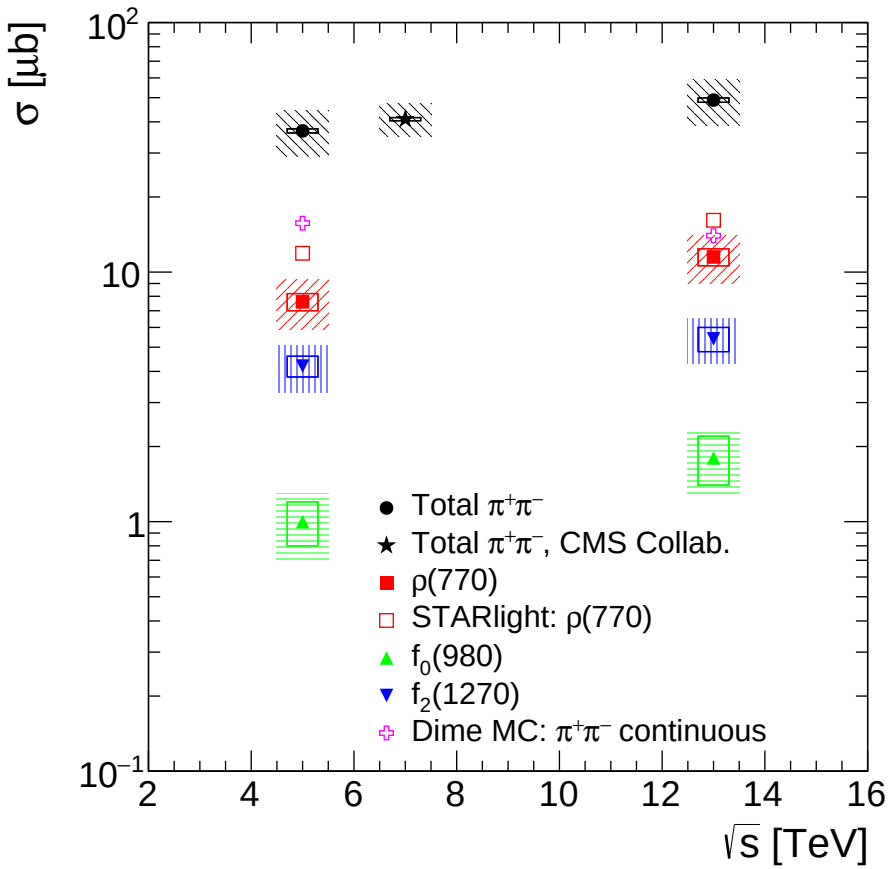
The Dime MC sample is used as background for continuum production. Resonance yields increases with $\sqrt{s}$.

Results

- Total cross section increases with $\sqrt{s}$.
- Cross section of resonance channel increases with $\sqrt{s}$.
- Cross section of continuum production in Dime MC decreases with $\sqrt{s}$.
- 7 TeV result: FSQ-12-004 PAS. No PID, different kinematic cut:

$$p_T(\pi) > 0.2 \text{ GeV/c},$$
$$|y(\pi)| < 2.0$$

Correction calculated from Starlight and Dime MC.



Summary

- Exclusive $\pi\pi$ events are selected.
- Tracks are identified by their mean energy-loss.
- Differential cross sections studied.
- Resonances fitted by interfering relativistic Breit-Wigner functions.
- $\sqrt{s}$ dependence of resonance production is studied (5 and 13 TeV, +7 TeV from another analysis)

- Actively discussed in the CMS+TOTEM subgroup meeting.
- Talk at Zimányi School 2016 and SCOPES meeting at Belgrade.
- Currently working on documentation: *AN2015-288*
- MSc thesis was submitted last Tuesday.
- Future plans: PhD at Eötvös Loránd University and Wigner RCP at Budapest, researching exclusive physics.

Thank you for your attention!