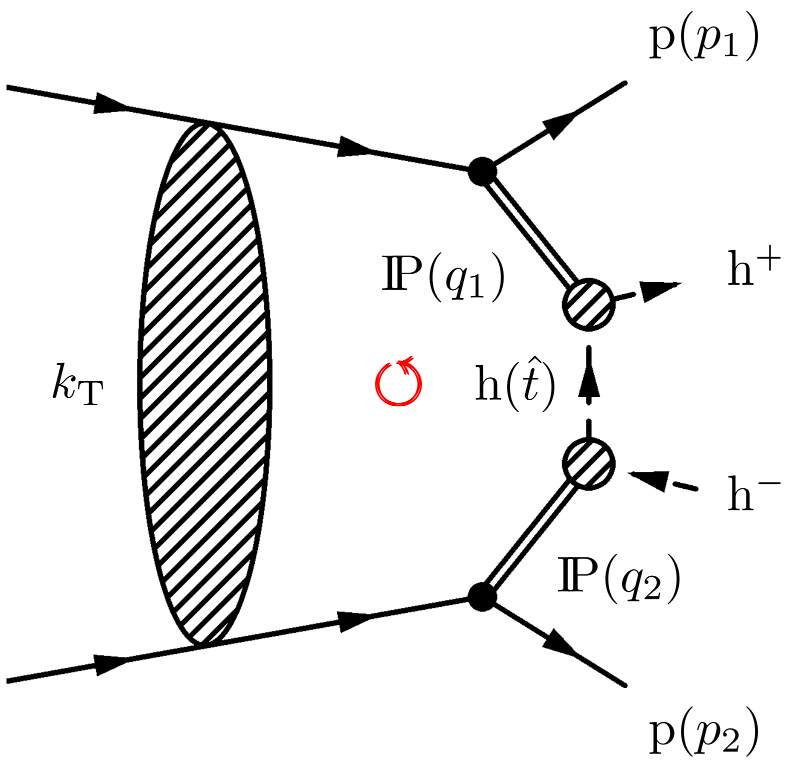
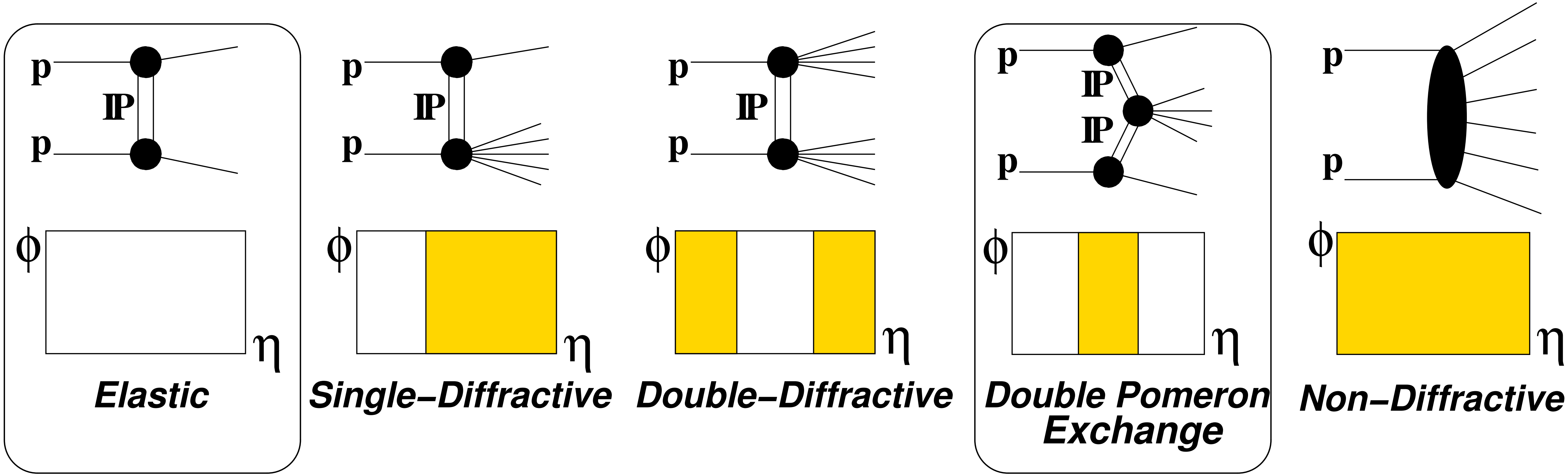


Nonresonant central exclusive production from CMS+TOTEM

Ferenc Siklér
Wigner Research Centre for Physics, Budapest
for the CMS and TOTEM Collaborations

Zimányi School 2023
Budapest, December 4, 2023

Proton-proton collisions

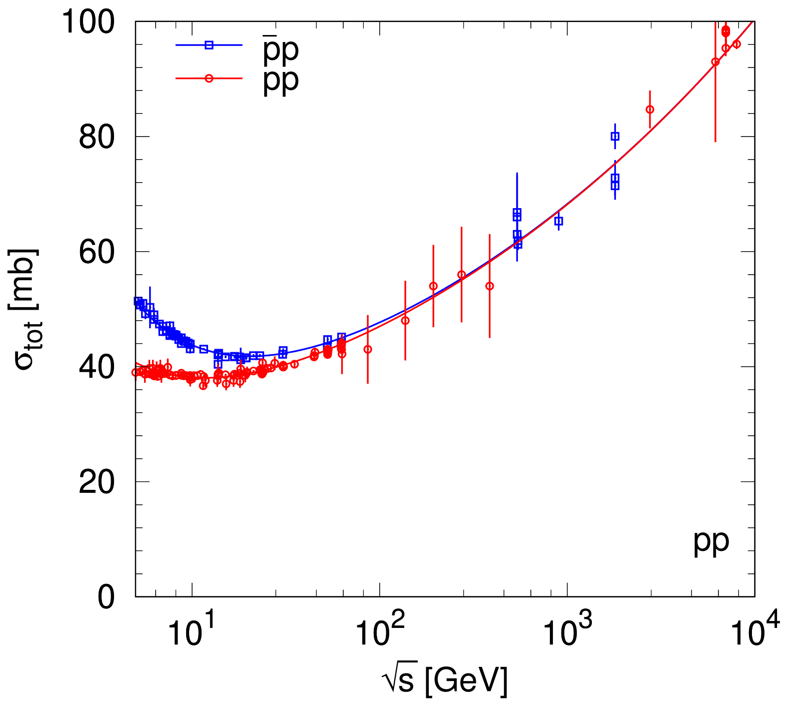


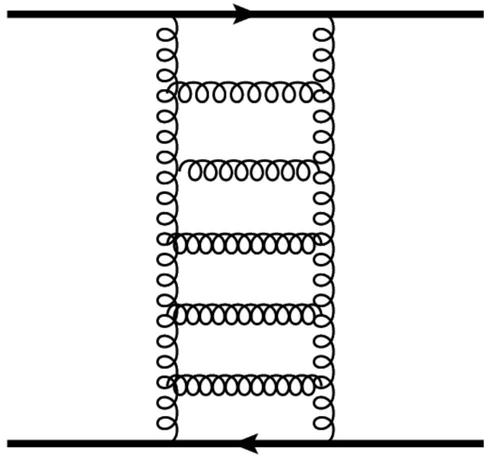
- Types
  - elastic: no additional particles
  - diffractive: one or both protons are excited and dissociate
  - what is the exchanged particle? actually, is it a particle?

New result: detailed study of double pomeron exchange (nonresonant processes)

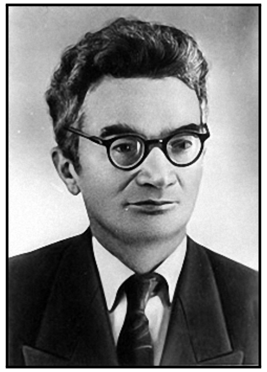
Physics Analysis Summary at: https://cds.cern.ch/record/2867988

Pomeron ($\mathbb{P}$)

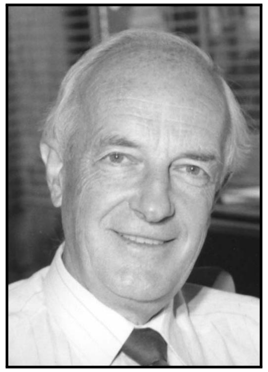




- Problems
  - the pp and $\bar{p}p$ cross sections are similar
  - they keep rising; exchange?
  - force carrier must have zero charges
  - gluon ladder? nonperturbative


Isaak Pomeranchuk


Vladimir Gribov


Sandy Donnachie

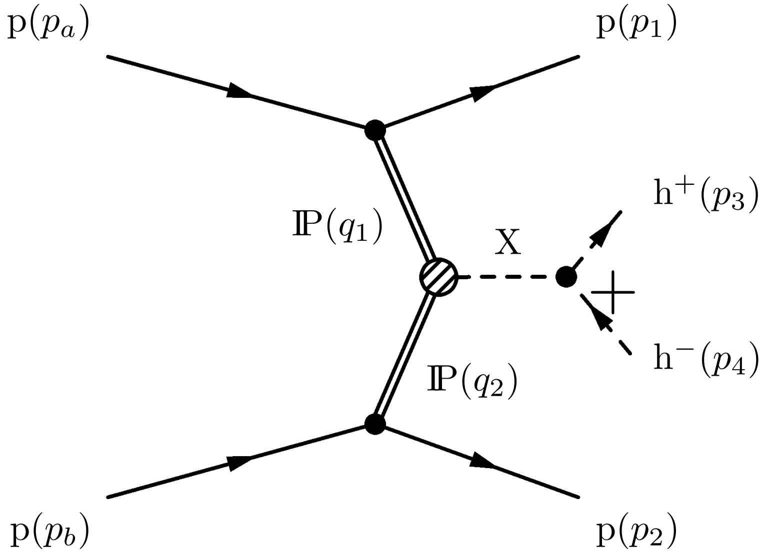

Peter Landshoff

$$\sigma_{\text{tot}}(s) = C_{\mathbb{P}}(s/s_0)^{\alpha_{\mathbb{P}}(0)-1} + (C_f \pm C_\rho)(s/s_0)^{\alpha_{\mathbb{R}}(0)-1}$$

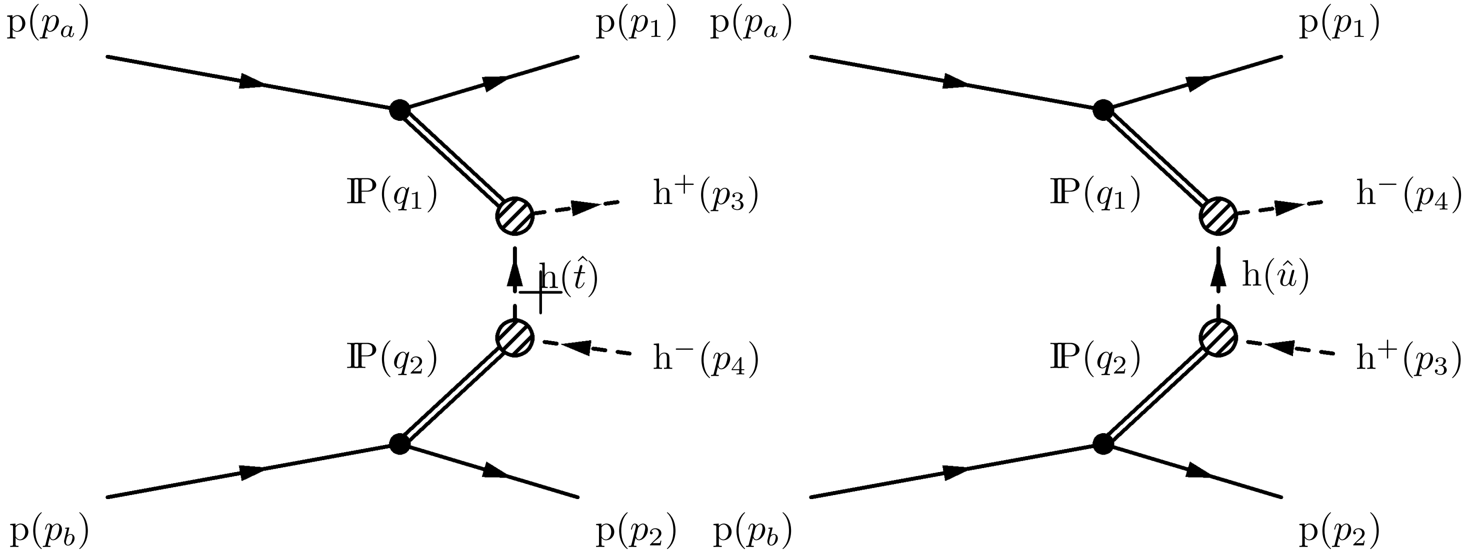
  - pomeron trajectory with intercept $\alpha_{\mathbb{P}}(0)$

