The XXXI International Workshop on Deep Inelastic Scattering (DIS2024)

Diffractive measurements at CMS and TOTEM

09 April 2023

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The University of Kansas

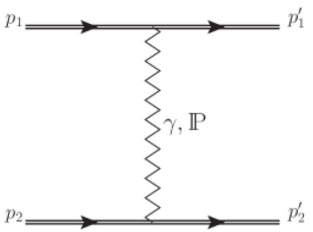
** also with the Ben Gurion University of the Negev*

On behalf of the CMS and TOTEM Collaborations

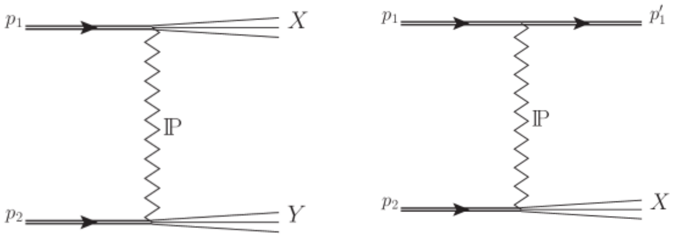
U.S. DEPARTMENT OF ENERGY Office of Science
Grant DE-SC0023908

Diffractive interactions at the LHC

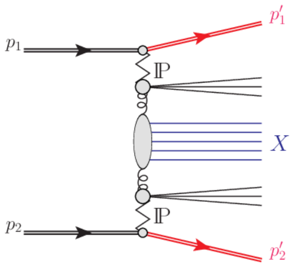
- t-channel exchange of color neutral particles (QED, QCD)



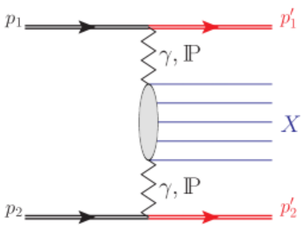
Elastic scattering



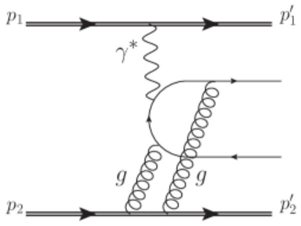
Single/double diffractive dissociation



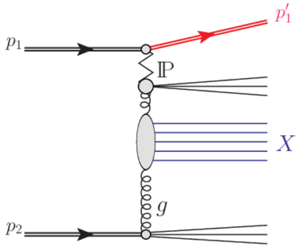
Double pomeron exchange



Central exclusive production



Exclusive photoproduction



Single-diffraction with central system

- Spans over large kinematic region (MeV – TeV), and large cross-section range
- Provide a rich scientific program for LHC experiments

See Ronan McNulty's talk

Soft diffraction: Purely nonperturbative processes

Hard diffraction: Substantial fraction of proton kinetic energy is transferred (~a few%)

Introduction

Diffractive interactions at the LHC

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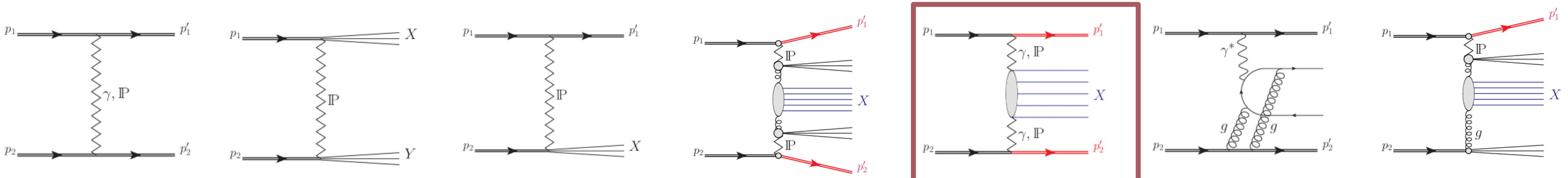

Elastic scattering

Single/double diffractive dissociation

Double pomeron exchange

Central exclusive production

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Single-diffraction with central system

- Spans over large kinematic region (MeV – TeV), and large cross-section range
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Soft diffraction: Purely nonperturbative processes

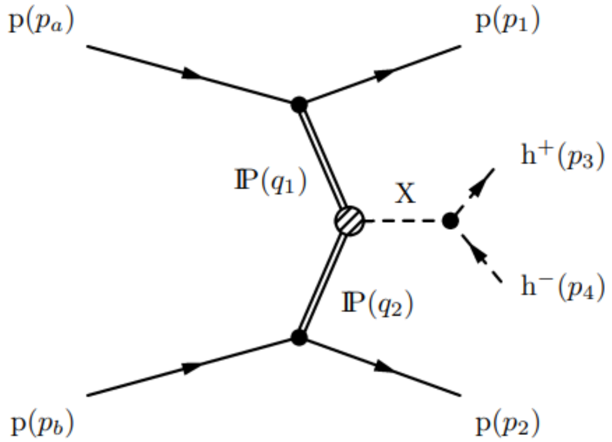
New results

Hard diffraction: Substantial fraction of proton kinetic energy is transferred (~a few%)

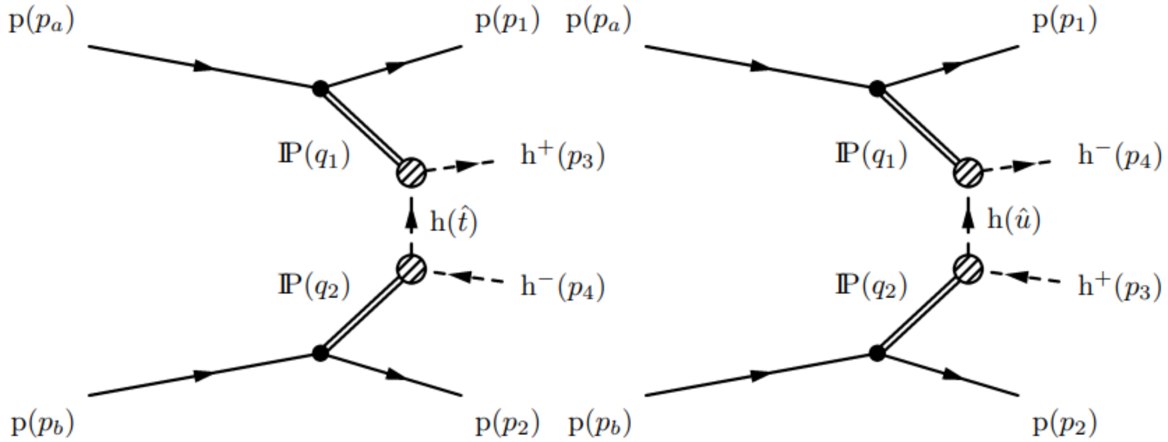
Introduction

Soft central exclusive production processes

- A clean laboratory for the study of various nonperturbative phenomena (glueballs, …)
- Dominated by double-pomeron exchange (DPE) at high momentum transfer (t)



Resonant production



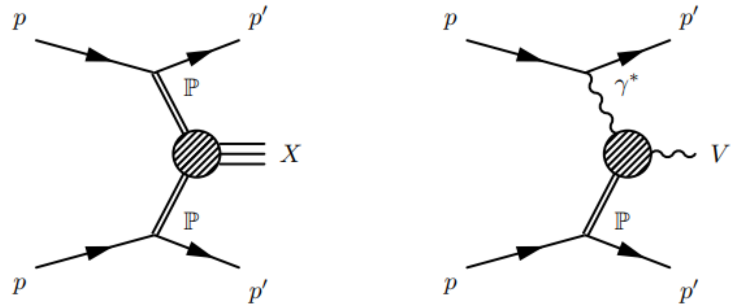
Nonresonant production (continuum)

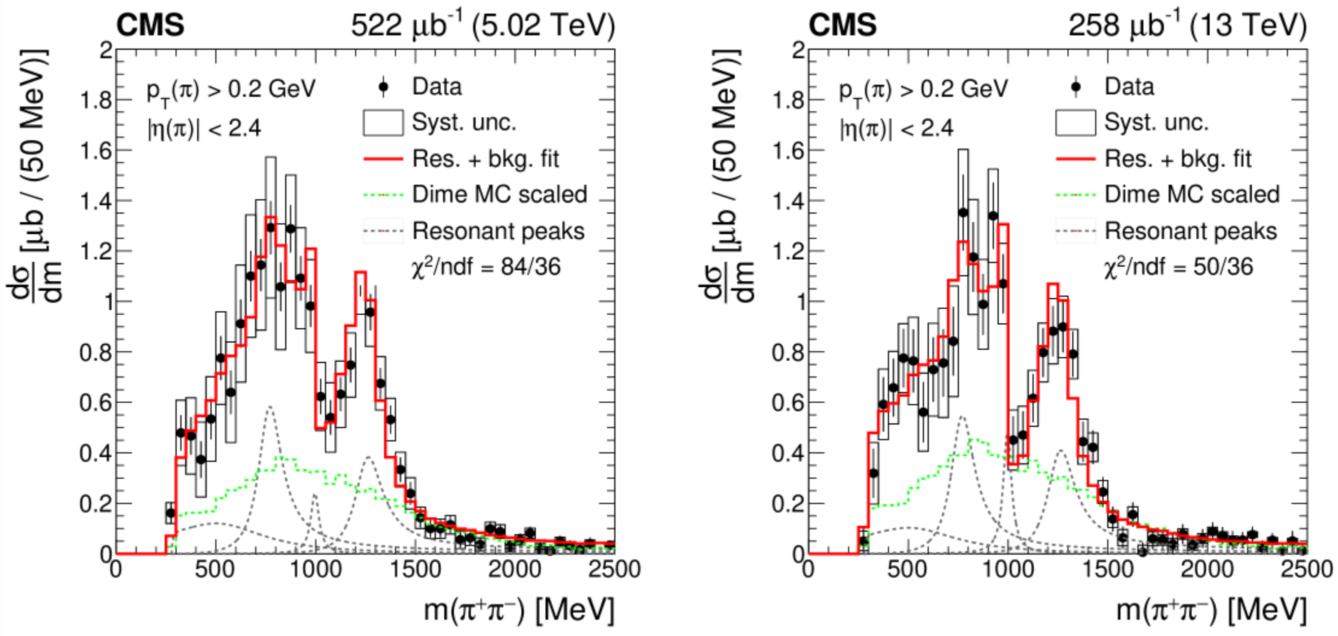
Introduction

EPJC 80 (2020) 718

First measurements of exclusive di-pions

- Imposed rapidity gap selection criteria (DPE + Photoproduction)
- Resonant production at 5.02 and 13 TeV data



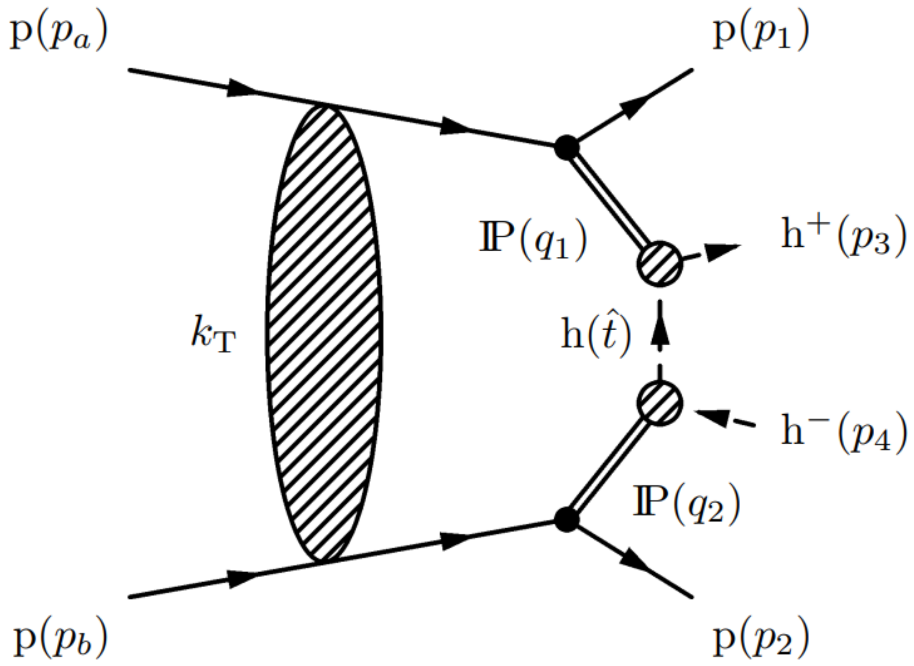


Resonant production

- Measured production cross-section in the pT>0.2 GeV, |η|<2.4 fiducial region
- Modeled by Breit-Wigner functions ∗ Gaussian

Resonance	$\sigma_{pp\to p'p'X\to p'p'\pi^+\pi^-}$ [μb]	
	$\sqrt{s} = 5.02$ TeV	$\sqrt{s} = 13$ TeV
$f_0(500)$	1.4 ± 0.7 (stat) ± 0.4 (syst) ± 0.03 (lumi)	1.2 ± 0.5 (stat) ± 0.4 (syst) ± 0.03 (lumi)
$\rho^0(770)$	2.6 ± 0.6 (stat) ± 0.6 (syst) ± 0.1 (lumi)	2.4 ± 0.8 (stat) ± 0.6 (syst) ± 0.1 (lumi)
$f_0(980)$	0.4 ± 0.1 (stat) ± 0.1 (syst) ± 0.01 (lumi)	0.7 ± 0.2 (stat) ± 0.2 (syst) ± 0.02 (lumi)
$f_2(1270)$	2.2 ± 0.4 (stat) ± 0.3 (syst) ± 0.1 (lumi)	2.3 ± 0.5 (stat) ± 0.3 (syst) ± 0.1 (lumi)

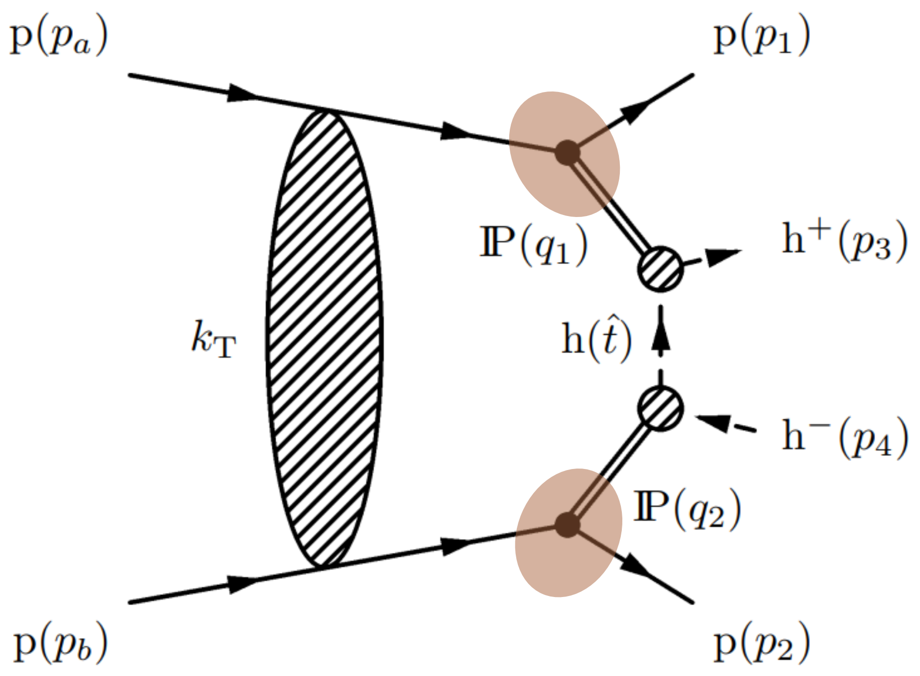
Nonresonant central exclusive production



$$\mathcal{M} = \mathcal{M}_{13}(t_1, s_{13}) \frac{F_m^2(\hat{t})}{\hat{t} - m^2} \mathcal{M}_{24}(t_2, 24) + \hat{t} \leftrightarrow \hat{u} + \mathcal{M}_{res}$$

Introduction

Nonresonant central exclusive production



Proton – Pomeron interaction ($\sim s^{\alpha_{IP}}$):

$$\mathcal{M}_{ik}(t,s) = i\sigma_0(s/s_0)^{\alpha_{IP}(t)}\mathcal{F}_p(t)$$

Where $\mathcal{F}_p(t)$ is the proton-pomeron Form Factor

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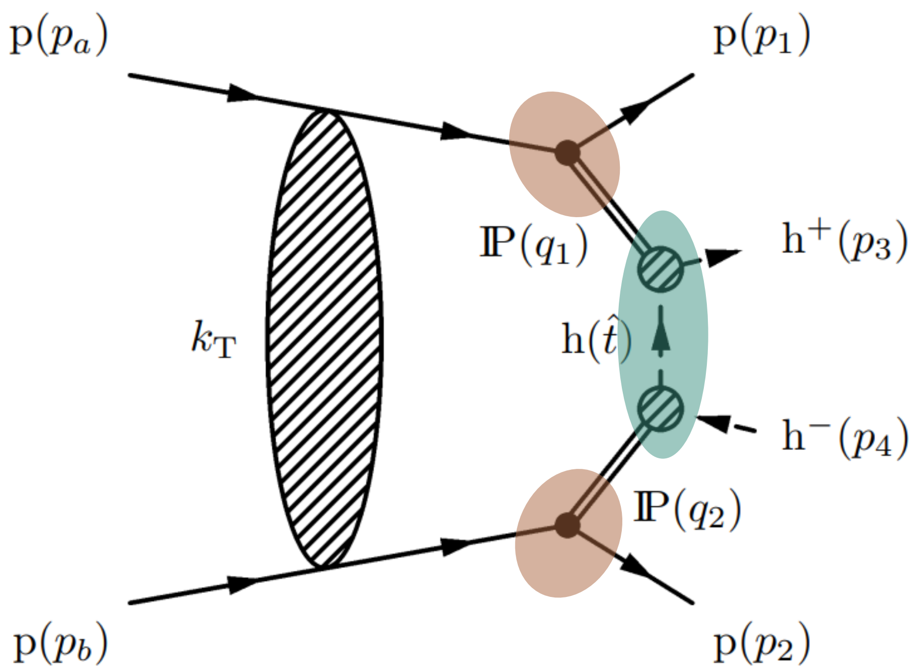

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Pomeron – meson interaction: $\frac{1}{\hat{t}-m^2} F_m^2(\hat{t})$

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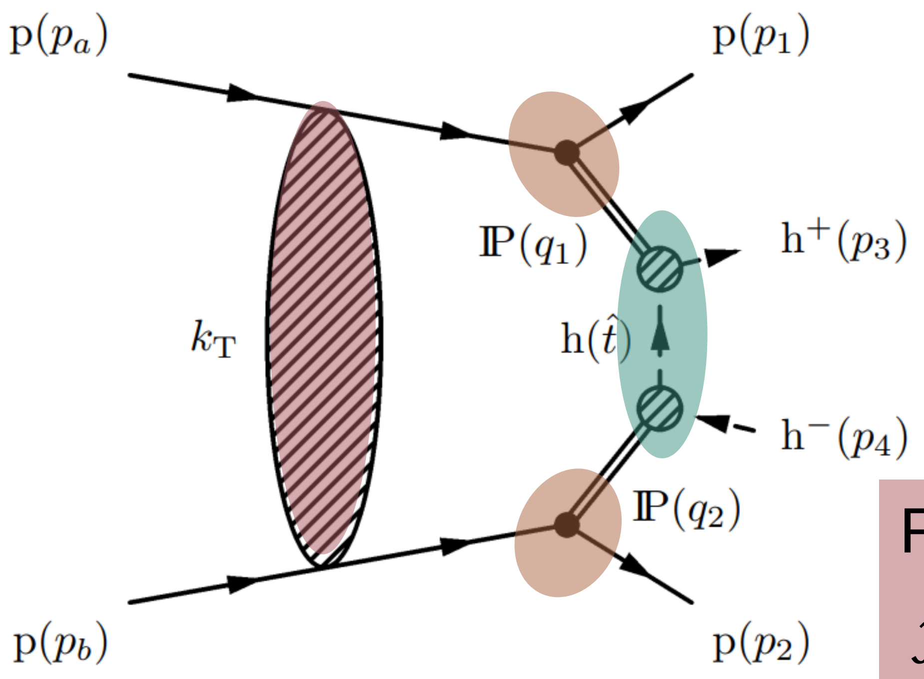

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Rescattering amplitude

$$\mathcal{M}_{res} = \int d^2\vec{k}_T \, \mathcal{M}(p_1 - k_T, p_2 - k_T) \mathcal{F}_p(t'_1)\, \mathcal{F}_p(t'_2) S(k_T)$$

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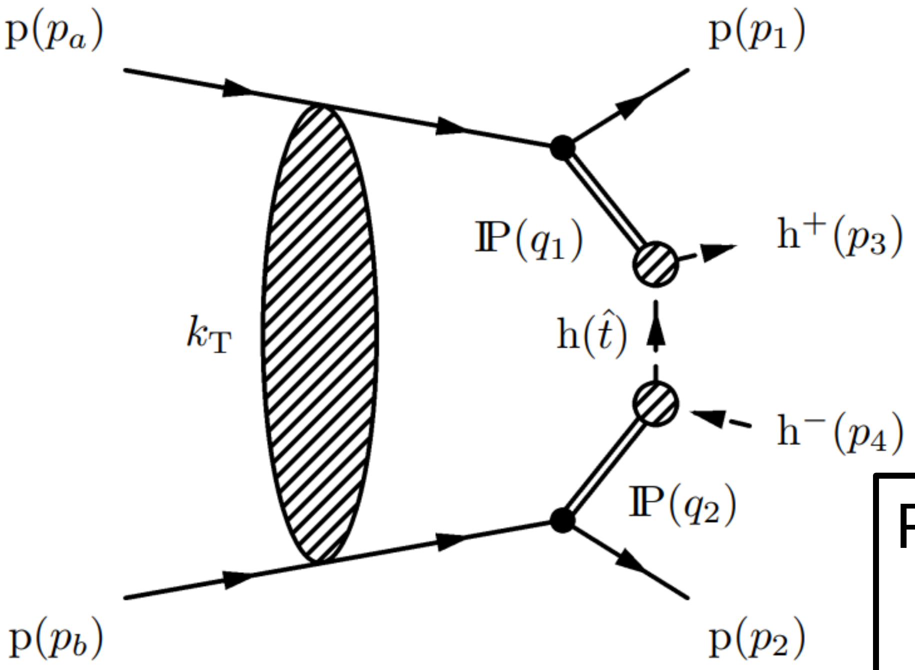

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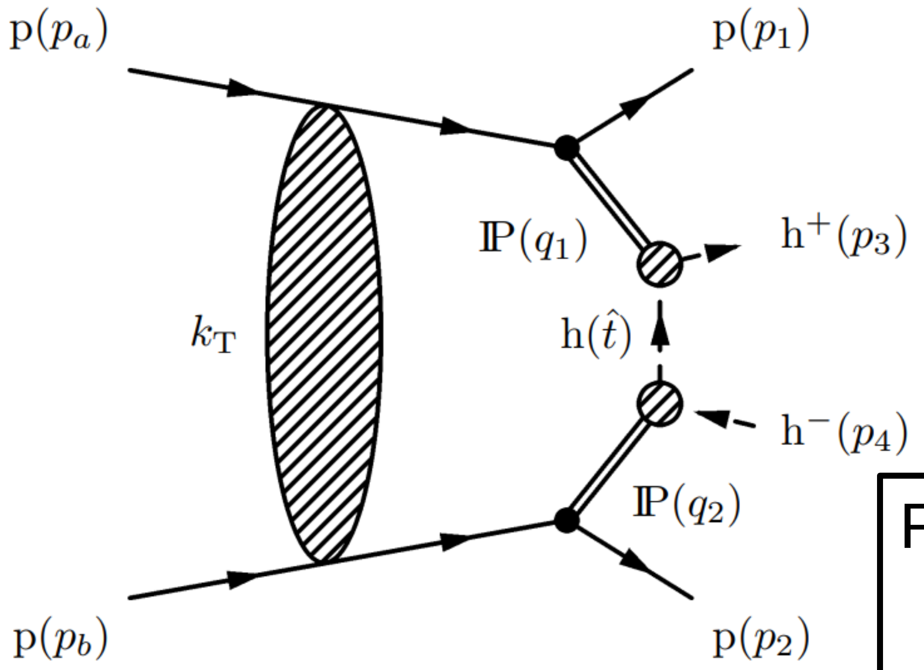

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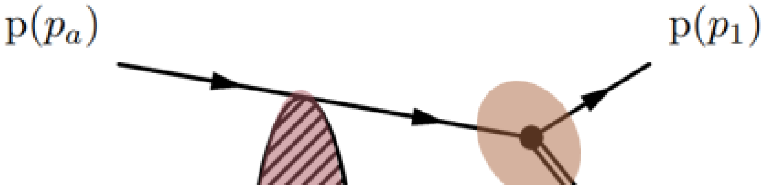


Nonresonant central exclusive production

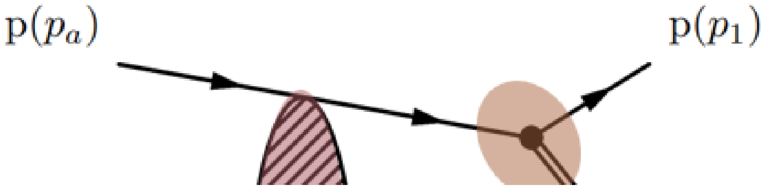
- Proton-pomeron Form Factor $\mathcal{F}_p(t)$:

  One channel model:

$$\mathcal{F}_p(t) = e^{B/2t}$$

Introduction

Nonresonant central exclusive production



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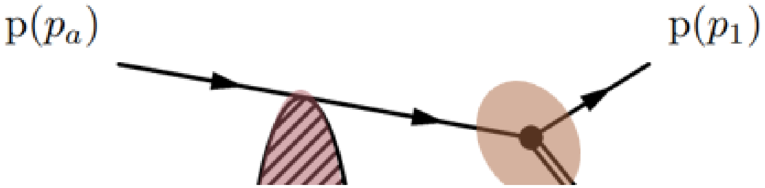
Two-channels model (two diffractive states)

$|p\rangle = a_i|\phi_i\rangle$, with coupling γ_i

$$\mathcal{F}_i(t) = e^{-[b_i(c_i - t)]^{d_i} + [b_i c_i]^{d_i}}$$

Introduction

Nonresonant central exclusive production



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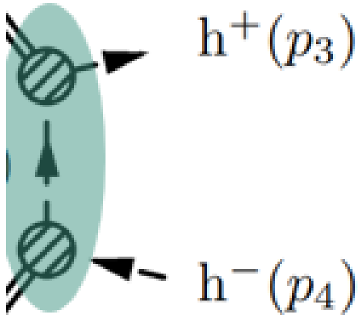
- Pomeron-meson Form Factor $\mathcal{F}_m(t)$:



$$F_m(\hat{t}) = \begin{cases} \exp(b_{\mathrm{exp}}(\hat{t} - m^2)), & \text{Exponential} \\ \exp(b_{\mathrm{ore}}[a_{\mathrm{ore}} - \sqrt{a_{\mathrm{ore}}^2 - (\hat{t} - m^2)}]), & \text{Orear, PRL } \mathbf{12} \text{ (1964) 112} \\ 1/(1 - b_{\mathrm{pow}}(\hat{t} - m^2)) & \text{Power-law} \end{cases}$$

Nonresonant central exclusive production – MC model

- Implemented in DIME event generator https://dimemc.hepforge.org/

Parameter	DIME-1	DIME-2	DIME-3	DIME-4	Remark
σ_P [mb]	23	33	60	50	pomeron strength
α_P	1.13	1.115	1.093	1.11	pomeron intercept, $= 1 + \Delta$
α'_P [GeV^{-2}]	0.08	0.11	0.075	0.06	pomeron slope
γ_i	1 ± 0.55	1 ± 0.4	1 ± 0.42	1 ± 0.47	dimensionless coupling to eigenstate i
2 $\lvert a_i \rvert^2$	1 ± 0.08	1 ± 0.5	1 ± 0.52	1 ± 0.5	a_i is the amplitude of eigenstate i
b_1 [GeV^{-2}]	8.5	8	5.3	7.2	
b_2 [GeV^{-2}]	4.5	6	3.8	4.2	pomeron coupling to eigenstates (b_2 to d_1)
c_1 [GeV^2]	0.18	0.18	0.35	0.53	
c_2 [GeV^2]	0.58	0.58	0.18	0.24	
d_1	0.45	0.63	0.55	0.6	
d_2	0.45	0.47	0.48	0.48	

Harland-Lang, Khoze, Ryskin, EPJC **74** (2014) 2848

Nonresonant central exclusive production

- φ distribution is connected to the quantum mechanical amplitude of the process
- Di-pion production data can be fitted with a simple functional form

$$\frac{d^3\sigma}{dp_{1,T}dp_{2,T}d\phi} = [A(R - cos\phi)]^2 + c^2$$

- Dip at $\phi = \text{acos}(R)$ can be understood as an effect of additional pomeron exchanges, resulting from the bare and rescattered amplitudes

- Free parameters can be fitted using model-motivated functional forms

  PLB 464 (1999) 279, PLB 477 (2000) 13

$$A(t_1, t_2) = 4\sqrt{t_1 t_2} A_0 e^{b(t_1+t_2)},$$

$$R(t_1, t_2) \approx \frac{1.2(\sqrt{-t_1} + \sqrt{-t_2}) - 1.6\sqrt{t_1 t_2} - 0.8}{\sqrt{t_1 t_2} + 0.1},$$