Theory – resonances vs background

resonant



nonresonant continuum



- Nonresonant continuum

The matrix element for the nonresonant continuum process is

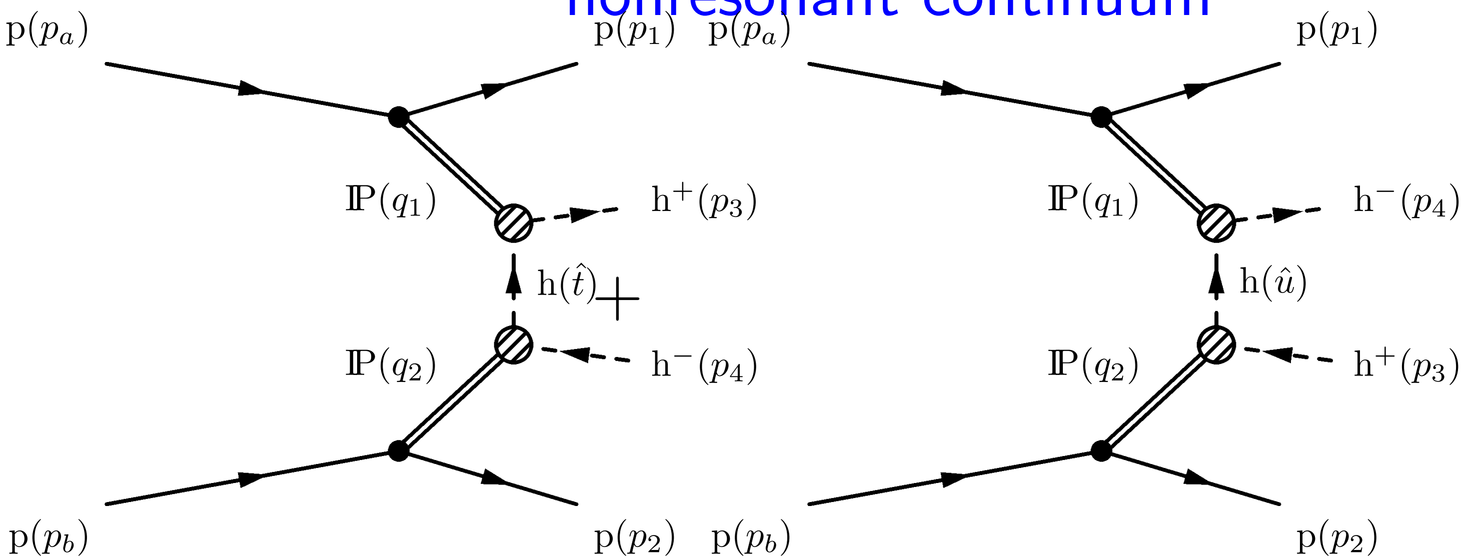
$$\mathcal{M} = M_{13}(t_1, s_{13})\frac{F_m^2(\hat{t})}{\hat{t}-m^2}M_{24}(t_2, s_{24}) + M_{14}(t_1, s_{14})\frac{F_m^2(\hat{u})}{\hat{u}-m^2}M_{23}(t_2, s_{23})$$

where M_{ik} denotes the "interaction" between a scattered proton and a created hadron, $s_{ik} = (p_i + p_k)^2$, $\hat{t} = (p_3 - q_1)^2 = (p_4 - q_2)^2$ and $\hat{u} = (p_4 - q_1)^2 = (p_3 - q_2)^2$.

The pomeron-meson form factor $F_m(\hat{t})$ and the usual **propagator** $1/(\hat{t} - m^2)$

Theory – double pomeron exchange

nonresonant continuum



- Nonresonant continuum

  At high hadron-proton energies ($> 20\,\mathrm{GeV}$) the **pomeron exchange dominates**

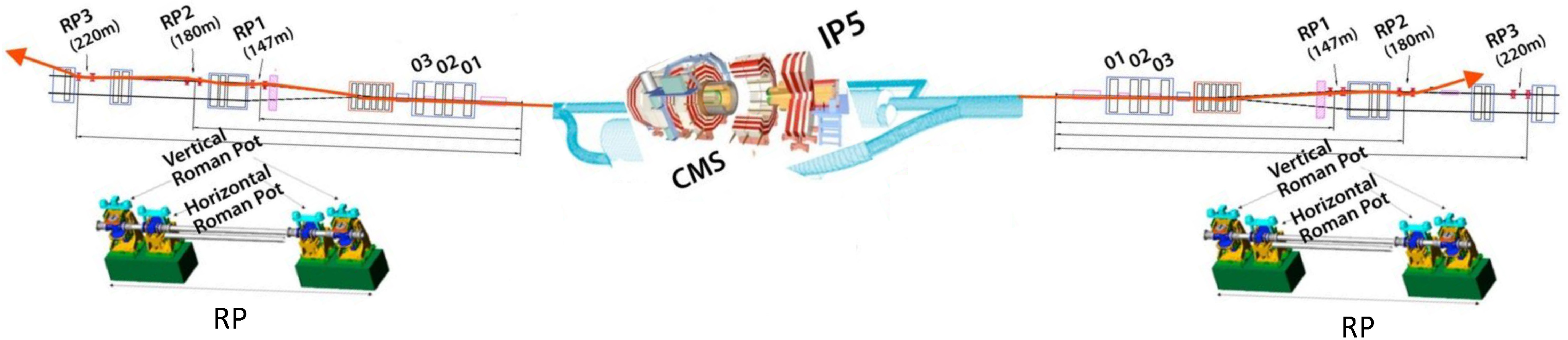
  $$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} \exp\left(\frac{B_{\mathbb{P}}}{2} t_i\right)$$

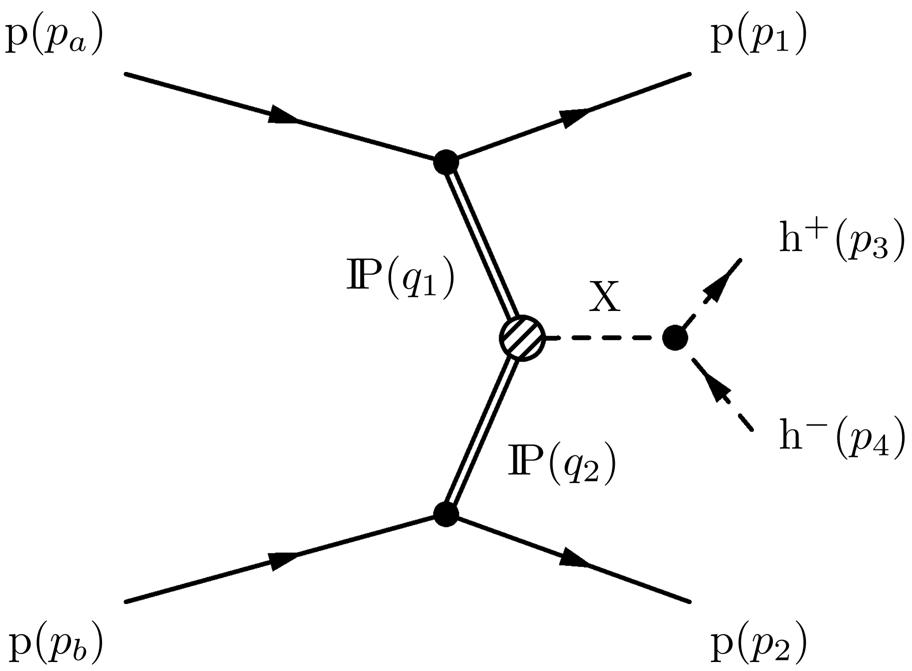
  Taking into account the reggeon exchange as well

  $$\ldots + \left[(a_f + i) s_{ik} C_f \pm (a_\rho - i) s_{ik} C_\rho\right] \cdot \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{R}}(t_i)-1} \exp\left(\frac{B_{\mathbb{R}}}{2} t_i\right)$$

The weight of an event (or the cross section) is proportional to $|\mathcal{M}|^2/s^2$

Central exclusive production – data

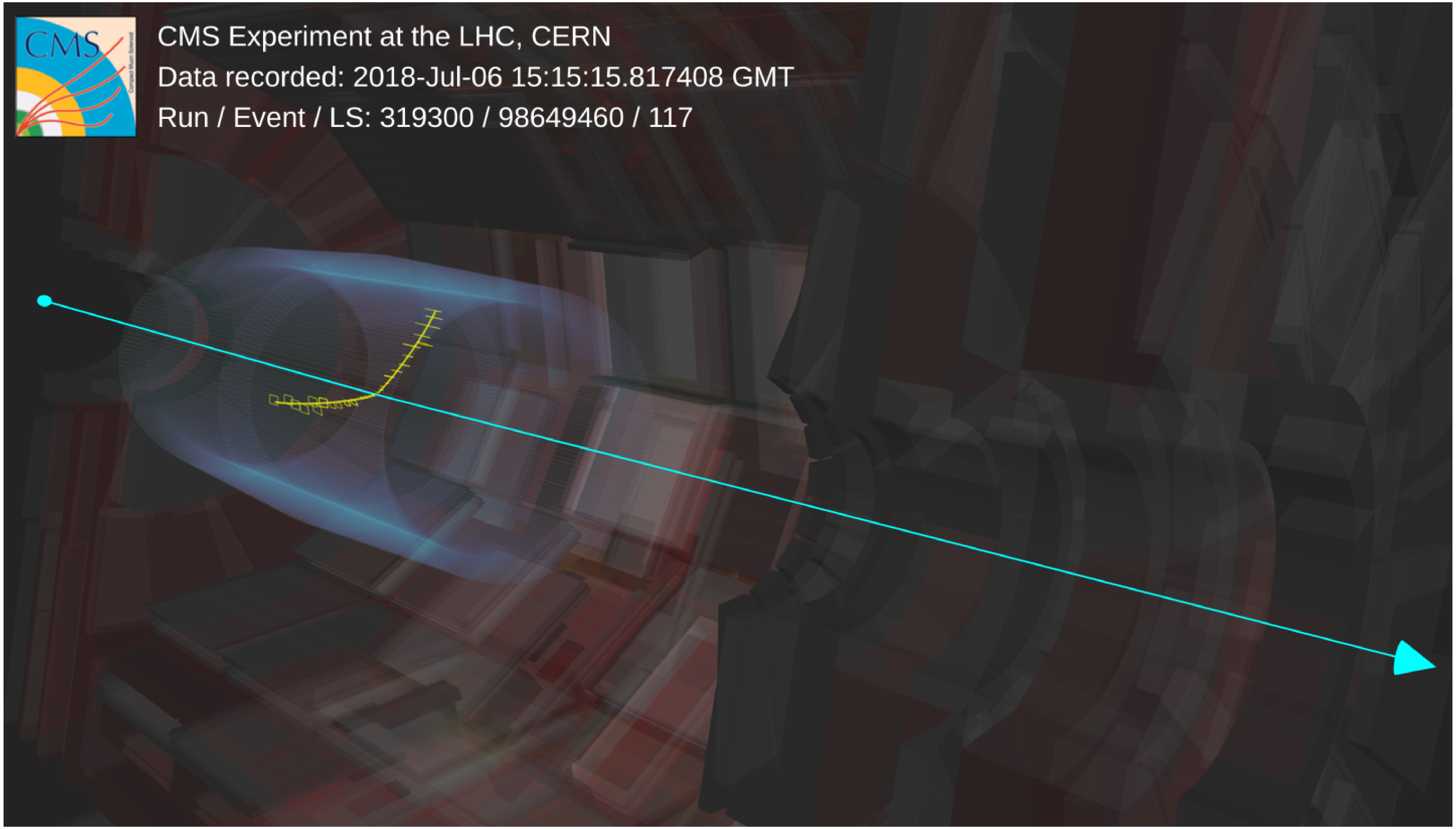




- CMS+TOTEM dataset ($\beta^* = 90\,\mathrm{m}$, 2018)
  - about 80 M events with **two scattered protons** and only **two reconstructed central tracks**
  - part of those is double pomeron exchange (DPE), where a central system (X) was created
  - decayed to particle-antiparticle pair $\mathrm{h}^+\mathrm{h}^-$, mostly $\pi^+\pi^-$or $\mathrm{K}^+\mathrm{K}^-$, but some $\mathrm{p}\overline{\mathrm{p}}$
  - invariants: $p_{1,\mathsf{T}}, p_{2,\mathsf{T}}, \phi$; $m_{\mathrm{h}^+\mathrm{h}^-}$