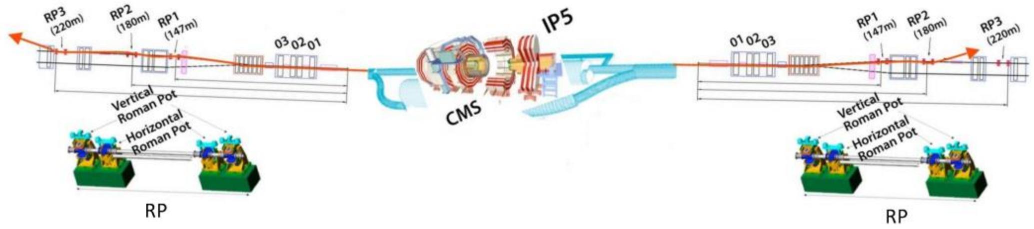
$$c(t_1, t_2) = c_0 e^{d(t_1+t_2)}.$$

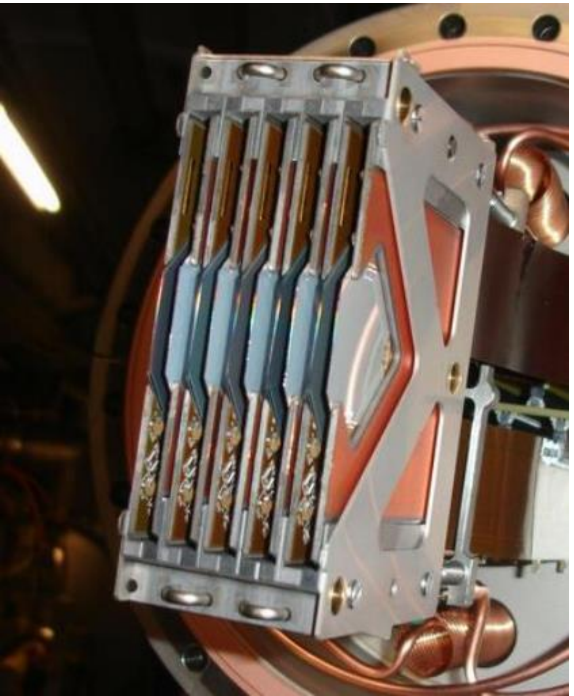
Proton tagging

Tagging scattered protons → tagging diffractive events

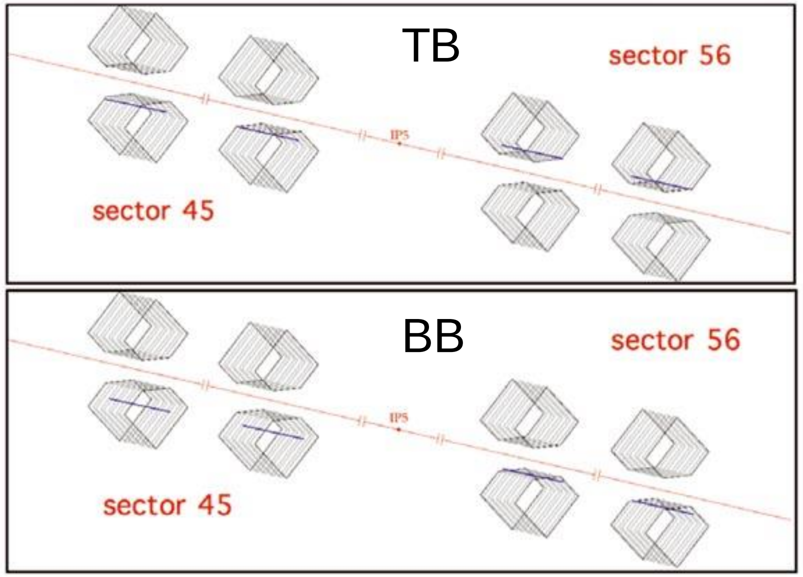
- TOTEM: **TOT**al cross section **E**lastic scattering and diffraction dissociation **M**easurements at the LHC

- Protons scattered at small angles are deflected away from the beam and measured by forward detectors.





- ➢ Two arms (sector 45 and 56)
- ➢ Two stations (at ~213 and 220m)
- ➢ Top and bottom pots
- ➢ Each station has 5+5 panes (‘v’ and ‘u’)
- ➢ Each plane has 4x128 strips



https://cerncourier.com/a/totem-sees-elastic-scattering-and-lhcf-completes-first-run/

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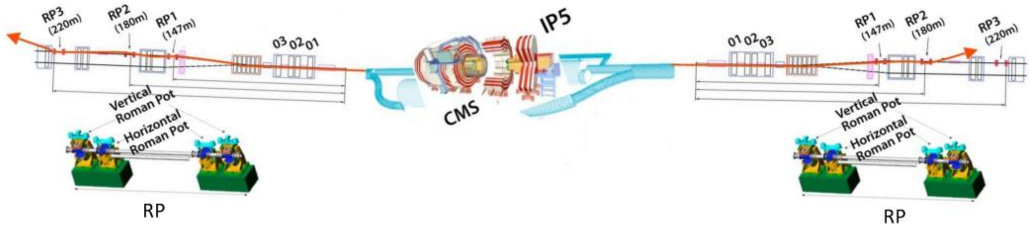

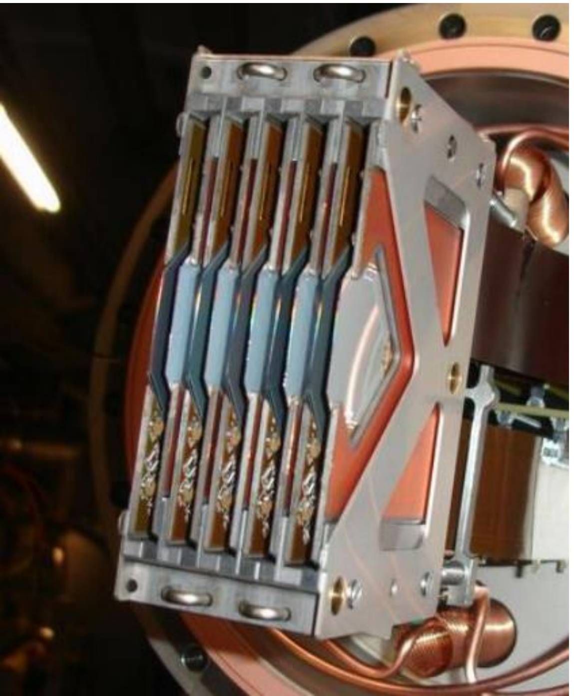

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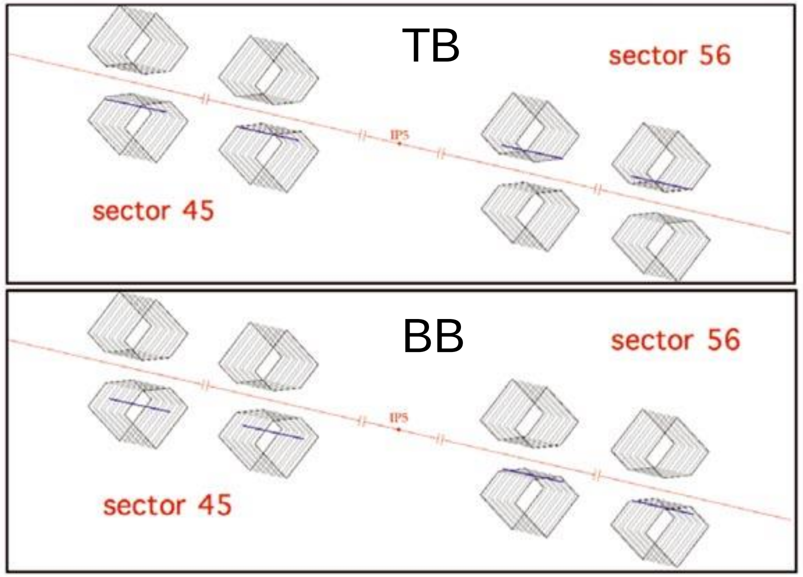
Detectors are operational only at low beam intensity



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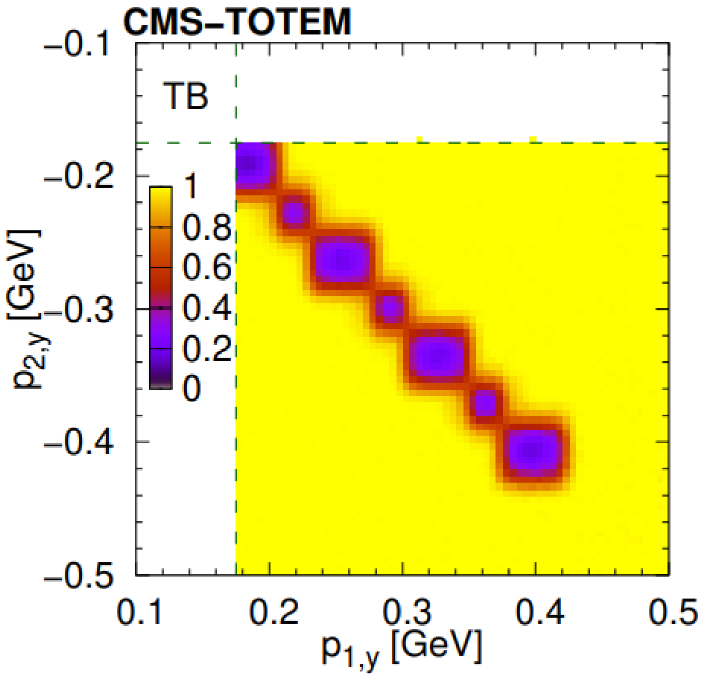
Exclusive production of hadrons

Analysis overview

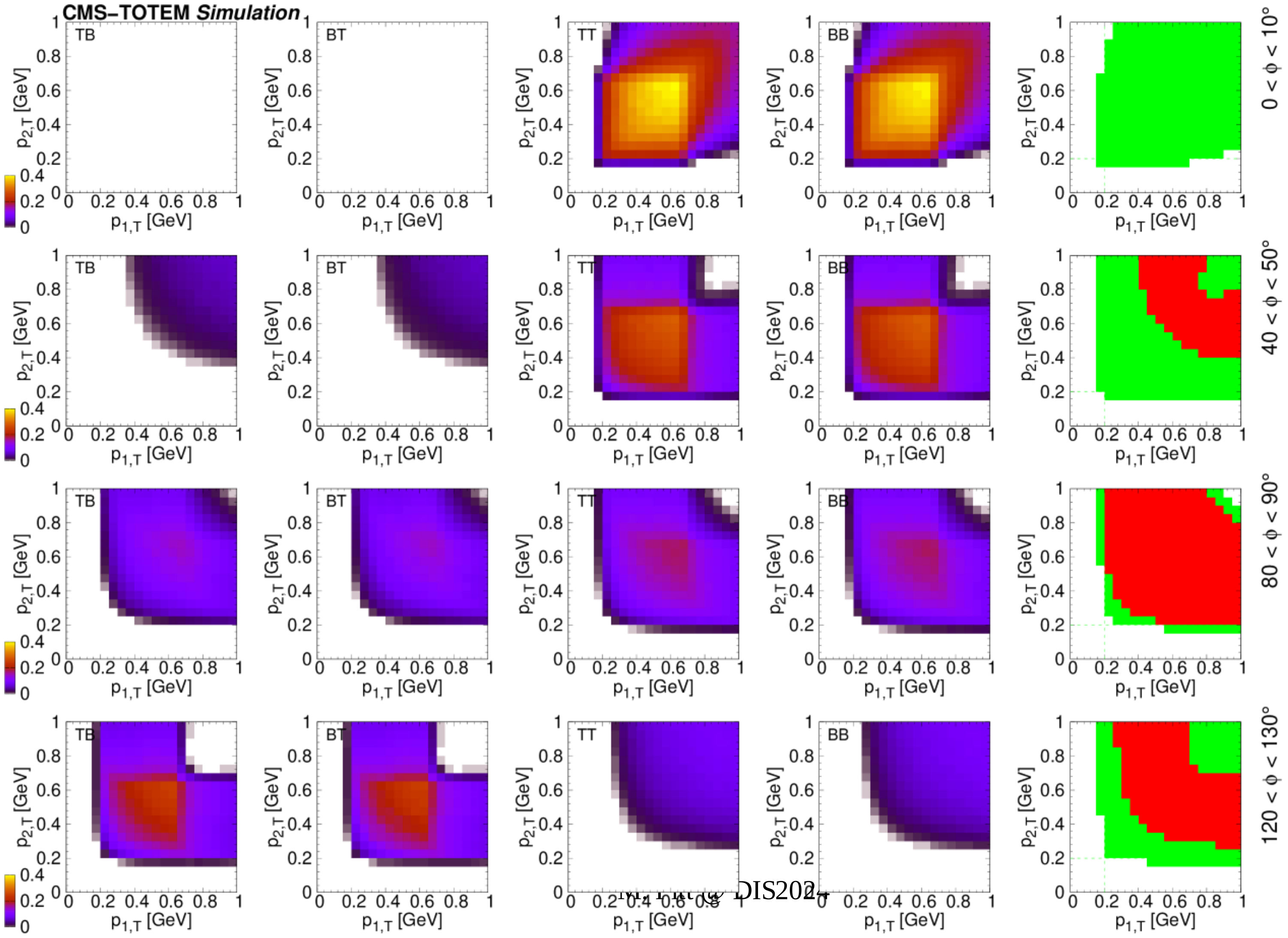
arXiv:2401.14494
(Accepted for publication in PRD)

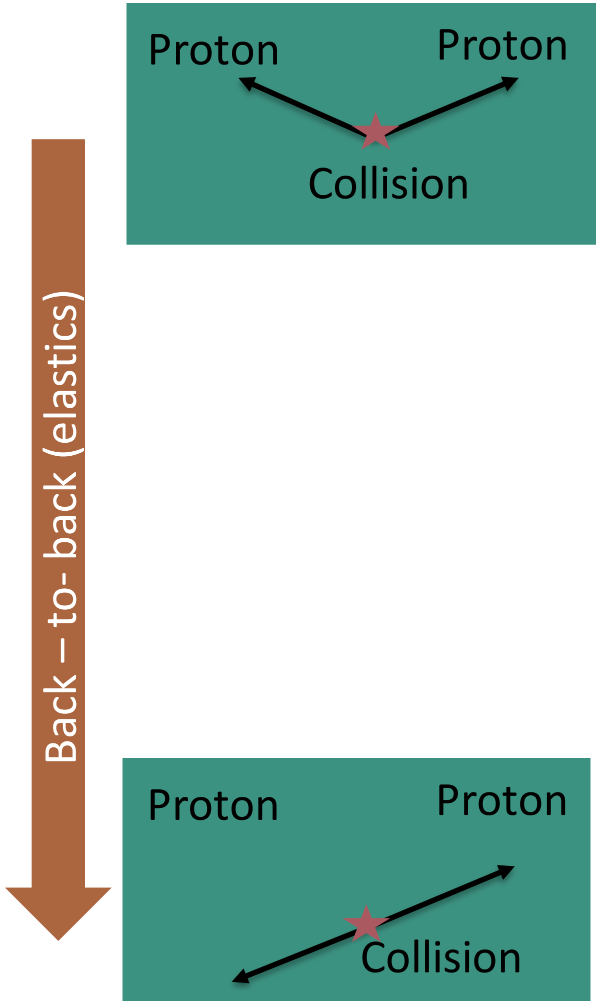
- Using data collected by CMS + TOTEM experiments in 2018 to utilize proton tagging
- Data recorded during LHC special high-β* runs
- Events are triggered by forward proton detectors in 4 configurations: TT TB BT BB
  - TB&BT: elastic veto was applied (trigger level)
  - Proton acceptance $0.175 < p_y < 0.670$ GeV
  - Hadron track acceptance $p_T > 0.1$ GeV
  - 2 tracks + 2 protons at the final state



Proton reconstruction efficiency

Coverage:
Partial, Full

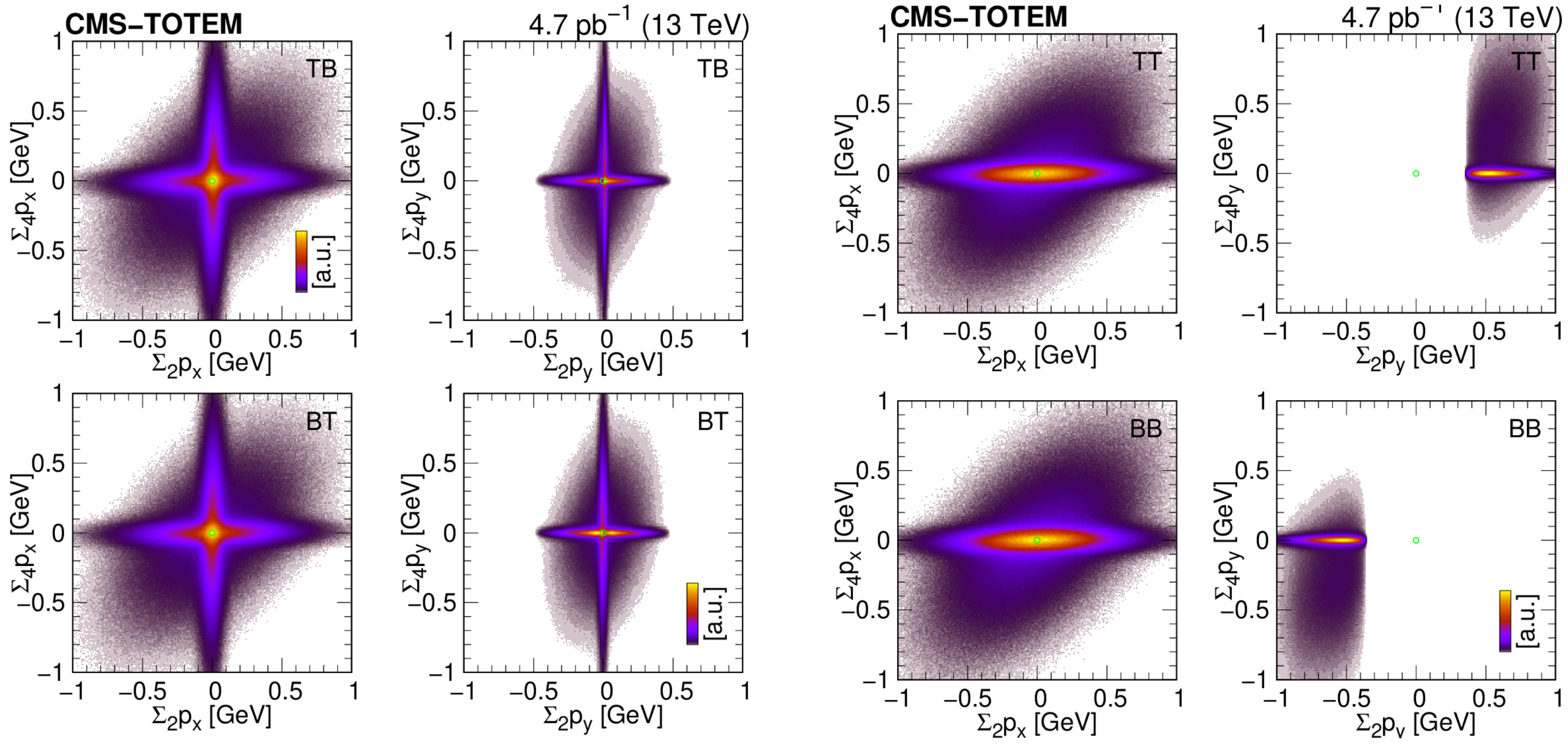




Exclusive production of hadrons

Proton – track matching

- Sum of the scattered proton and central hadron momenta and the sum of the scattered proton momenta



Σ_4 proton and central hadron
Σ_2 only scattered protons

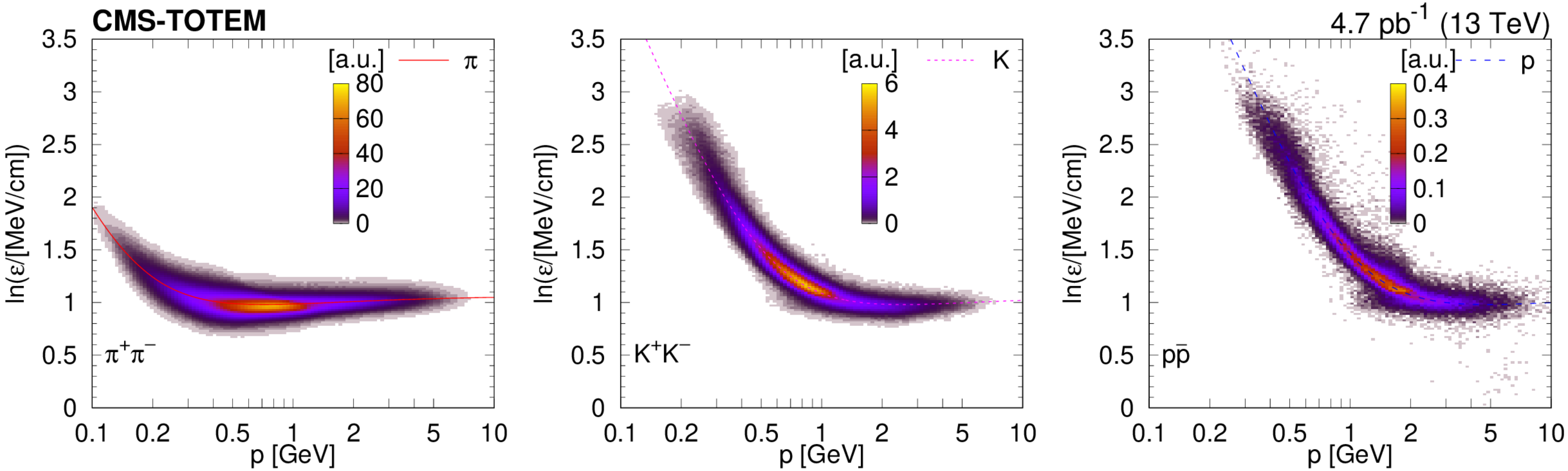
TT/BB topology:
kinematic cut at p_y>175 MeV is visible

TB/BT topology:
Elastic protons (pileup) are visible

In all topologies inelastic backgrounds is present (a slanted area)

Performance of the CMS tracker

- Particle ID based on dE/dX measurement, and probability $P_h(\varepsilon, p)$ is contracted
- Select 2 track events of the same type: $P_{2,h} \cdot P_{2,h} > 10 \cdot P_{1,k} \cdot P_{1,k}$ for $k \neq h$



Performance of the CMS tracker

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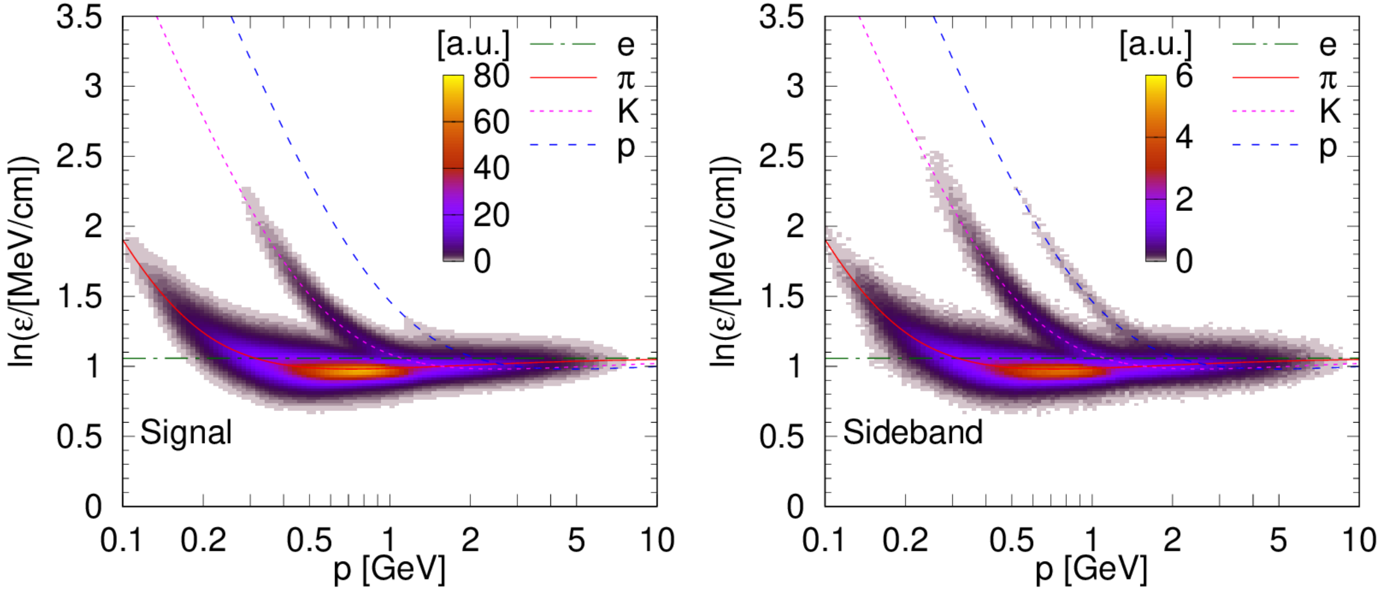
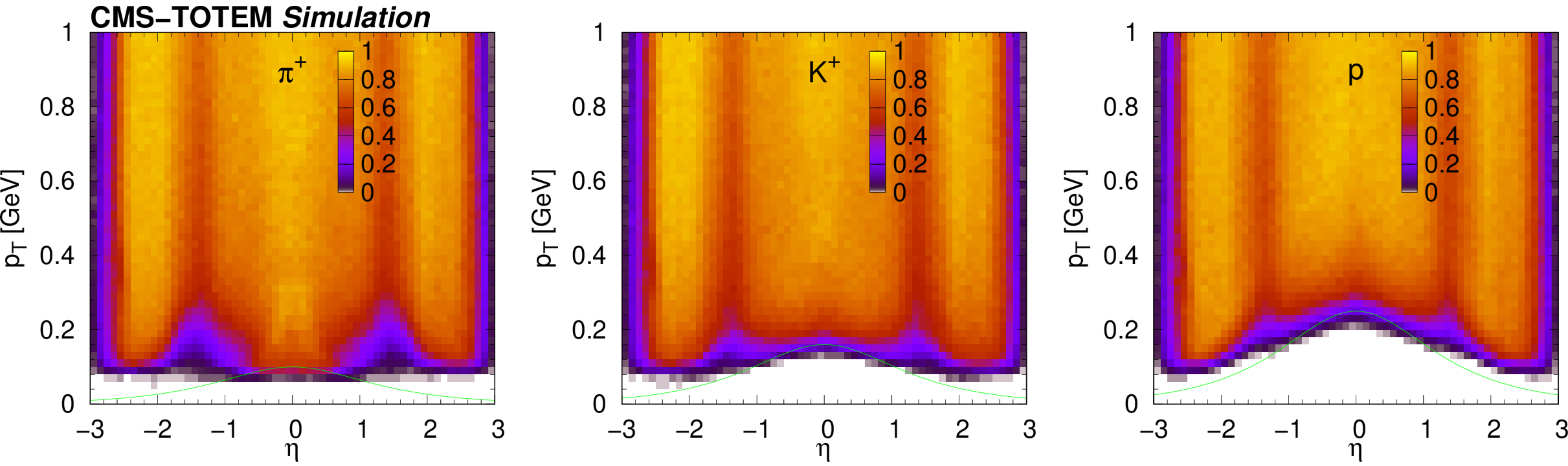
- Select 2 track events of the same type: $P_{2,h} \cdot P_{2,h} > 10 \cdot P_{1,k} \cdot P_{1,k}$ for $k \neq h$
- Impose track-RP matching – protons suppressed due to limited energy



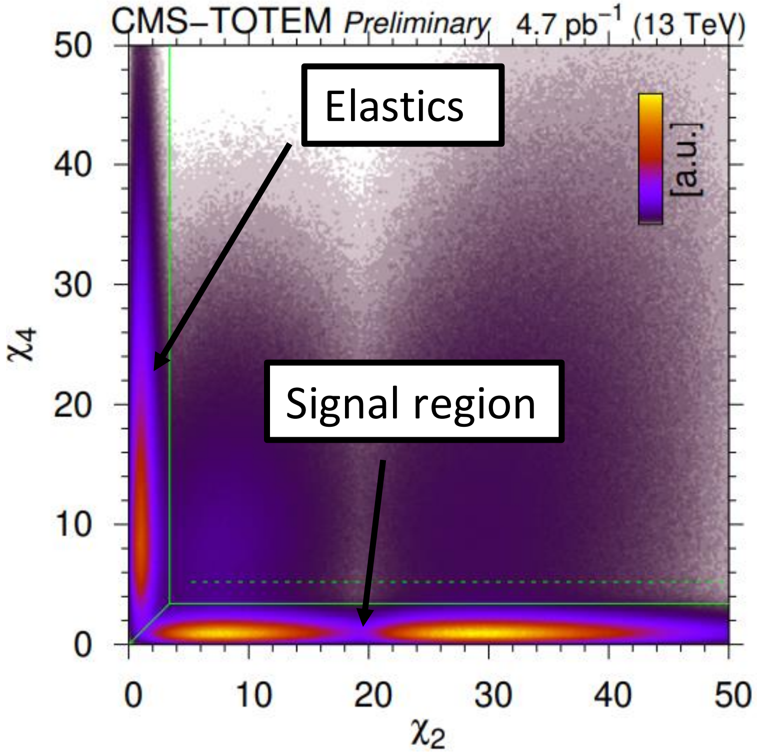
Performance of the CMS tracker

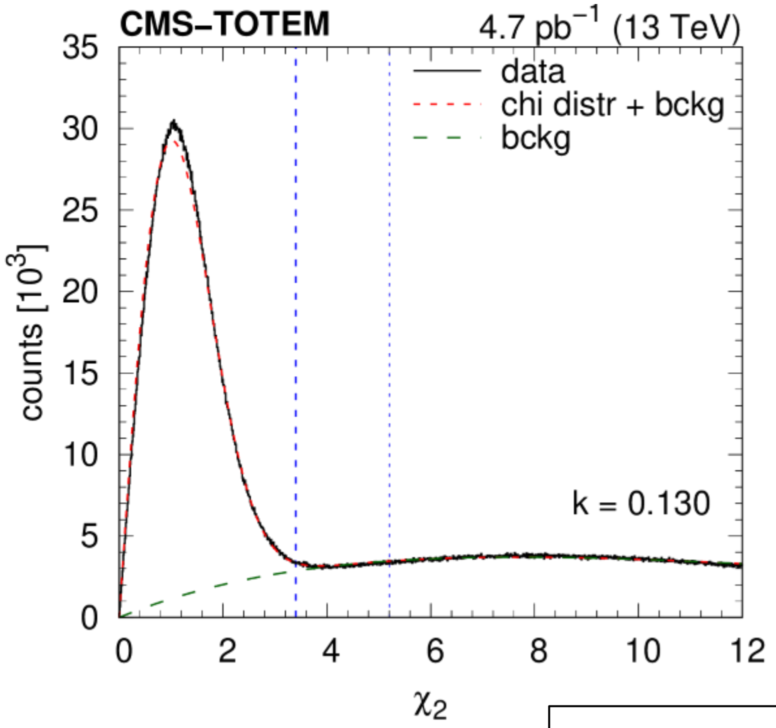
- The combined reconstruction and High-Level Trigger efficiency