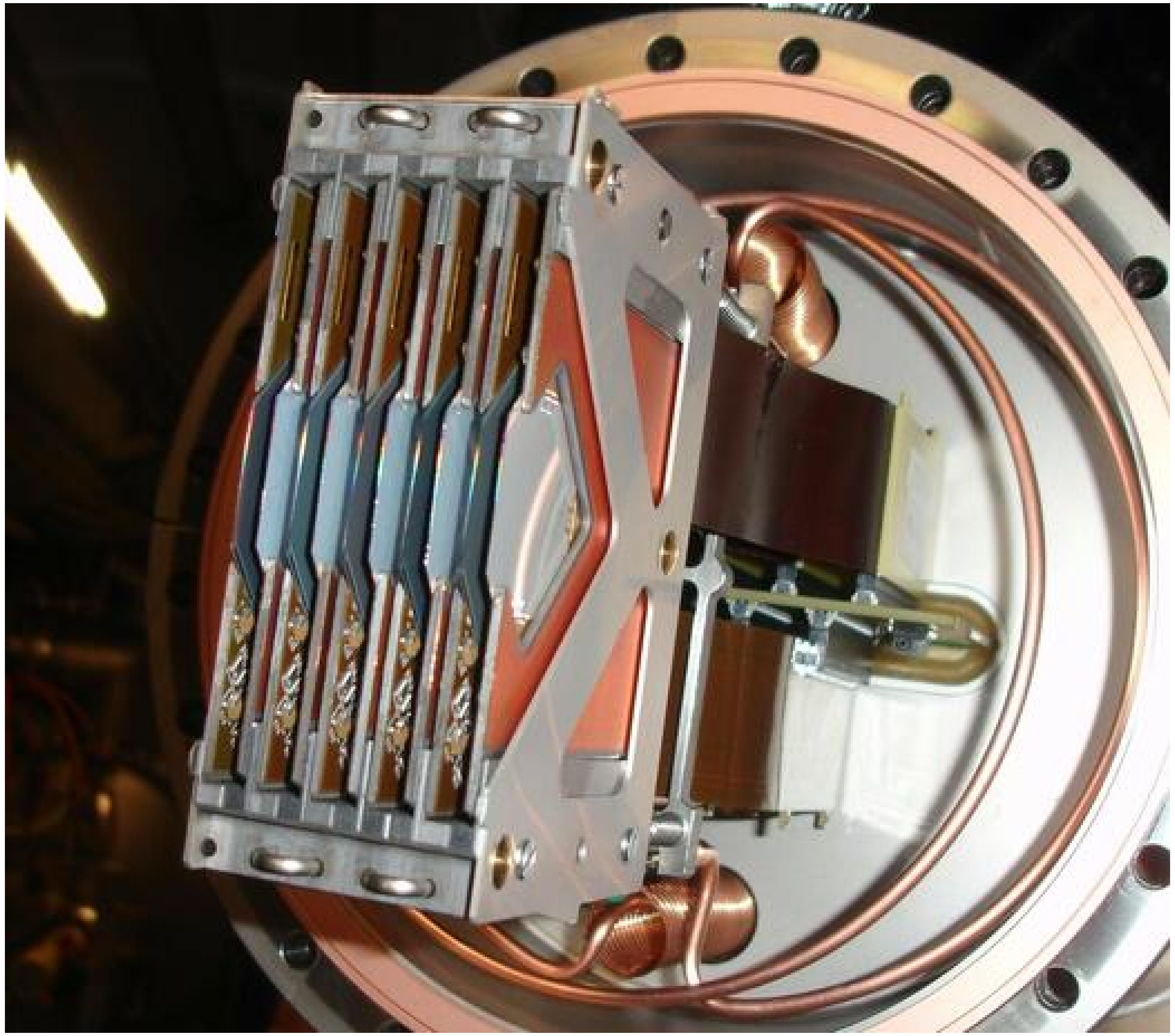
$\mathbb{P}\mathbb{P}$ collider → gluon-rich initial state

Event display



CMS-PHO-EVENTS-2023-026-2

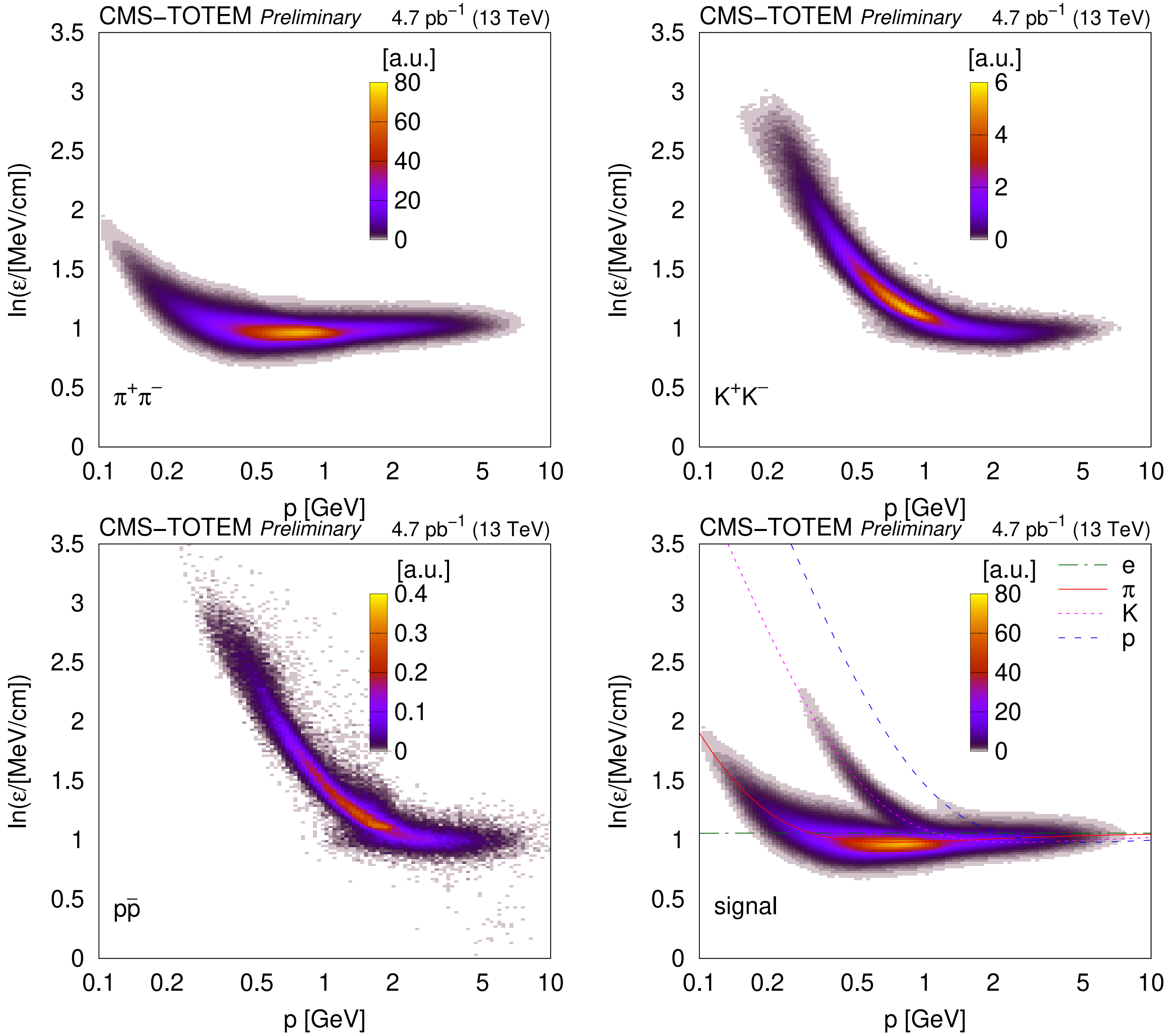
Scattered protons – roman pots



- Details
  - two arms (in sectors 45 and 56)
  - near and far stations (at ≈213 and 220 m)
  - top and bottom pots
  - within a pot:
    5 planes in ‘u’ and
    5 planes in ‘v’ directions
  - each plane has: 4 × 128 strips
- Two pots per arm
  → two measurements
  → location and momentum at IP

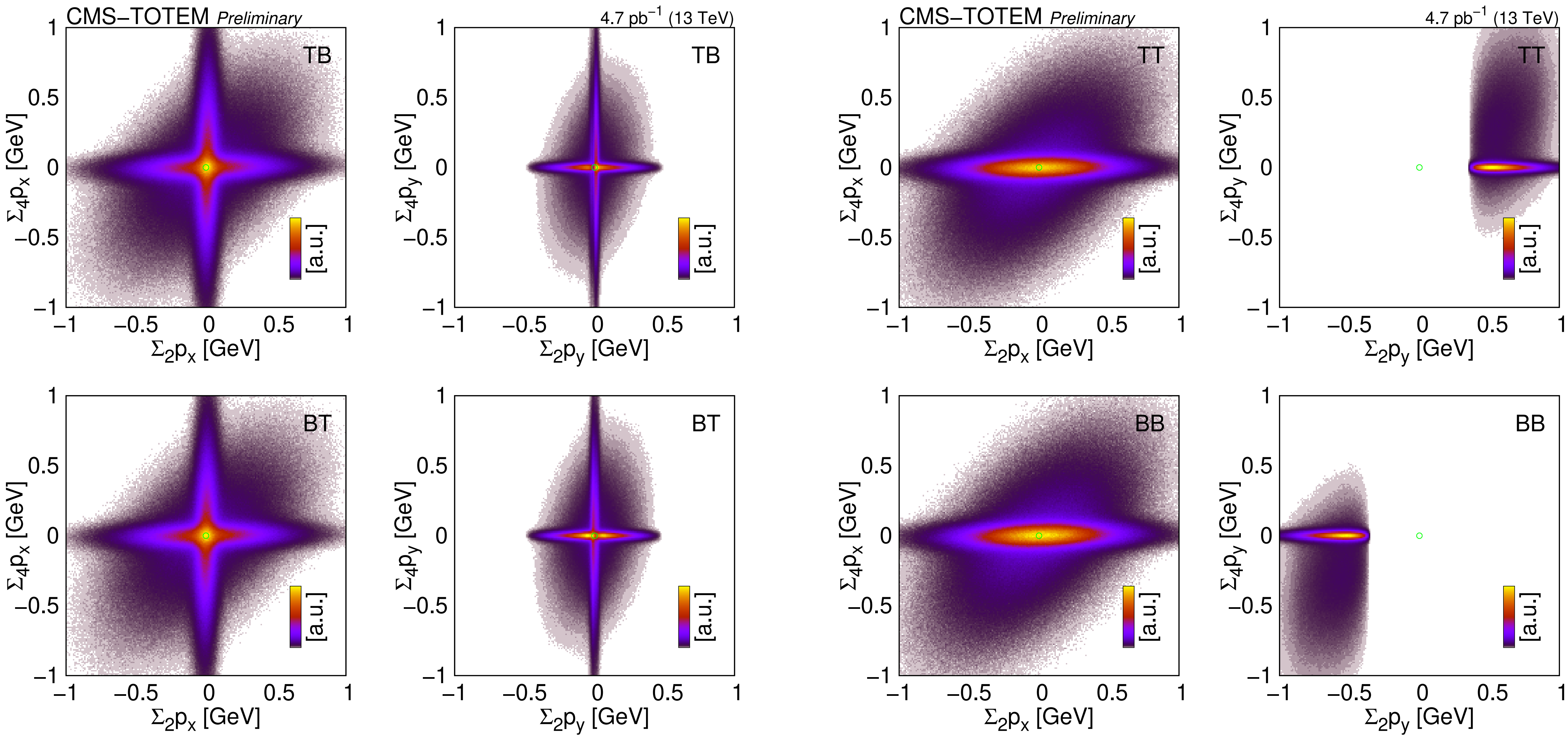
Novel tracklet fits, relative alignment of planes, strip-level efficiencies

Central hadrons – particle identification through dE/dx



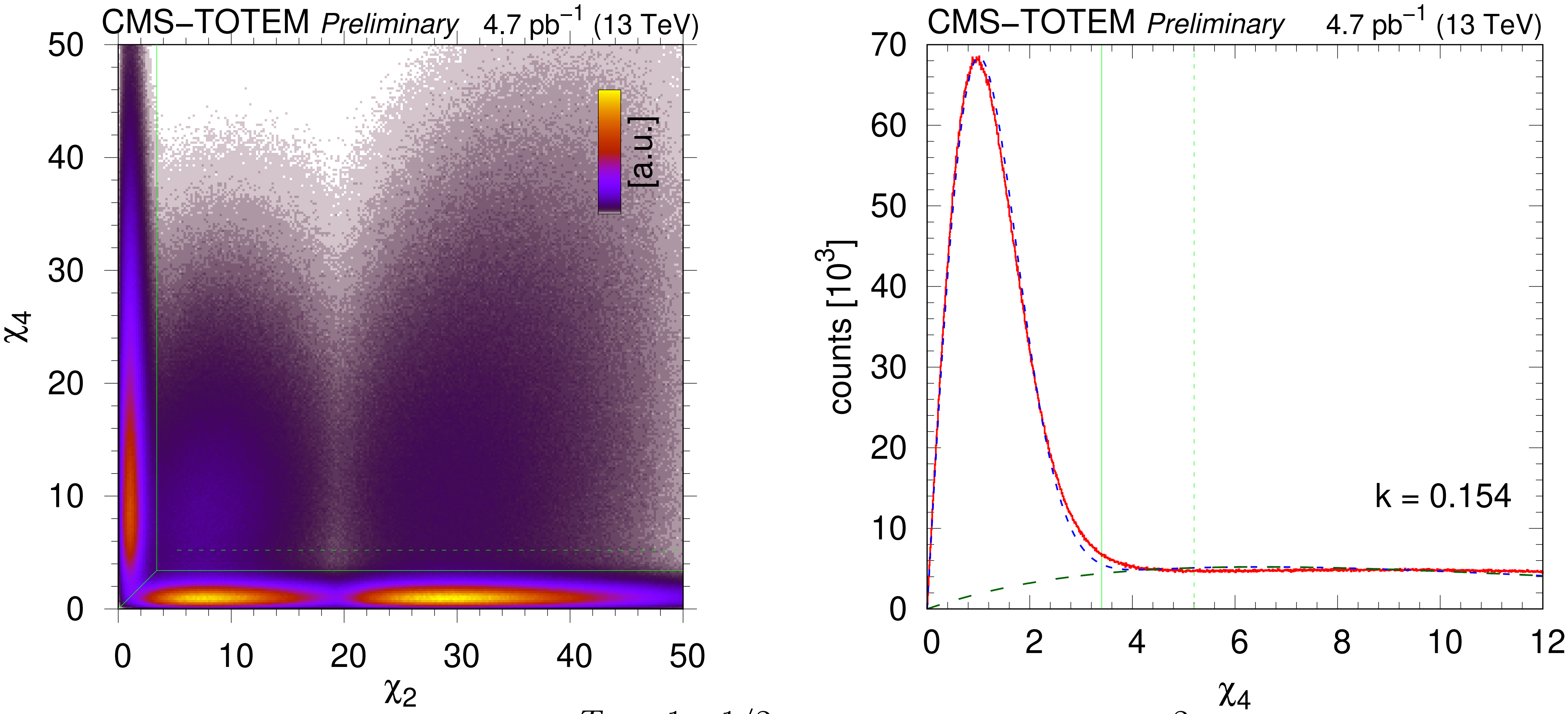
- Particle pair
  - identified as type $\mathrm{h}^+\mathrm{h}^-$ if $P_{1,\mathrm{h}} P_{2,\mathrm{h}} > 10 \cdot P_{1,i} P_{2,i}$ for all $i \neq h$
- Proof of exclusivity
  - $\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$, and $\mathrm{p}\bar{\mathrm{p}}$ pairs
  - conservation laws at work: charge, strangeness, baryon number

Event classification – true exclusive or pileup?



Based on $(\sum_4 p_x$ vs $\sum_2 p_x$, $\sum_4 p_y$ vs $\sum_2 p_y)$

Event classification – χ_4 – signal and sideband

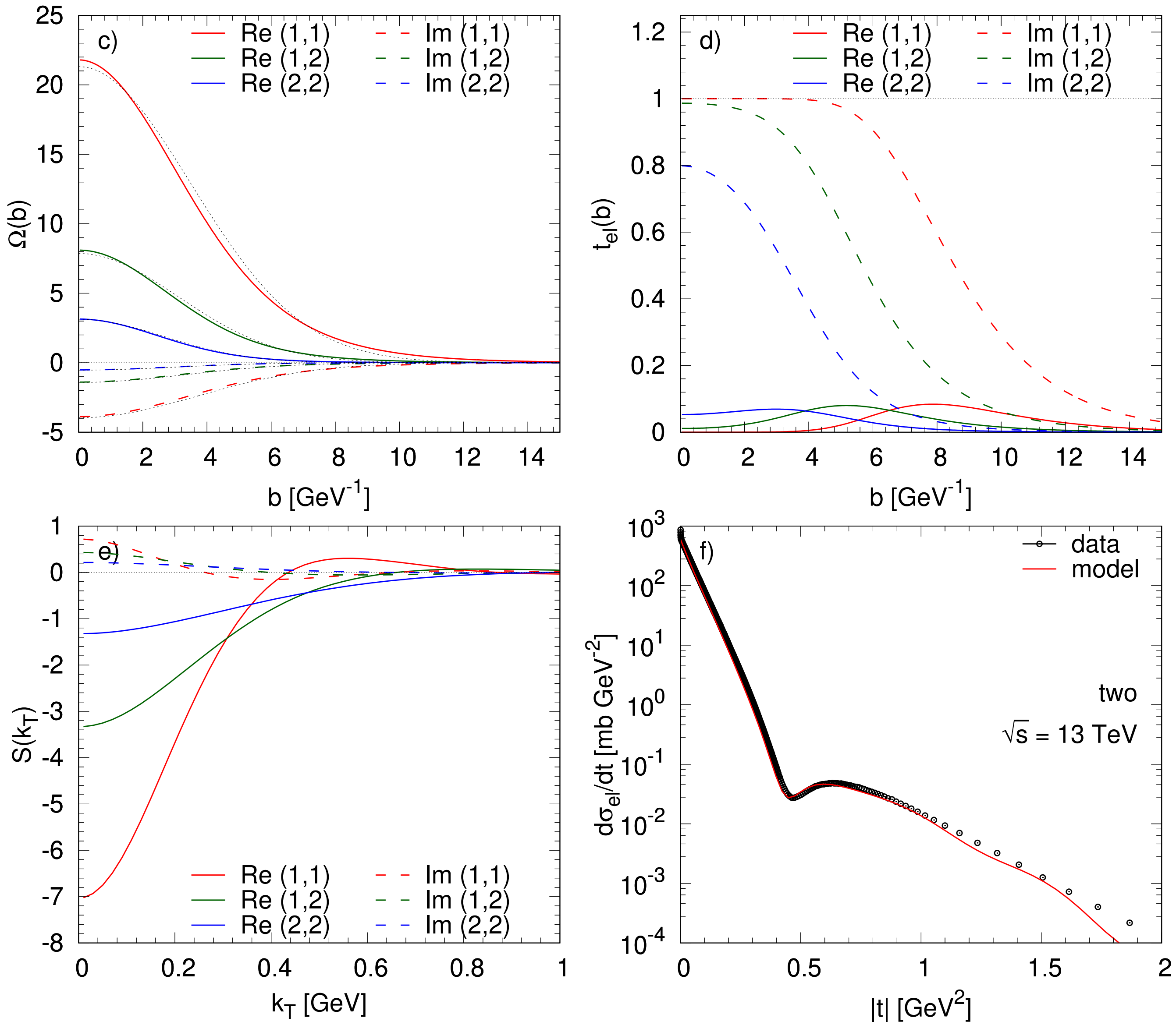


Mahalanobis distance $\chi(\mathbf{s}) = (\mathbf{s}^T V^{-1} \mathbf{s})^{1/2}$

$$A\chi \exp(-\chi^2/2) + B\chi \exp(-k\chi)$$

Components: signal (χ-distribution with fixed parameters) and background

Theory – elastic screening – two-channel



Khoze, Martin, Ryskin, EPJC **73** (2013) 2503
TOTEM Coll., EPJC **79** (2019) 785 and 861

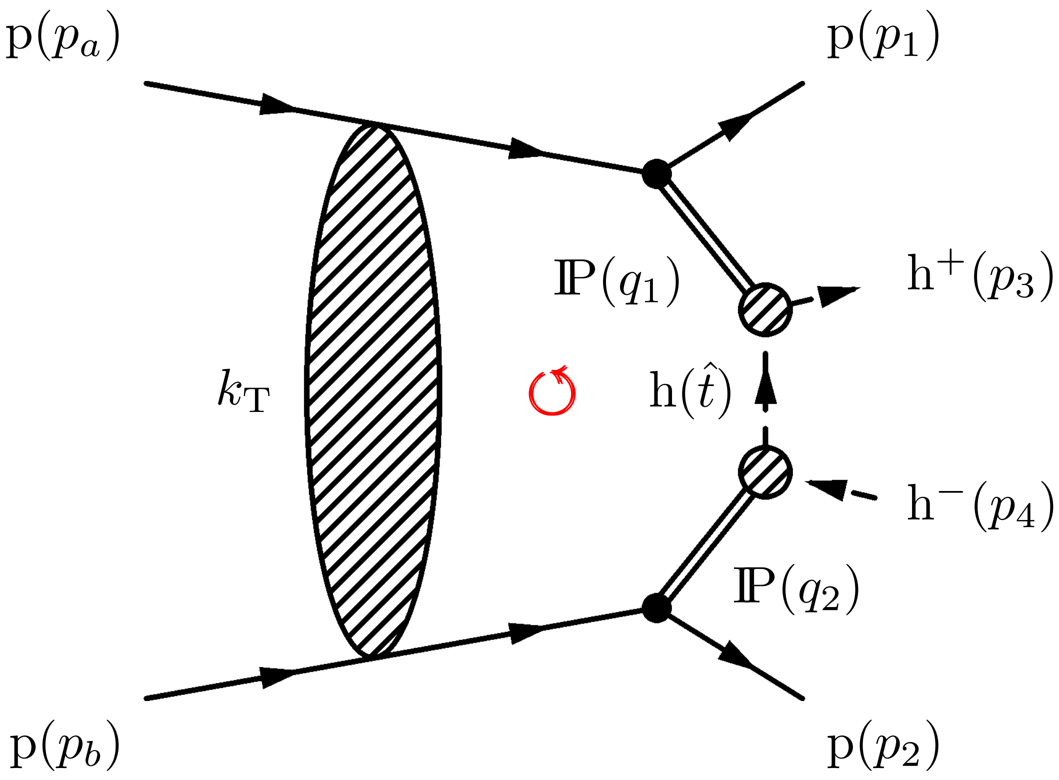
- linear combination of **diffractive eigenstates** $|p\rangle = \sum_i a_i |\phi_i\rangle$

- eigenstate-$\mathbb{P}$ couplings γ_i

- amplitude between i and j $\Omega_{ij}(k_\mathrm{T}) = \eta\,\sigma_0\,\gamma_i F_i(t)\,\gamma_j F_j(t)\,(s/s_0)^{\alpha_\mathbb{P}(t)-1}$

- elastic amplitude through $t_{\mathrm{el},ij}(b) = i\left(1 - e^{-\Omega_{ij}(b)/2}\right)$
  $T_\mathrm{el}(k_\mathrm{T}) = \sum_{i,j} |a_i|^2 |a_j|^2 \cdot$
  $\cdot\, 2\pi \int t_{\mathrm{el},ij}(b)\, J_0(k_\mathrm{T} b)\, b\, \mathrm{d}b$

Theory – nonresonant continuum – interference!