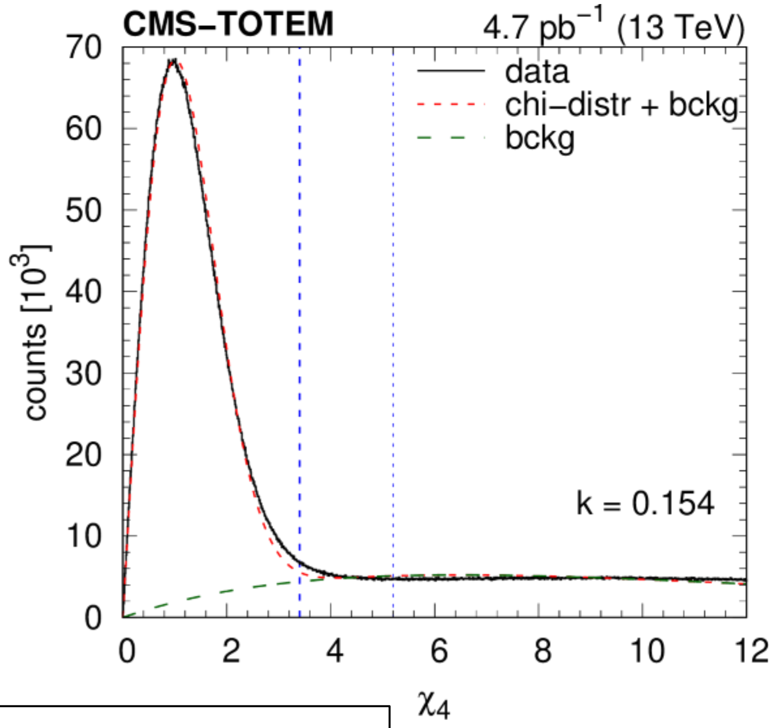


Event classification

- Based on the distributions $\vec{\Sigma}_2 = (\Sigma_2 p_X, \Sigma_2 p_Y)$, and $\vec{\Sigma}_2 = (\Sigma_2 p_X, \Sigma_2 p_Y)$ a classification variables (Mahalanobis distance) are constructed $\chi(\vec{\Sigma}) = \sqrt{\vec{\Sigma}^T V^{-1} \vec{\Sigma}}$, where $V(\Sigma)$ is the covariance matrix



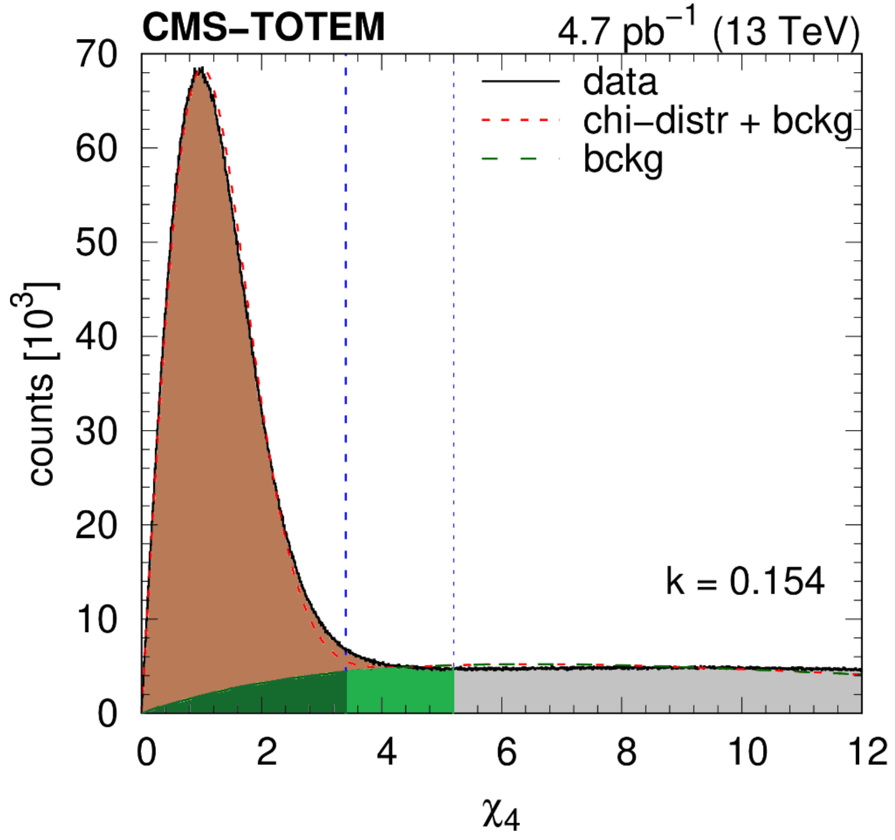


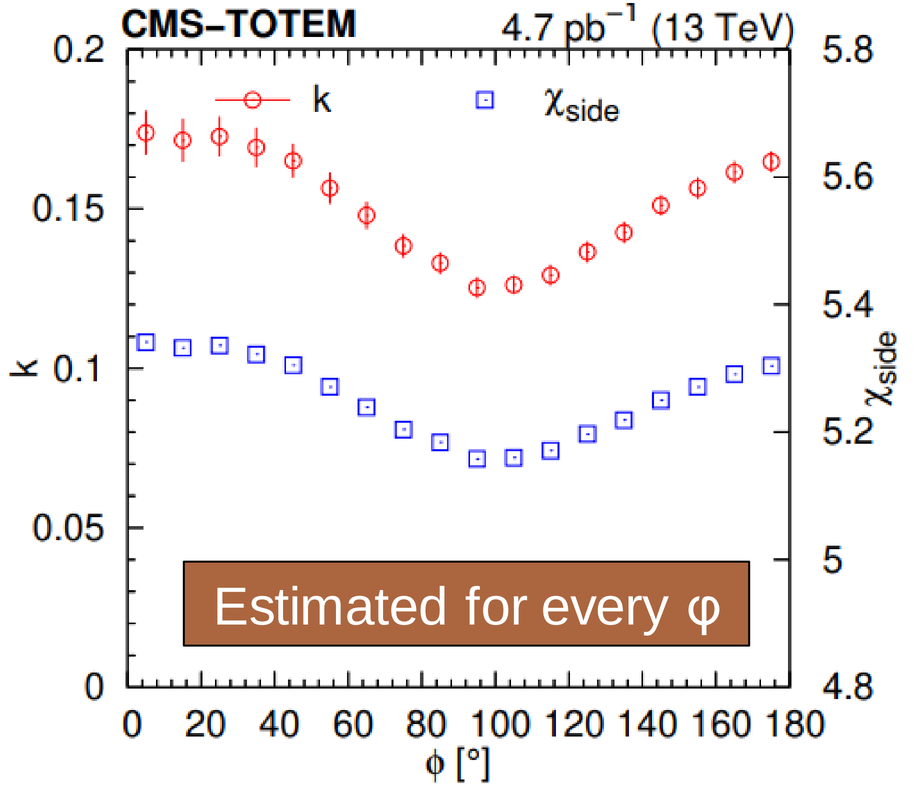


$$A\chi e^{-\chi^2/2} + B\chi e^{-k\chi}$$

Background subtraction

- Fitting the background component k, we can estimate background contamination in the signal region: $\int_0^{\chi_{SR}} \chi e^{-k\chi} = \int_{\chi_{SR}}^{\chi_{SB}} \chi e^{-k\chi}$, sensitive to fitted k parameter





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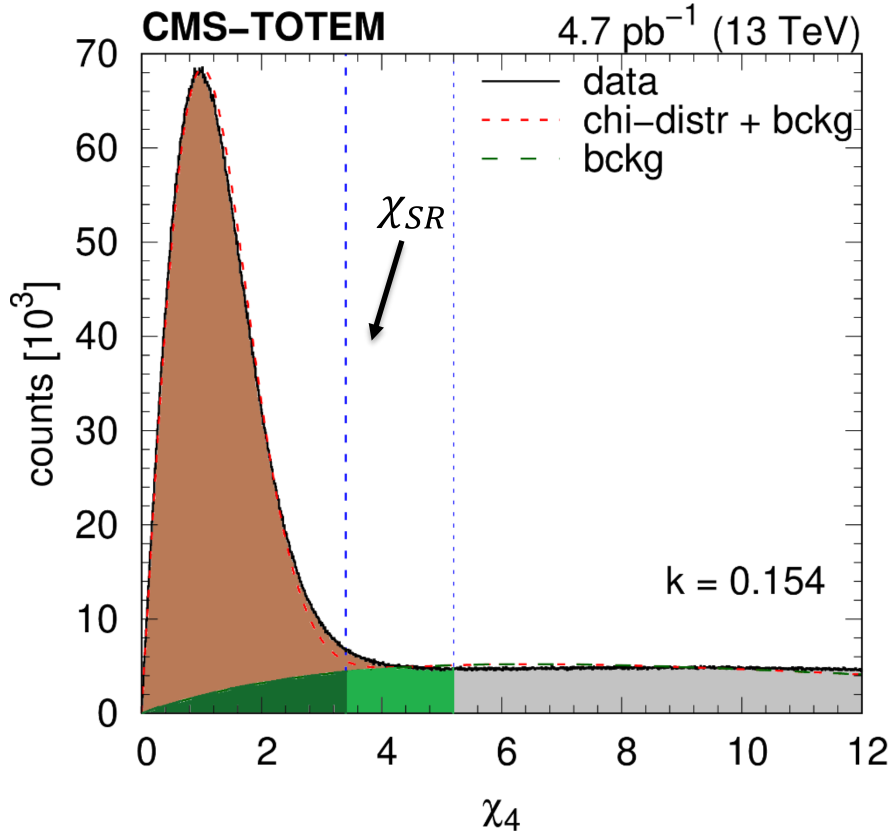

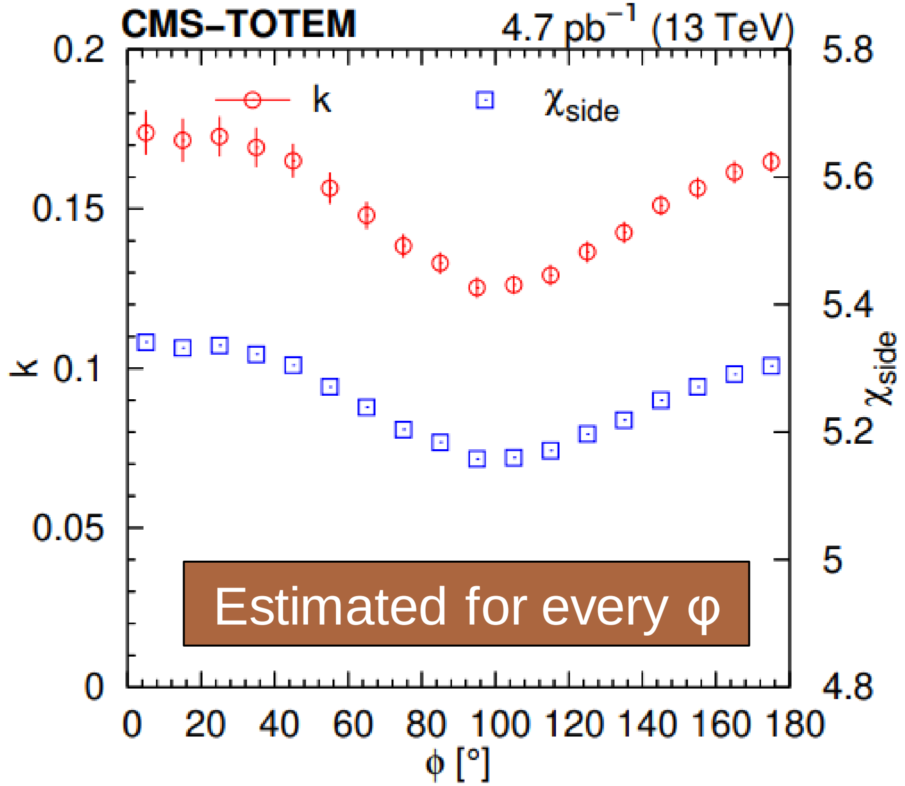

Exclusive production of hadrons

Background subtraction

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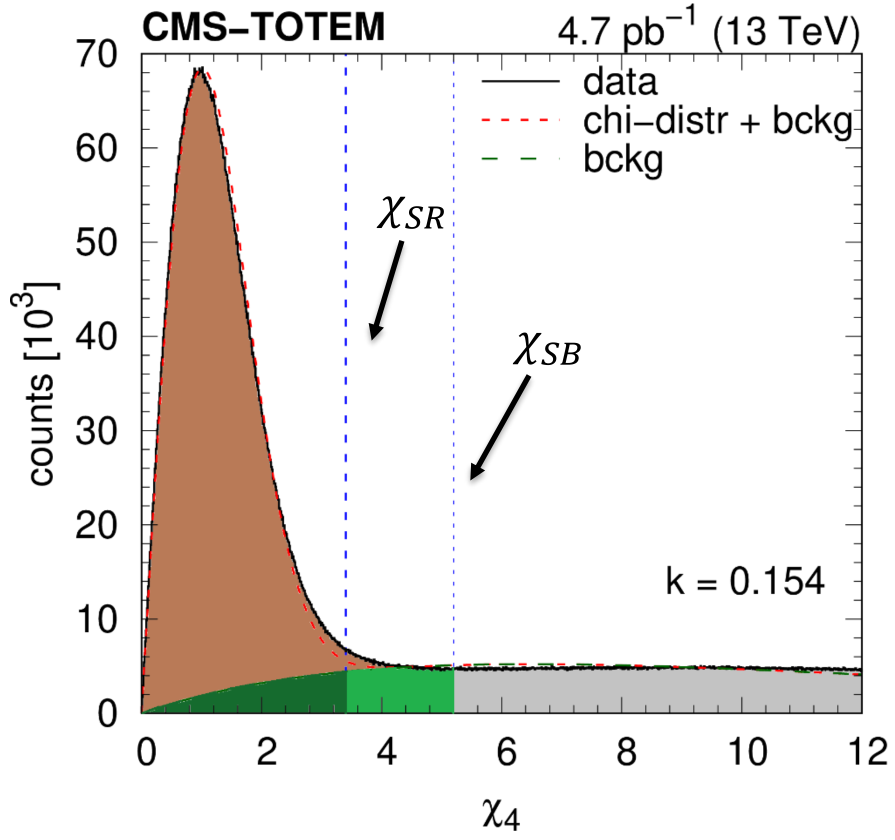
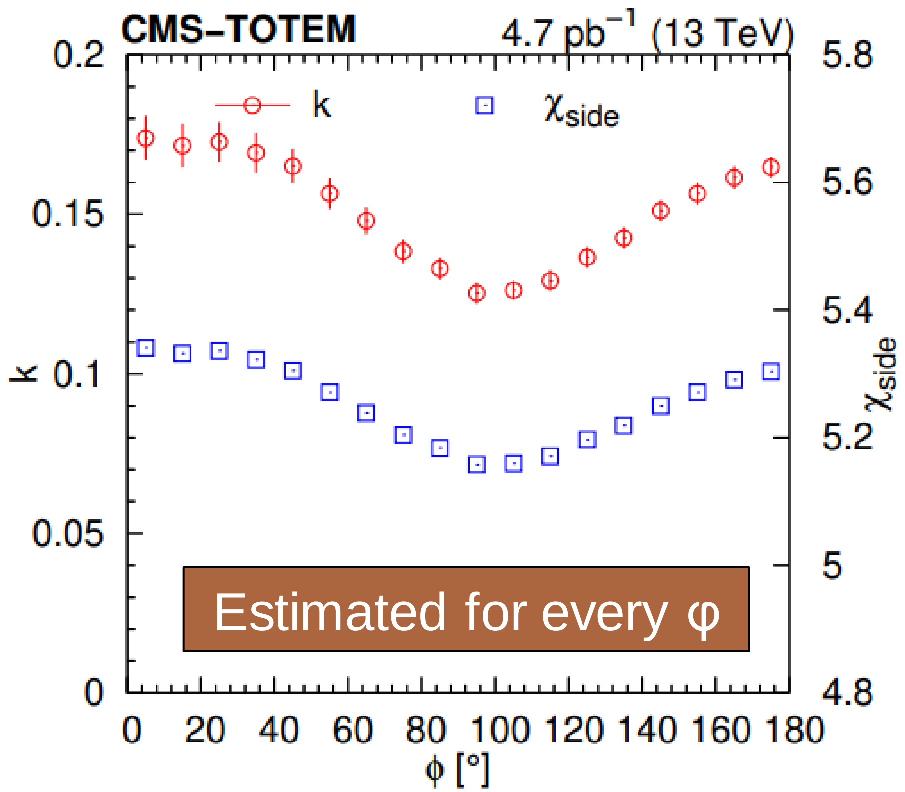




Systematics

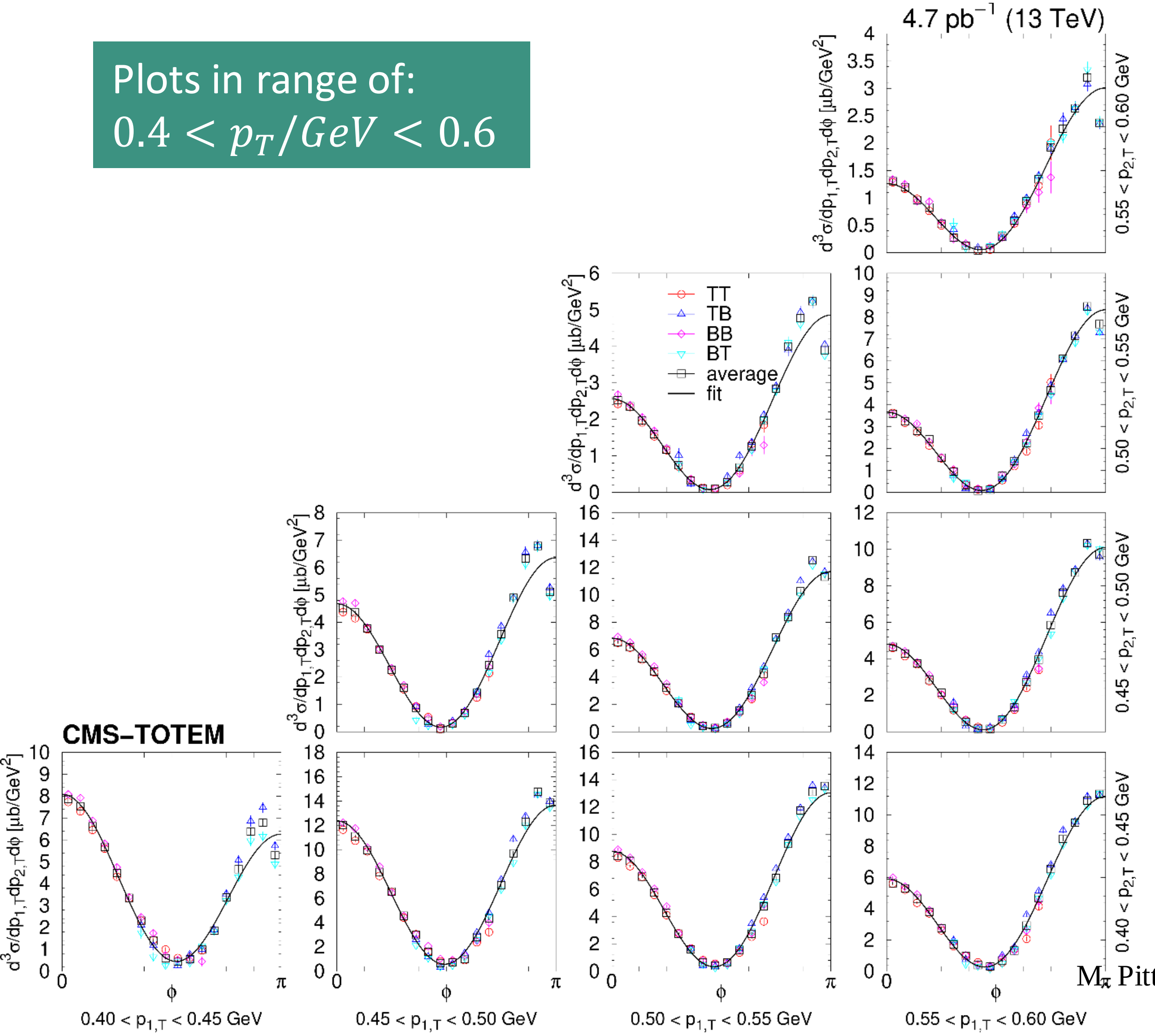
- Several sources, reasonable systematics (~5%)

Source	Value	Remark
Pileup correction	1.0%	through visible cross section (σ_{vis})
Lumisections with reduced RP availability	0.5%	
Integrated luminosity (L_{int})	2.5%	
HLT efficiency	small	neglected
Total normalisation-type	2.7%	
Roman pot efficiency	$\approx 3.0\%$	to be taken twice
Background removal	$< 0.5\%$	neglected
Lost events during background removal	-0.16%	neglected
Lost events due to looper cut	$< 0.5\%$	neglected
Single particle tracking efficiency	1.4%	to be taken twice
Particle identification efficiency	$< 1\%$	neglected
Total efficiency-type	4.7%	
Total systematics	5.4%	

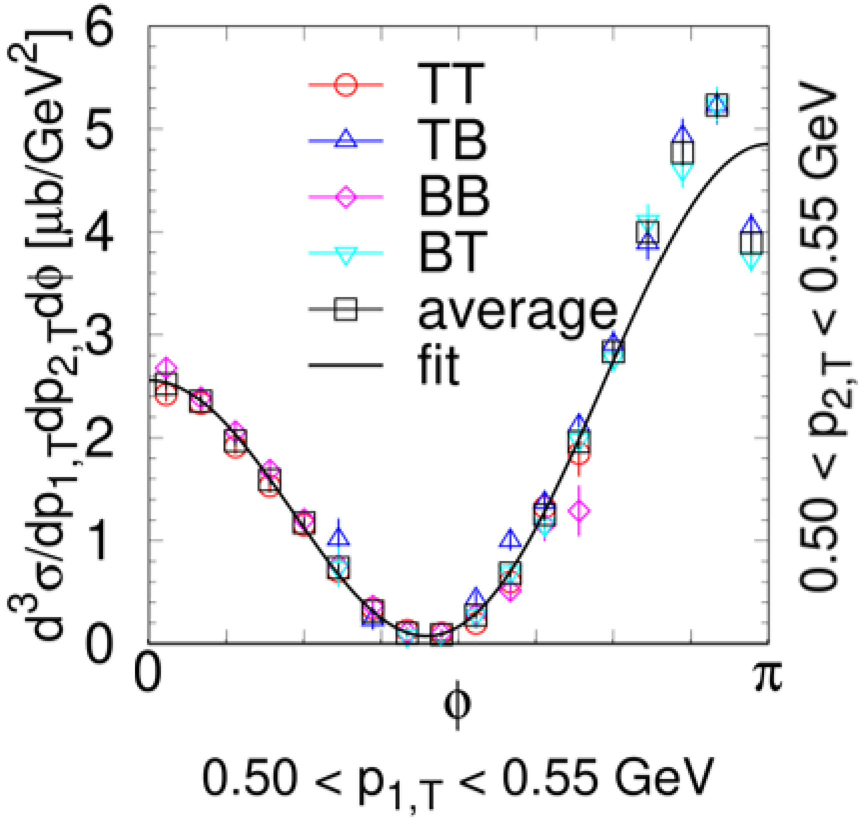
Results

- Measure differential cross-section if di-pions as a function of φ in p_T bins, μb/GeV^2

Plots in range of:
$0.4 < p_T/GeV < 0.6$

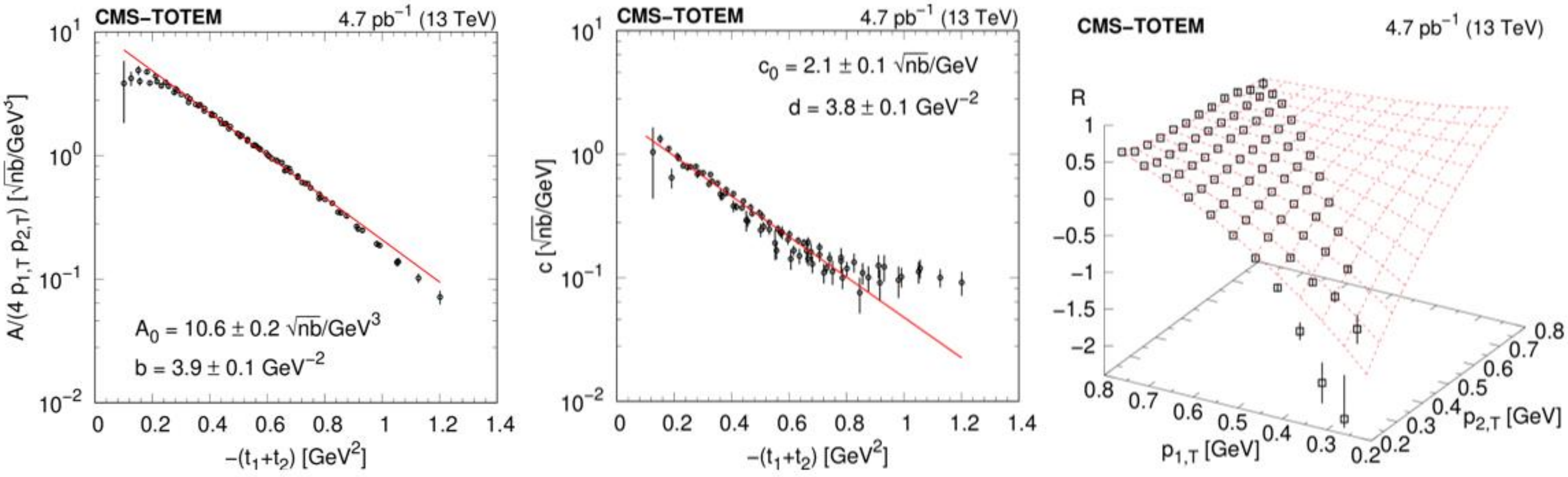


Example of single [p_{1T},p_{2T}] bin



Results

- From φ distributions parameters A, R, c as a function of p_T are fitted



Results

- From φ distributions Form-Factor are fitted
- Tuning is done with PROFESSOR (v2.3.3)

Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
Empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	9470/5796	10059/5795	11409/5796	
One-channel model				
σ_0[mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore}[GeV]	—	0.578 ± 0.022	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	7356/5793	7448/5792	8339/5793	
Two-channel model				
σ_0[mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore}[GeV]	—	0.718 ± 0.012	—	
$b_{exp/ore/pow}$[GeV$^{-2 \text{ or } -1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	−0.04 / −0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	5741/5786	6415/5785	7879/5786	

- **Diffractive Model**

(Proton-pomeron FF + Rescattering)

  - Empirical
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  - Two-channels

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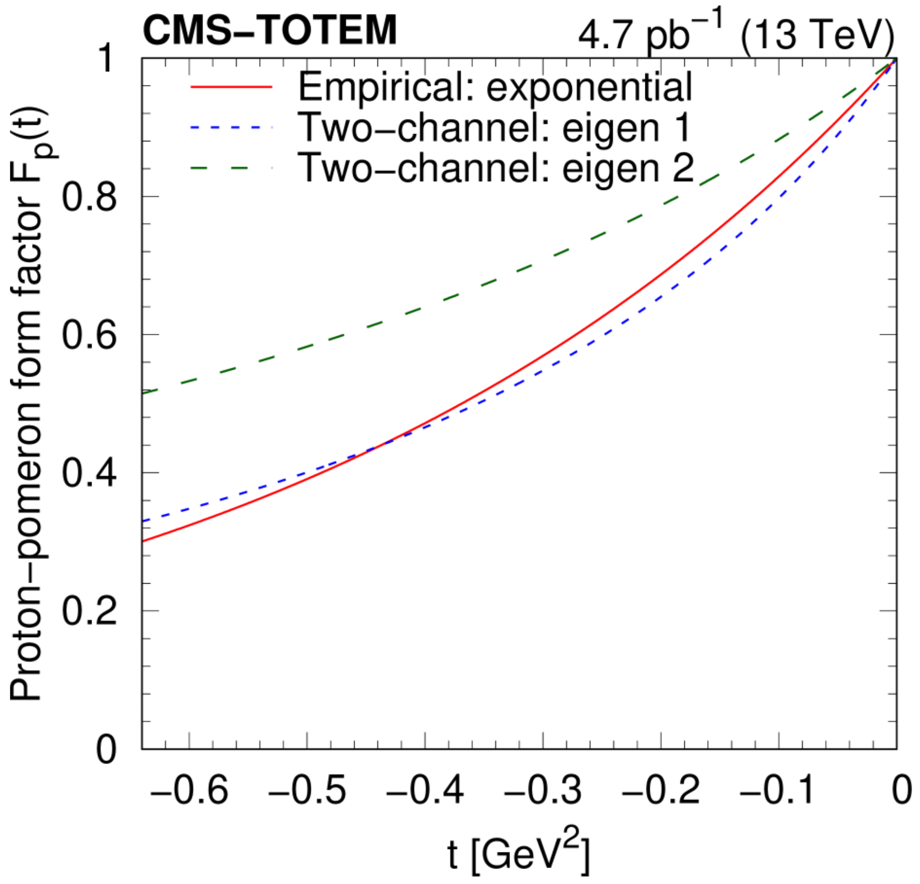

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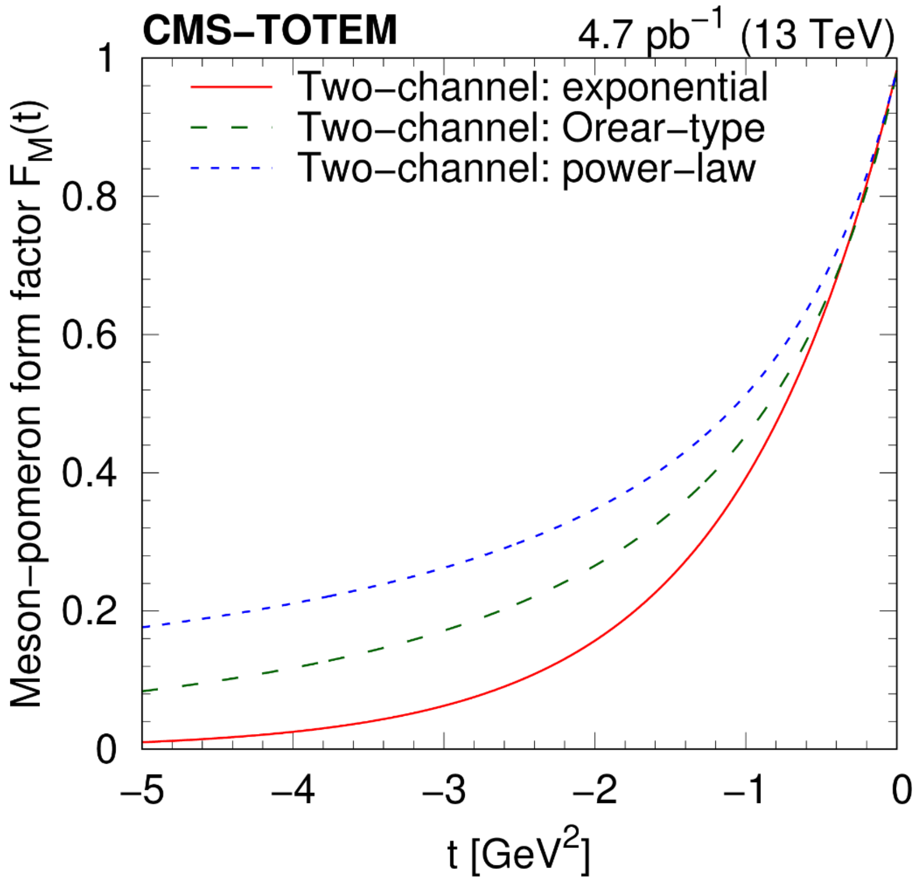