- Full treatment
  - incoming (outgoing) protons may scatter as well, additional complication
  - **screening effects** S, related to "rapidity gap survival"
  - several options for S
    - ∗ from measured $\mathrm{d}\sigma_\mathsf{el}/\mathrm{d}t$, **empirical** parametrisation (Fagundes et al)
    - ∗ from a theoretical calculation, **one- or two-channel** (eigenstates) (Khoze, Martin, Ryskin)
    - ∗ (Lebiedowicz, Nachtmann, Szczurek)

- Calculate

  Sum of bare ($\mathcal{M}_0$) and screened amplitudes at $(\mathbf{p_1}, \mathbf{p_2})$ of the scattered protons
  $\mathcal{M}(\mathbf{p_1}, \mathbf{p_2}) = \mathcal{M}_0(\mathbf{p_1}, \mathbf{p_2}) + \int \mathrm{d}^2\mathbf{k}_\mathrm{T} T_\mathsf{el}(k_\mathrm{T}) \mathcal{M}_0(\mathbf{p_1} - \mathbf{k}_\mathrm{T}, \mathbf{p_2} + \mathbf{k}_\mathrm{T})$
  Involves a loop integral over the momentum k_T exchanged

Models – Dime, working points

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	pomeron coupling to eigenstates
b_2 [GeV^{-2}]	4.5	6	3.8	4.2	
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	

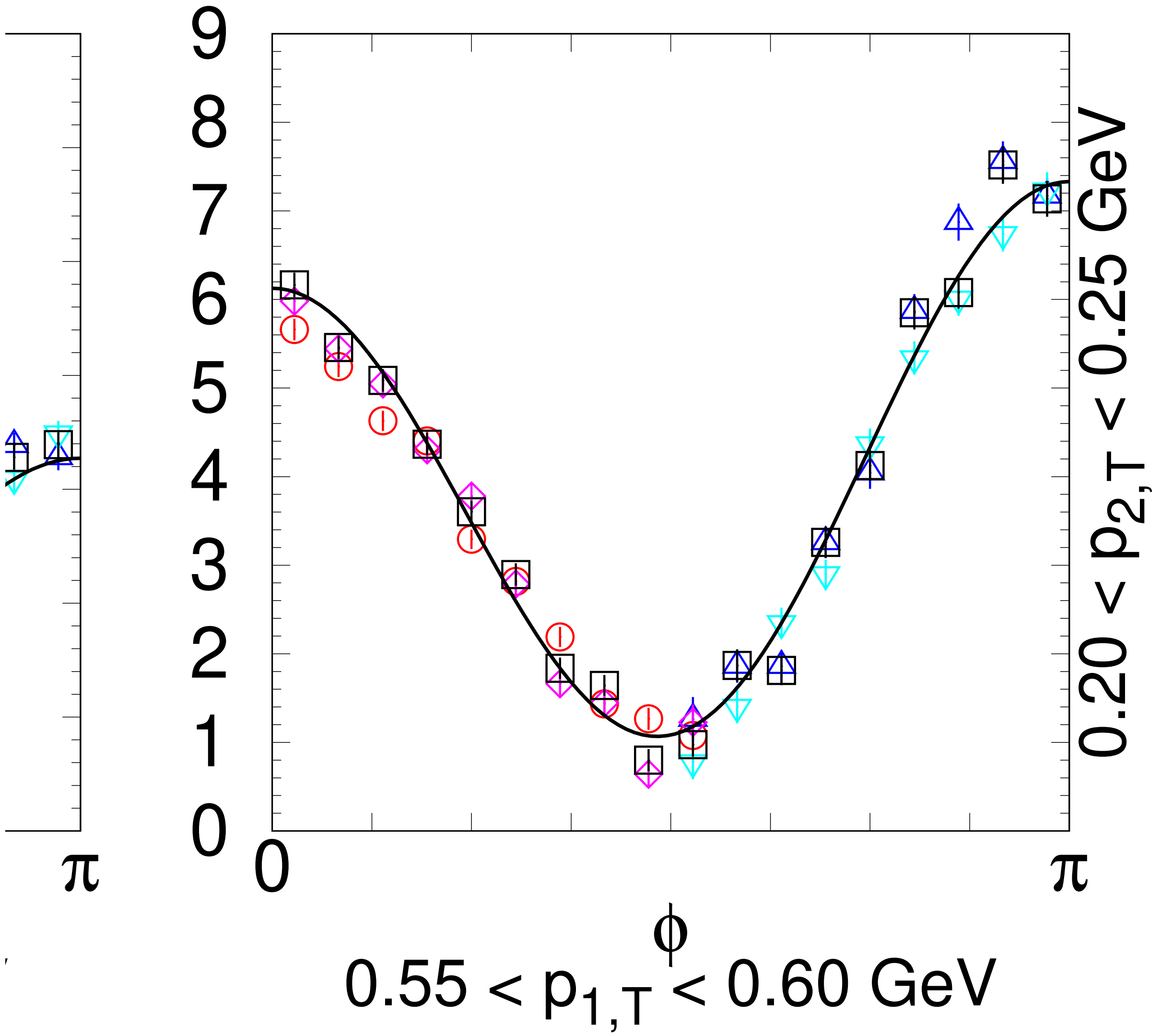
Harland-Lang, Khoze, Ryskin, EPJC **74** (2014) 2848

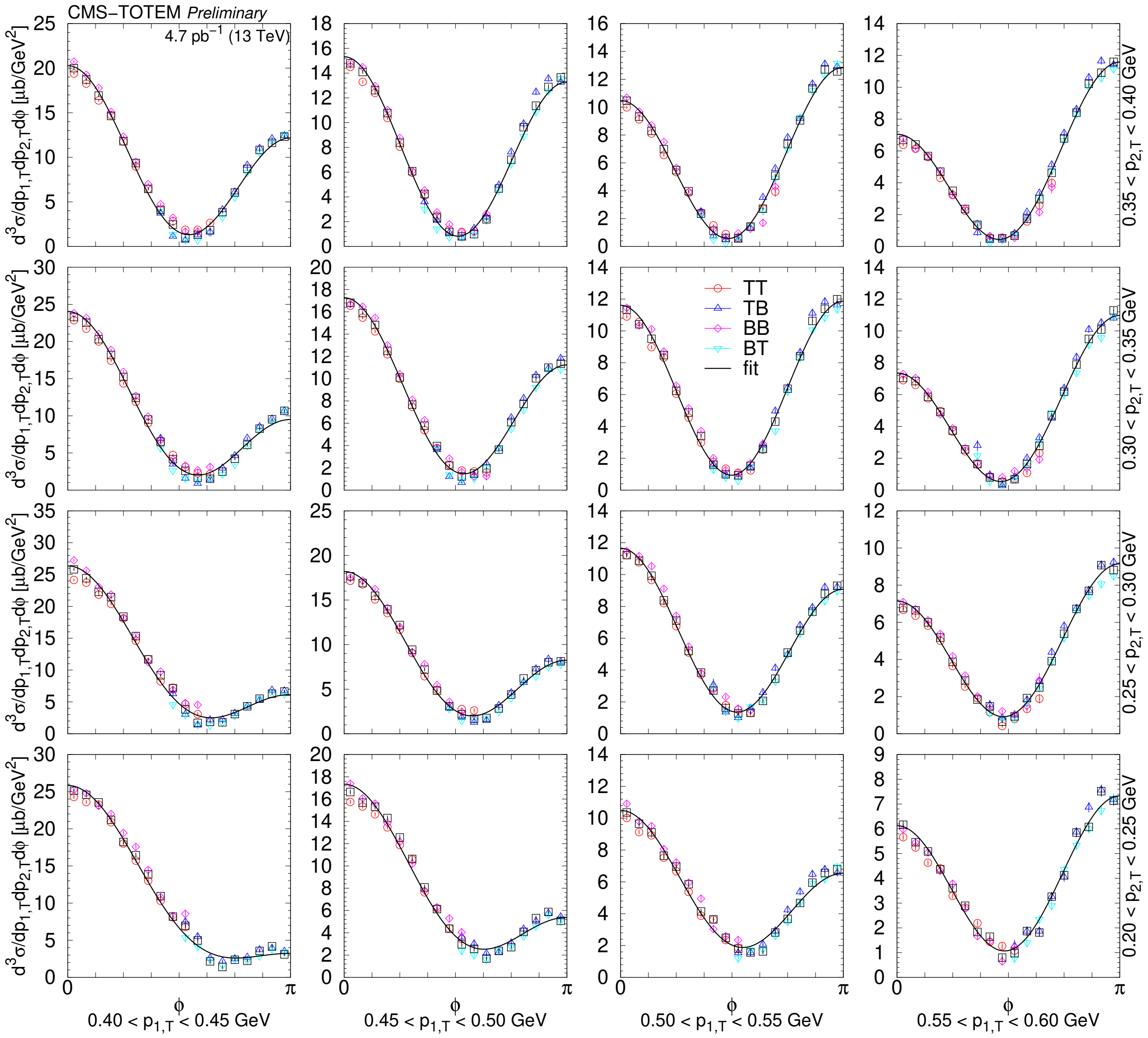
- Proton-pomeron(eigenstate) coupling
  - One-channel model: $F_p(t) = \exp(B_{\mathbb{P}}/2 \cdot t)$
  - Two-channel model:
    $F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$
- Pomeron-meson coupling

$$F_m(\hat{t}) = \begin{cases} \exp(b_{\text{exp}}(\hat{t} - m^2)), \\ \exp(b_{\text{ore}}[a_{\text{ore}} - \sqrt{a_{\text{ore}}^2 - (\hat{t} - m^2)}]), \\ 1/(1 - b_{\text{pow}}(\hat{t} - m^2)) \end{cases}$$