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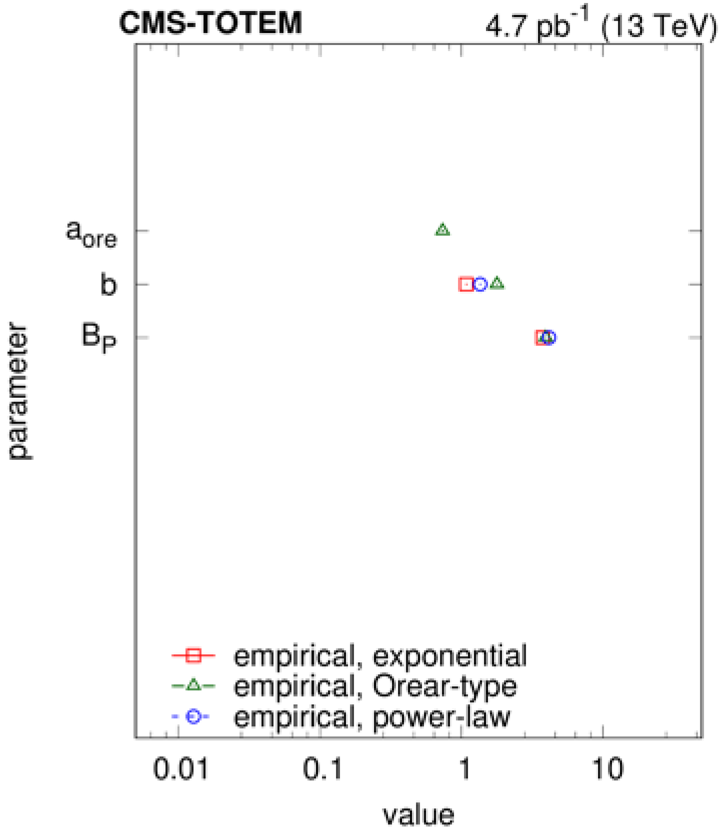
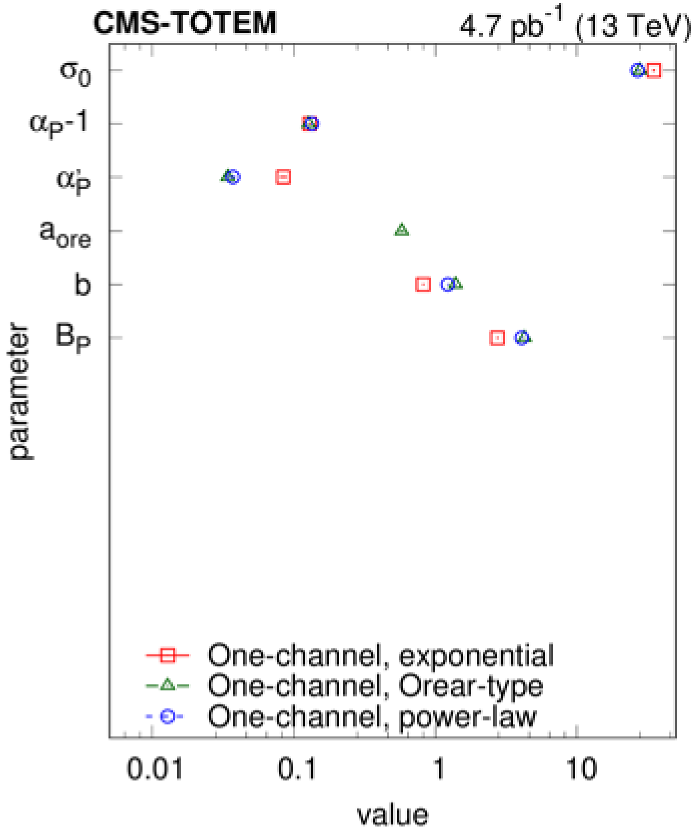
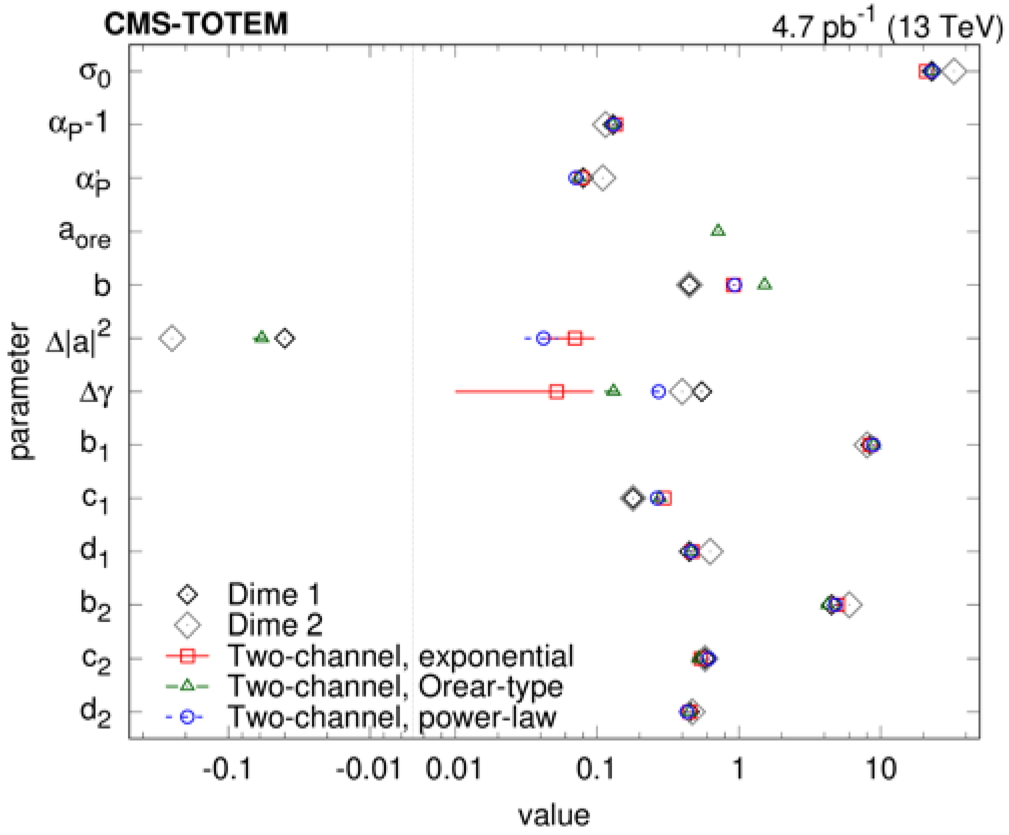


One-channel



Two-channels



Results

- From φ distributions Form-Factor are fitted
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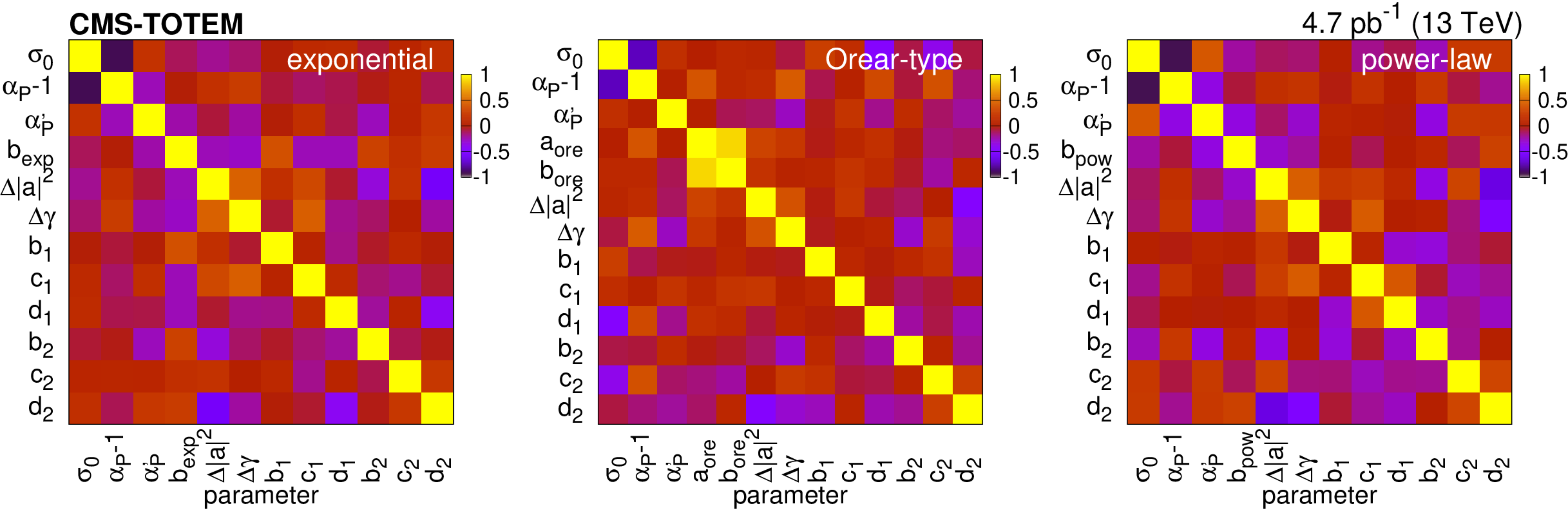
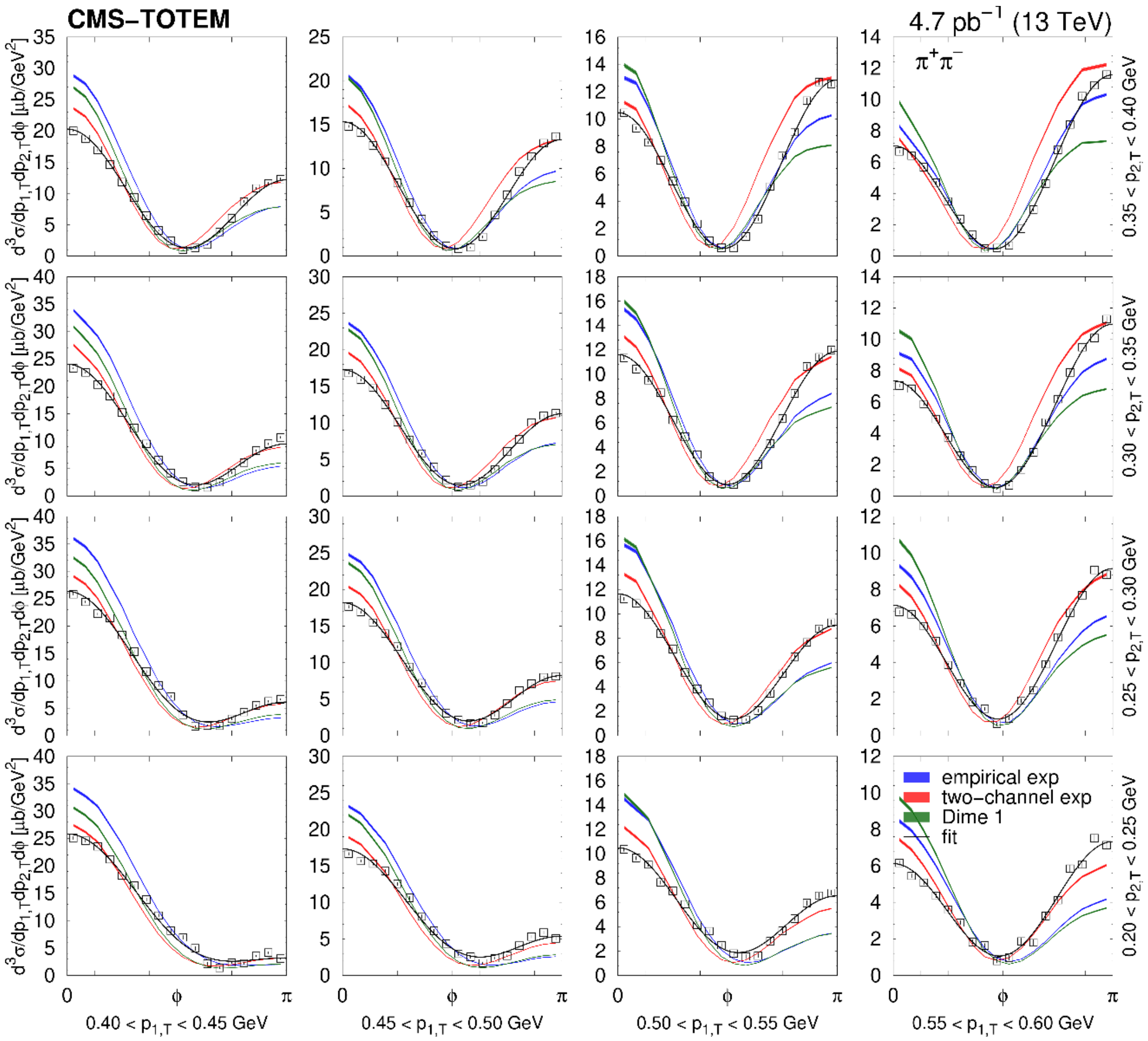
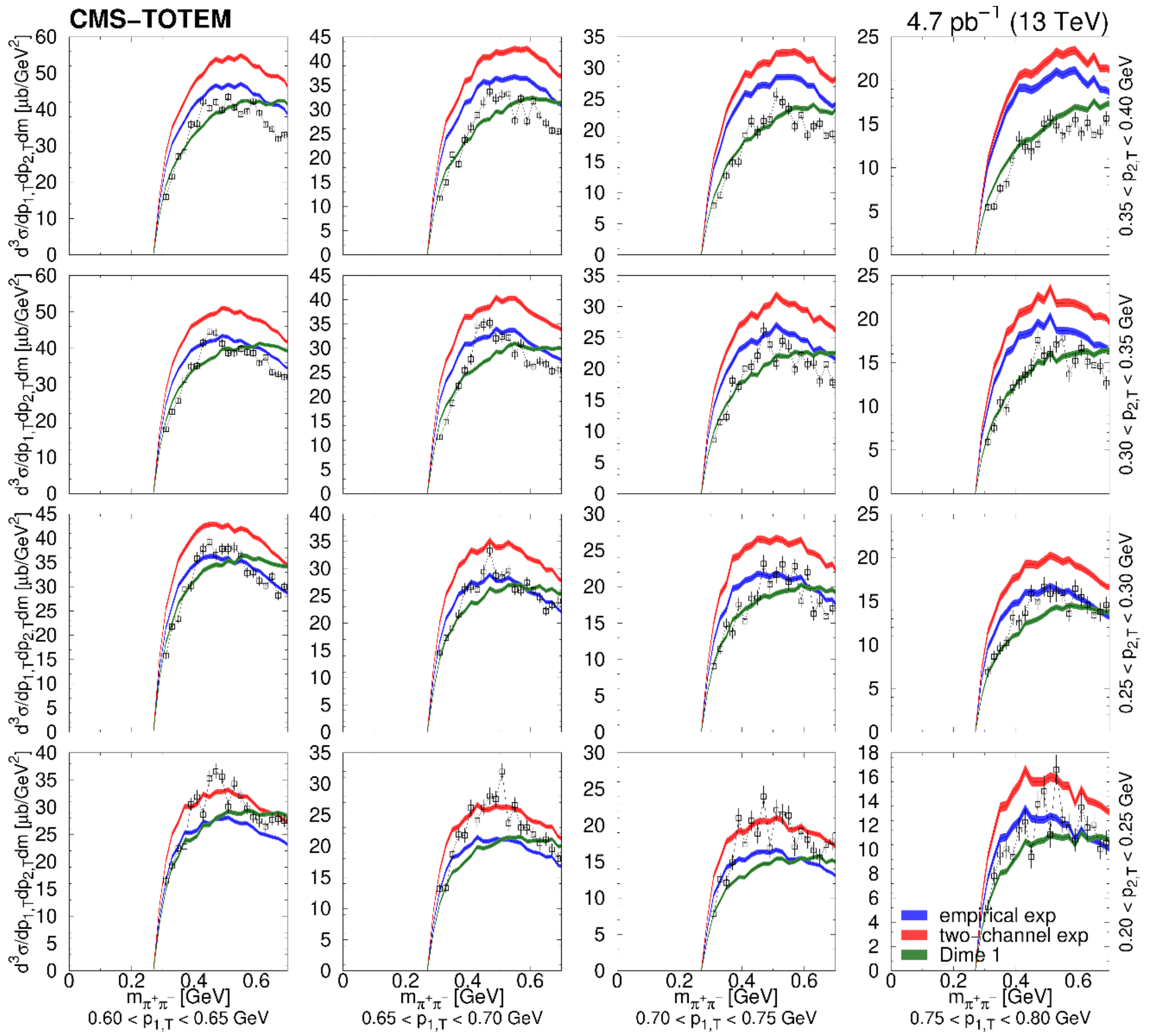
- Two – channel fit for different pomeron – meson form factors