Now using a new generator with proper physics content, from scratch

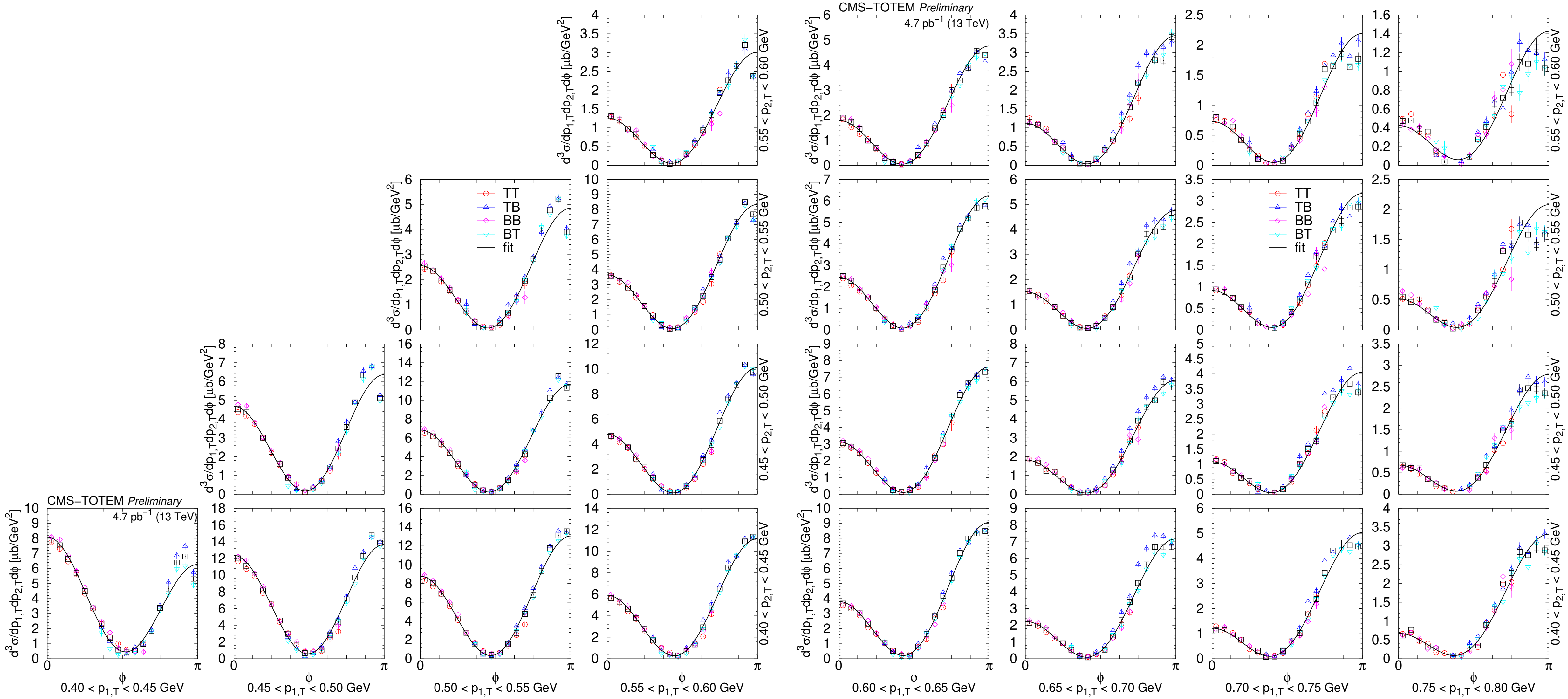
Measurements – nonresonant $\mathrm{d}^3\sigma/\mathrm{d}p_{1,T}\mathrm{d}p_{2,T}\mathrm{d}\phi$





As a function of ϕ in $(p_{1,T}, p_{2,T})$ bins, in units of [μb/ GeV^2], if $0.35 < m_{\pi\pi} < 0.65\,\mathrm{GeV}$

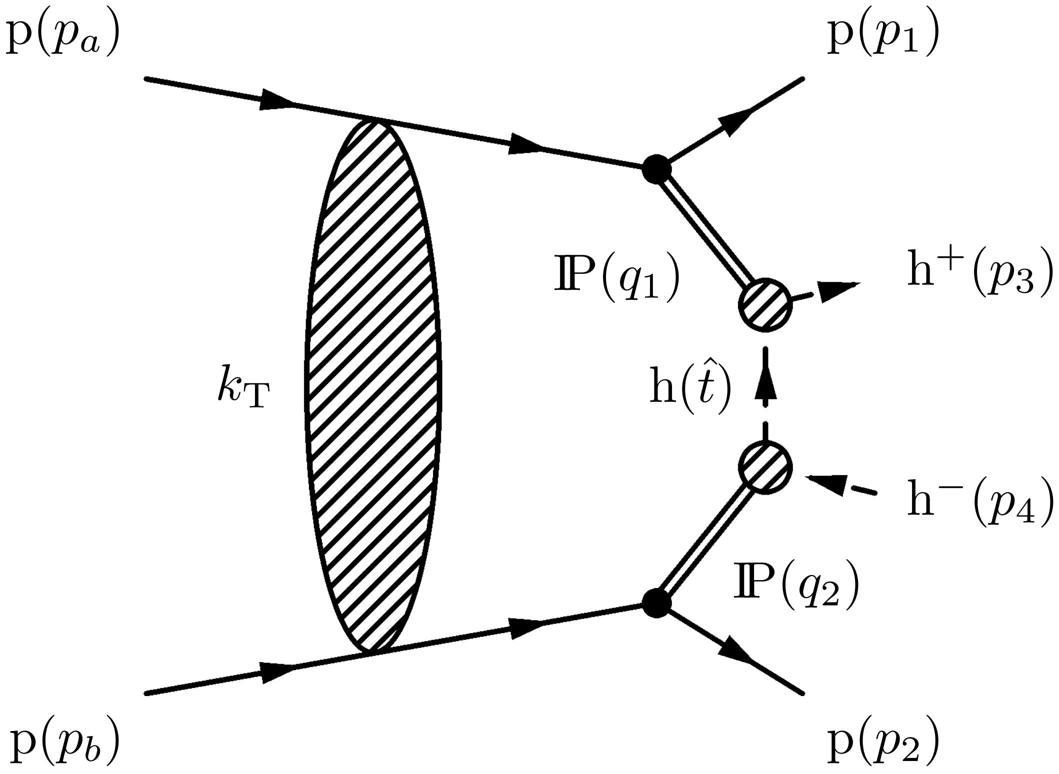
Measurements – nonresonant $\mathrm{d}^3\sigma/\mathrm{d}p_{1,T}\mathrm{d}p_{2,T}\mathrm{d}\phi$



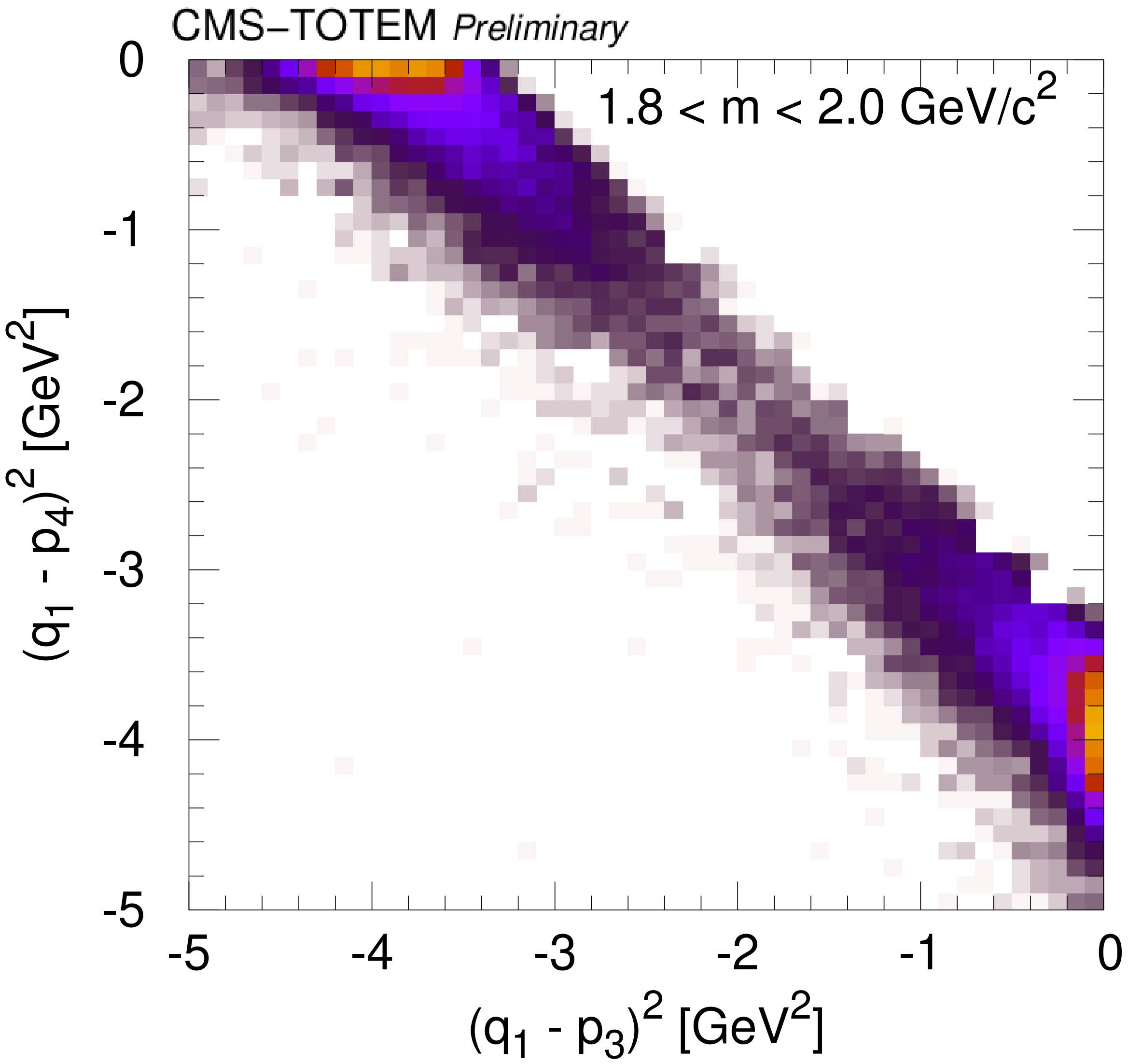
Curves of a phenomenology-motivated fits with the form $[A(R - \cos\phi)]^2 + c^2$ are plotted

(Close, Kirk, Schuler)

Virtual hadron – proof



Propagator of virtual hadron:
$1/(\hat{t} - m^2)$



The squared four-momentum differences between $\mathbb{P}$ and the hadrons $h^\pm$

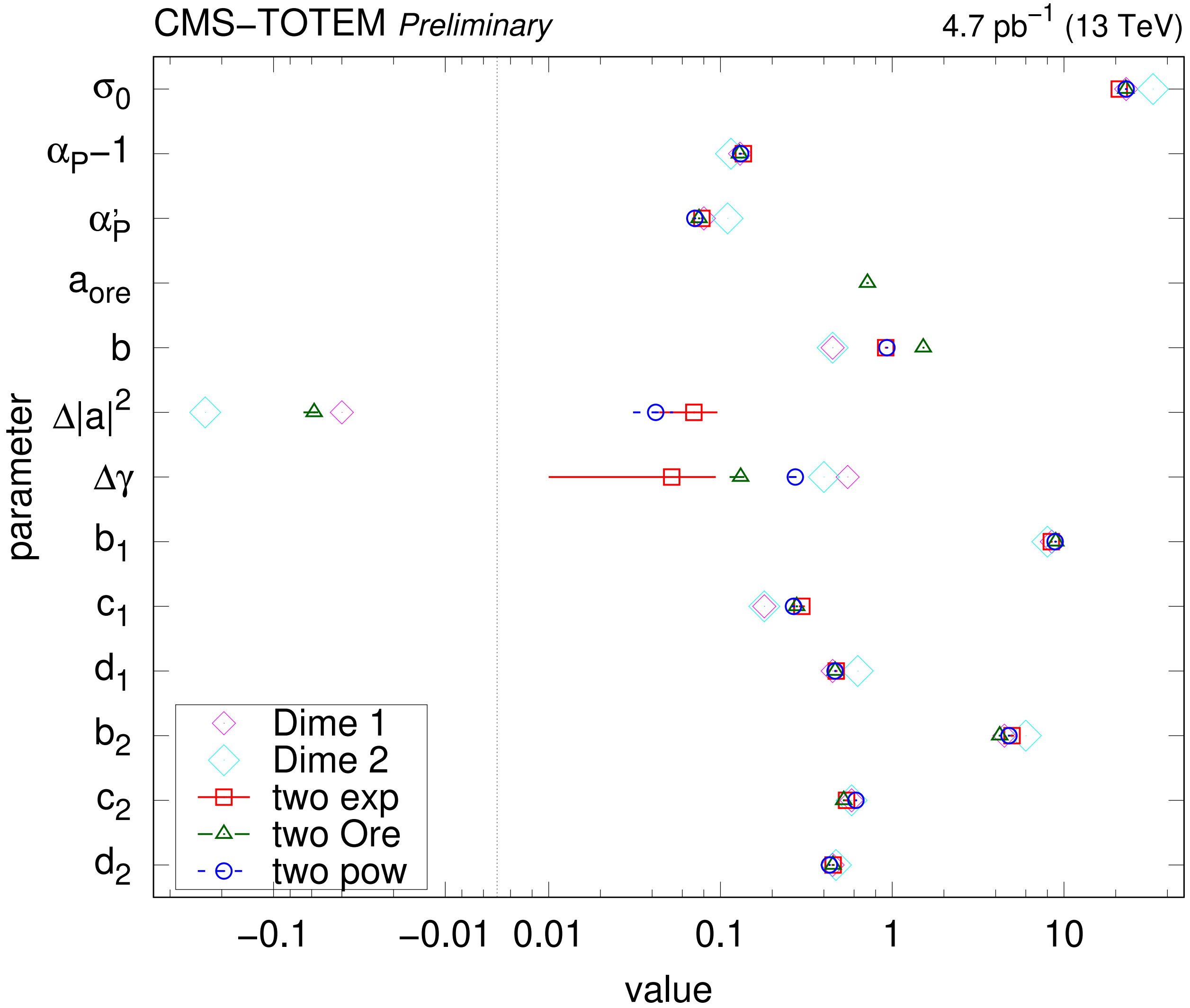
Model tuning – result

Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{\text{exp/ore/pow}}$[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	—	
$b_{\text{exp/ore/pow}}$[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	—	
$b_{\text{exp/ore/pow}}$[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	$5741/5786$	$6415/5785$	$7879/5786$	

- Models
  - empirical
    (measured elastic diff cross section)
  - one-channel
    (proton in ground state)
  - two-channel
    (two diff eigenstates of the proton)
- Form factors
  - pomeron-meson
    (exponential, Orear-type, power-law)
  - proton-pomeron

Model tuning – result

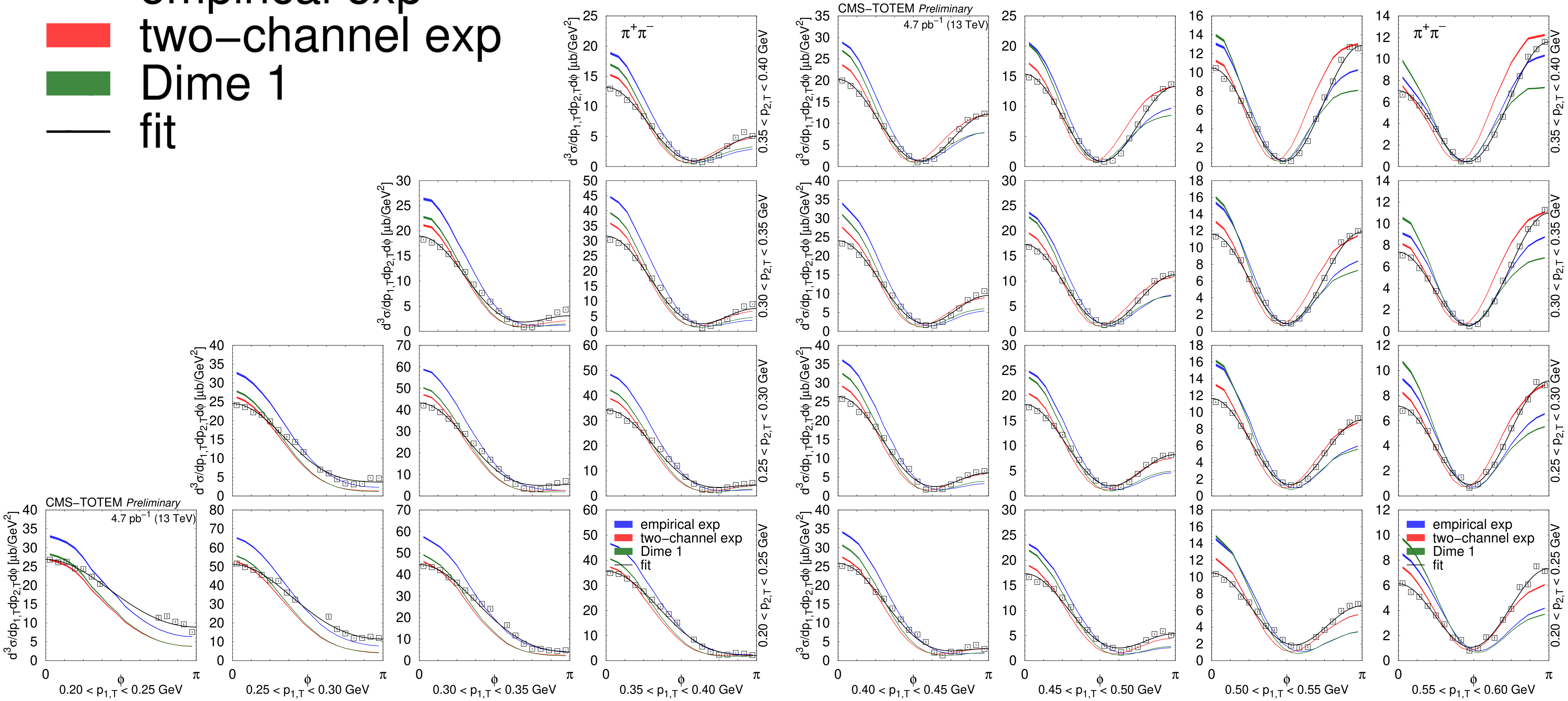
two-channel



Remarkable agreement with DIME (“soft model 1”), although with unexpected eigenstate weights ($a_1 \approx a_2$) and eigenstate-pomeron coupling ($\gamma_1 \approx \gamma_2$)!

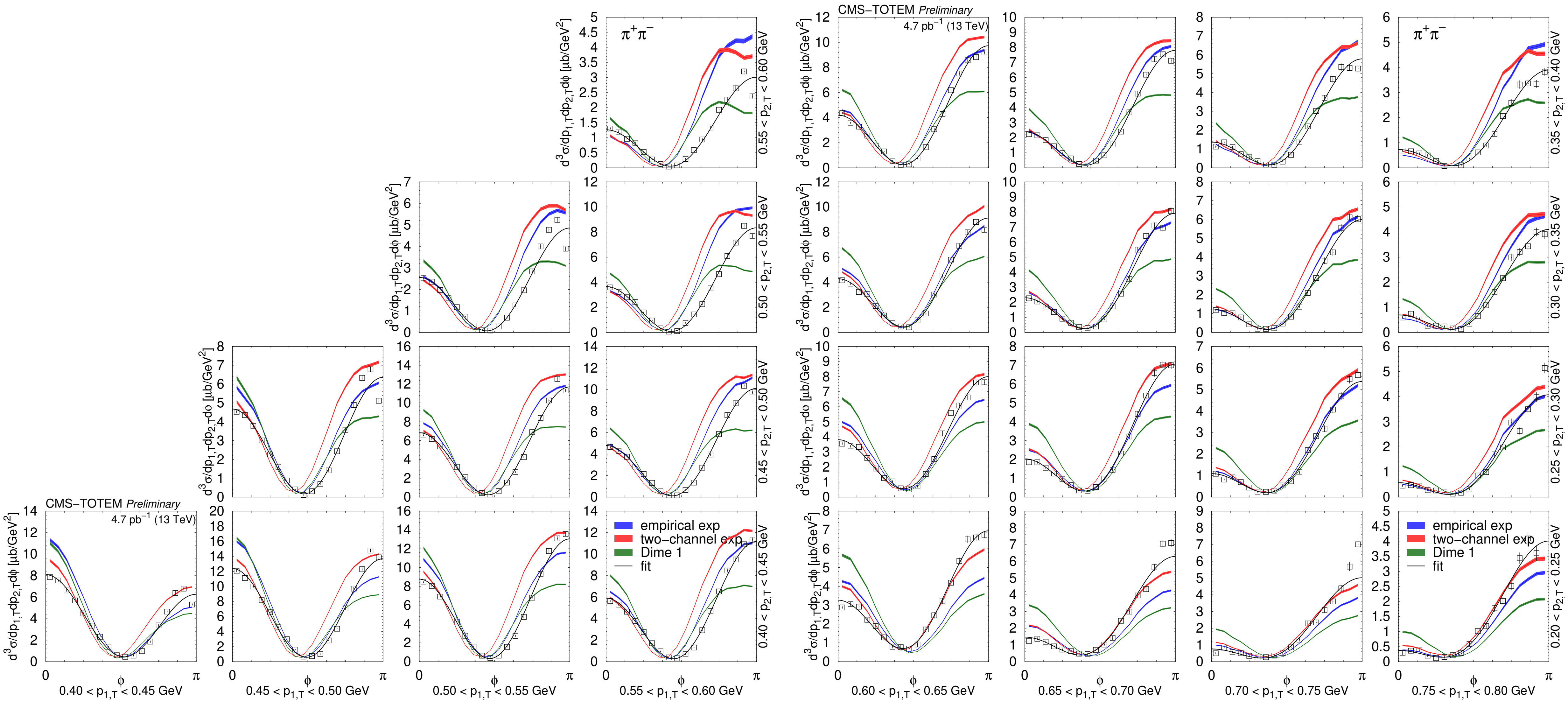
$d\sigma/d\phi - \pi^+\pi^-$

🟦 empirical exp
🟥 two−channel exp
🟩 Dime 1
— fit



Good quality

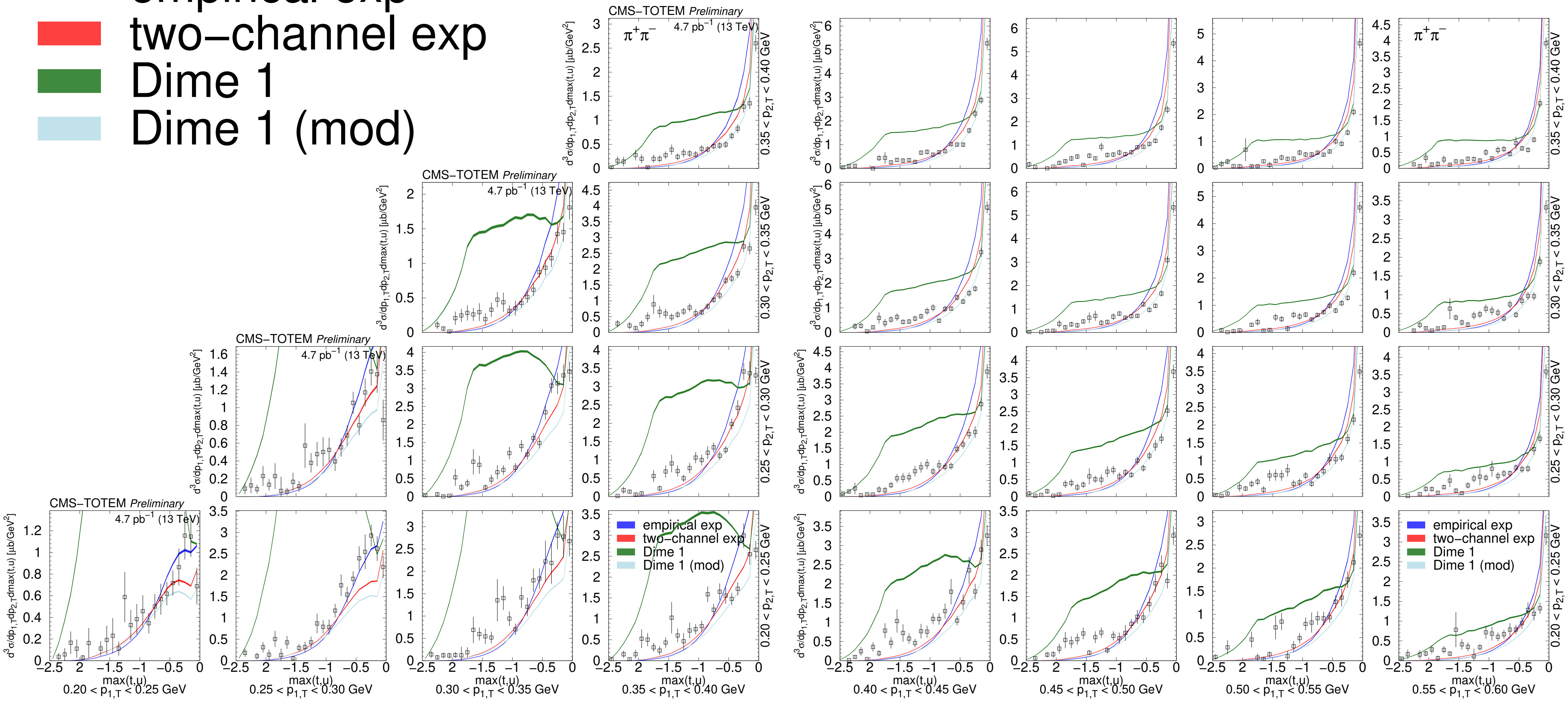
$\mathrm{d}\sigma/\mathrm{d}\phi$ – $\pi^+\pi^-$