Results

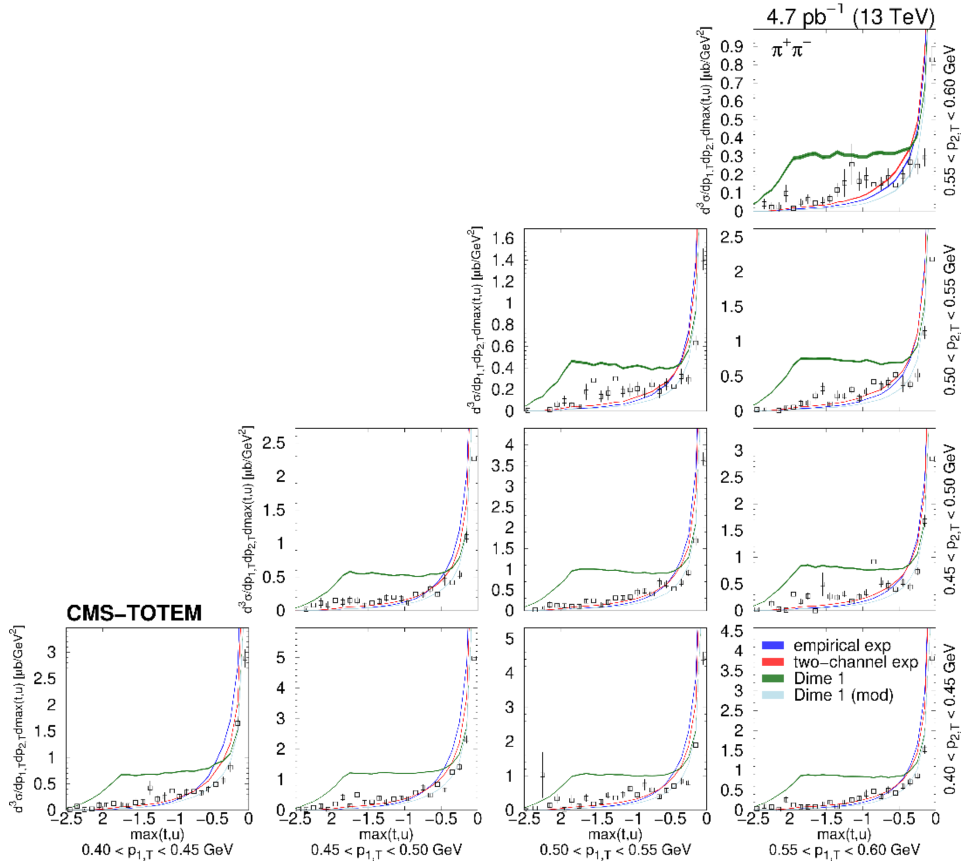
- Fitted distributions shows a good quality – a ground state protons is enough?

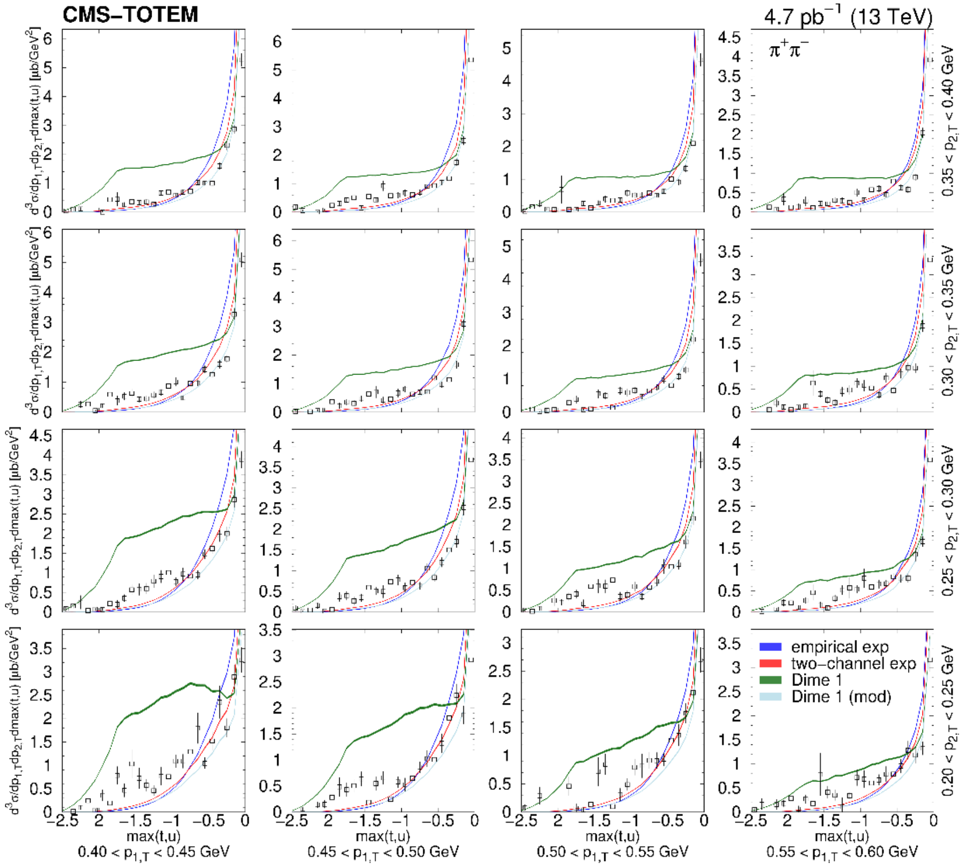




Results

- Fitted distributions shows a good quality – a ground state protons is enough?
- Virtual hadrons – important to fix the value of b_{exp} from 0.45 to 0.9 GeV^{-2}





Summary and discussion

Analysis

- ✓ Central exclusive production of charged pions at 13 TeV in resonance-free region
- ✓ Differential cross-sections in bins of $[p_{1T},p_{2T}]$
- ✓ Azimuthal angle φ between the surviving protons

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- ✓ First observation of parabolic minimum in φ distribution
  - Interference of the bare and the rescattered amplitudes
- ✓ First model tunning of pomeron related quantities
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Thank you for your attention

Backup

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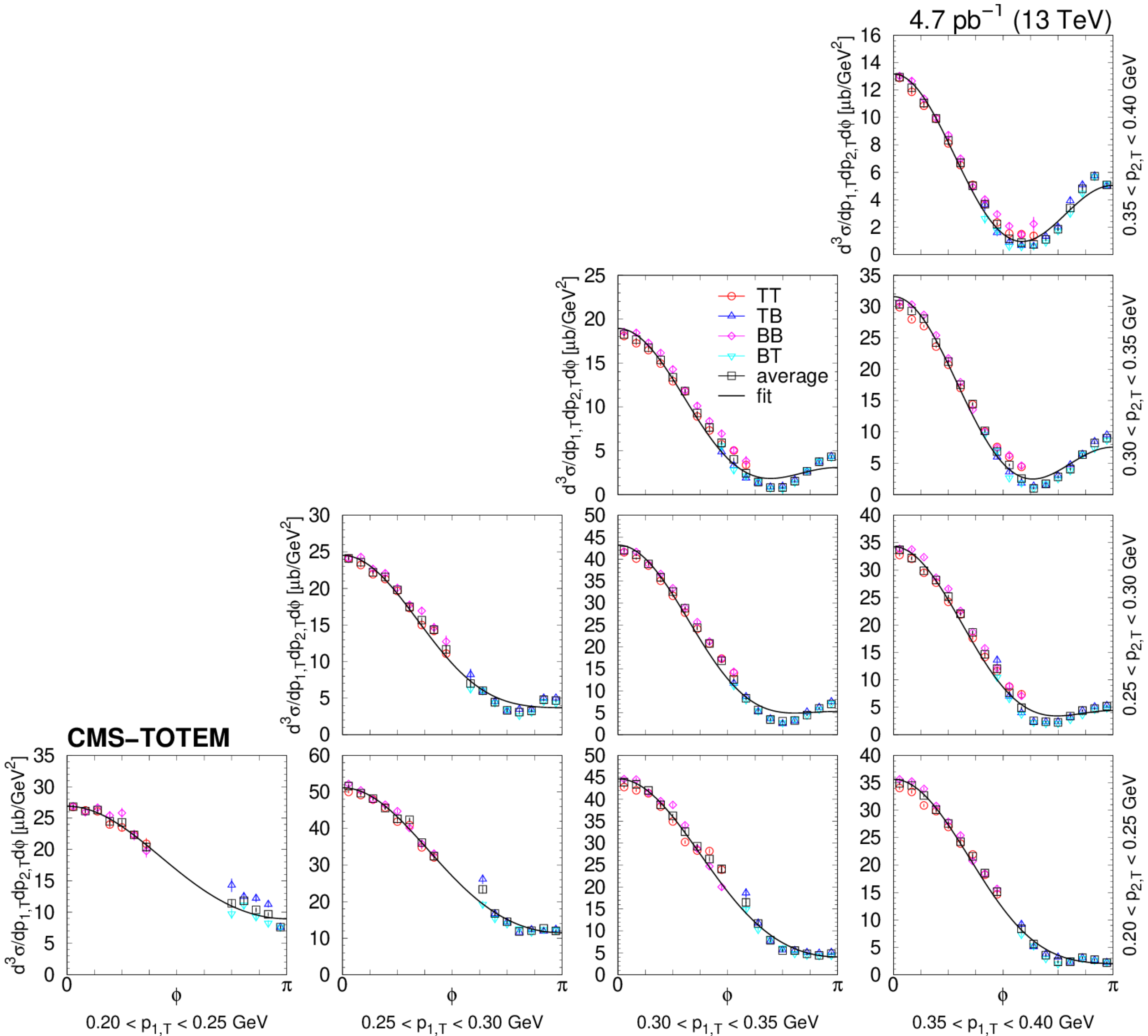

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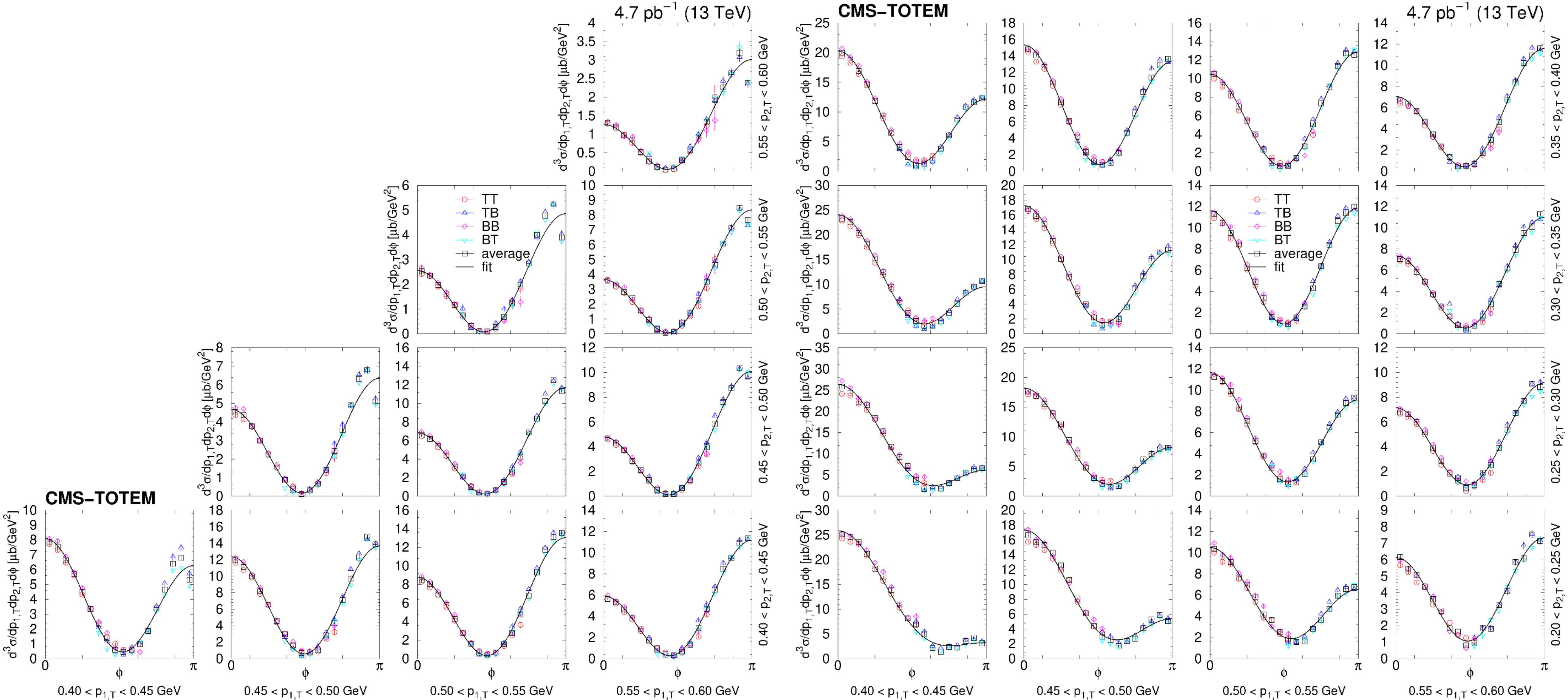

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