Maybe a ground-state proton is enough? But then what about $\mathrm{d}\sigma/\mathrm{d}t$

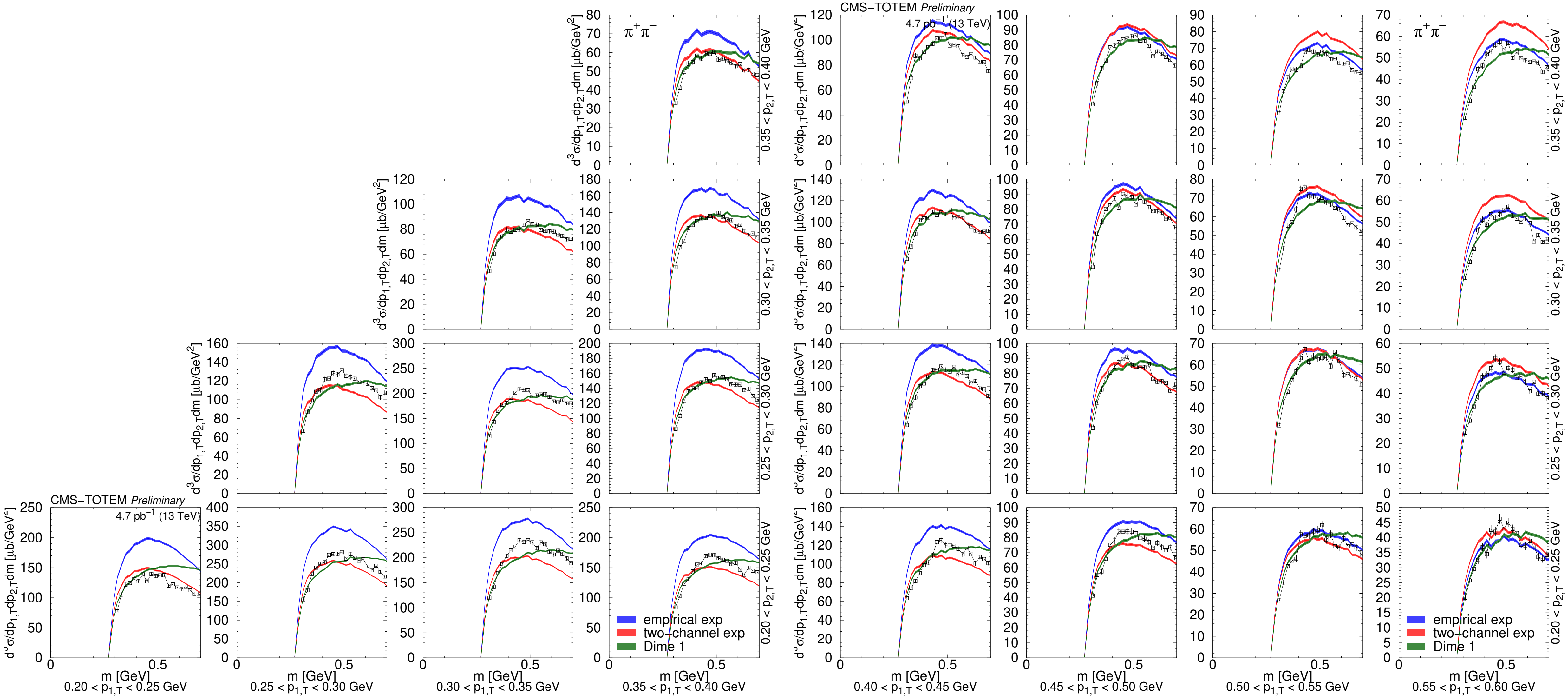
$d\sigma/d\max(\hat{t},\hat{u})$ – $\pi^+\pi^-$

🟦 empirical exp
🟥 two–channel exp
🟩 Dime 1
🟦 Dime 1 (mod)

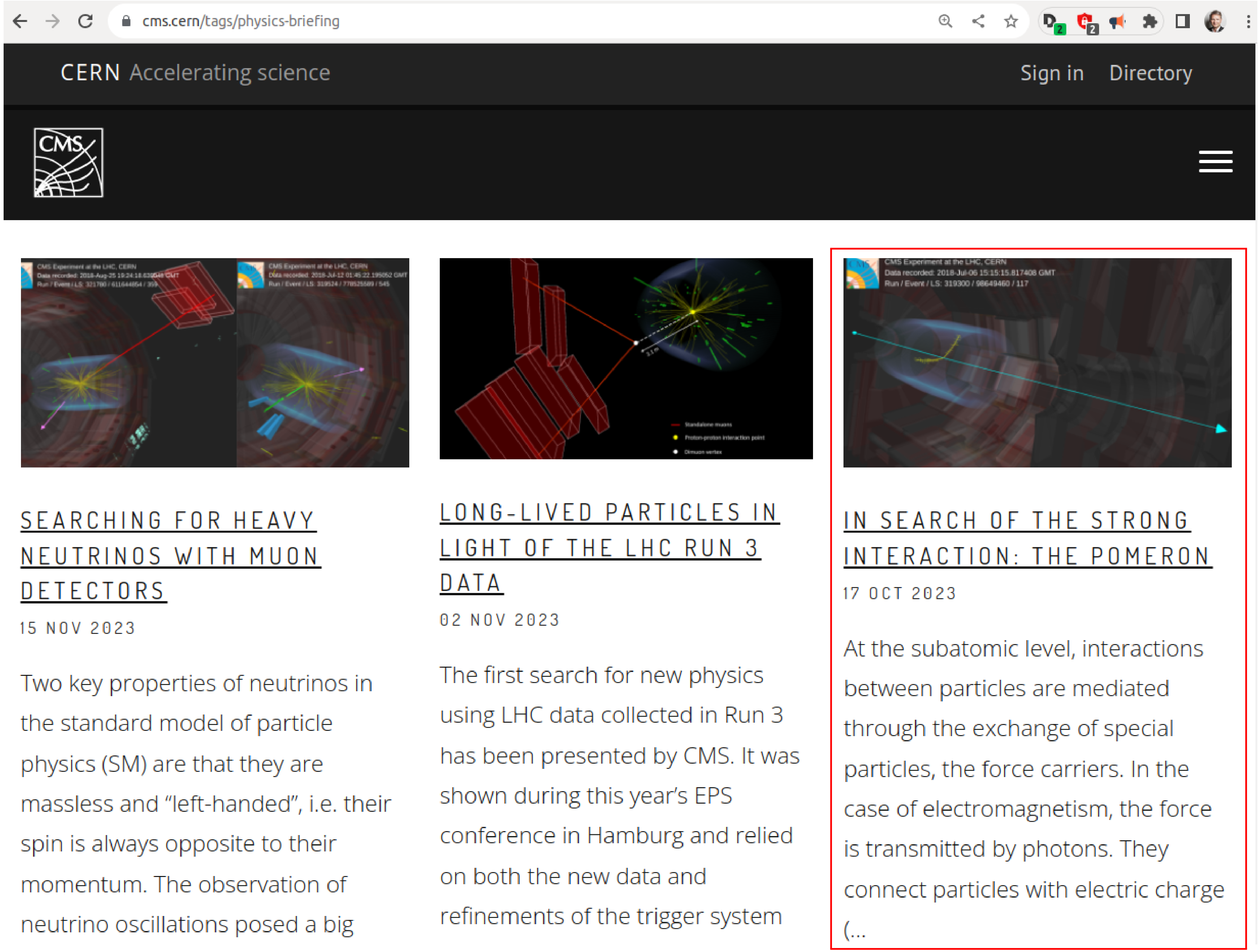


Virtual hadrons – important to fix the value of b_{exp} ($0.45 \rightarrow 0.9\,\text{GeV}^{-2}$)

$d\sigma/dm - \pi^+\pi^-$



Invariant mass spectra of the central two-hadron system



cms.cern/tags/physics-briefing

CERN Accelerating science

Sign in Directory

SEARCHING FOR HEAVY NEUTRINOS WITH MUON DETECTORS

15 NOV 2023

Two key properties of neutrinos in the standard model of particle physics (SM) are that they are massless and “left-handed”, i.e. their spin is always opposite to their momentum. The observation of neutrino oscillations posed a big

LONG-LIVED PARTICLES IN LIGHT OF THE LHC RUN 3 DATA

02 NOV 2023

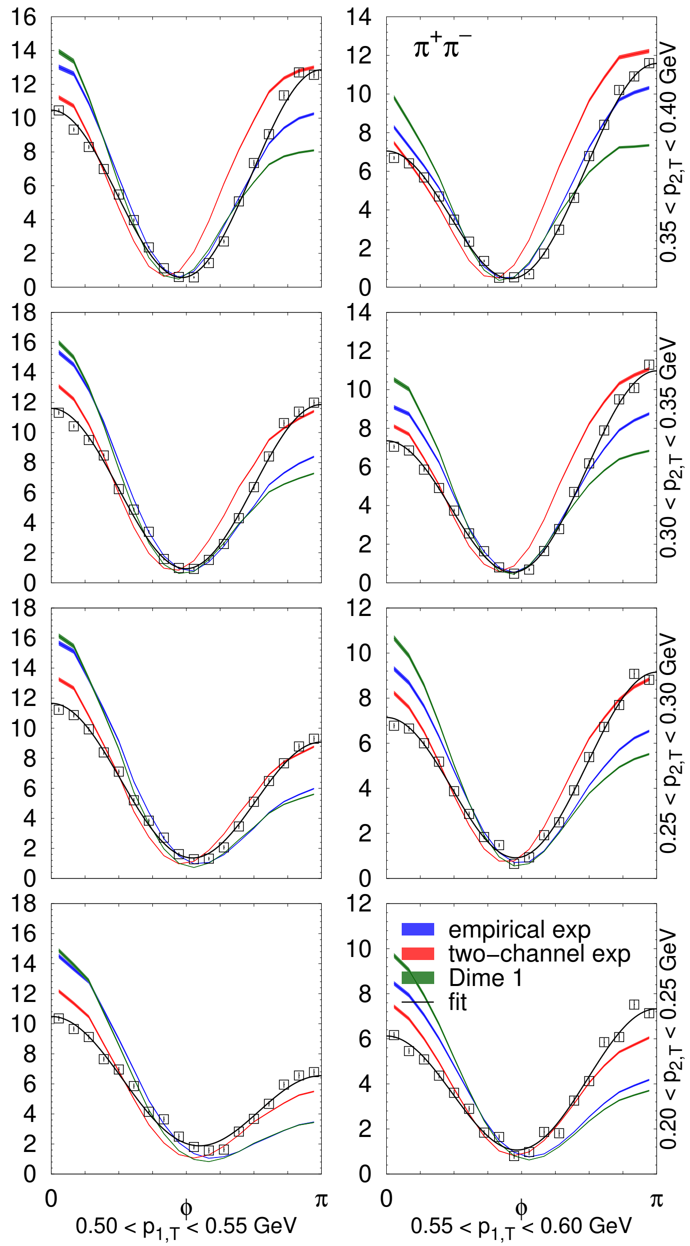
The first search for new physics using LHC data collected in Run 3 has been presented by CMS. It was shown during this year’s EPS conference in Hamburg and relied on both the new data and refinements of the trigger system

IN SEARCH OF THE STRONG INTERACTION: THE POMERON

17 OCT 2023

At the subatomic level, interactions between particles are mediated through the exchange of special particles, the force carriers. In the case of electromagnetism, the force is transmitted by photons. They connect particles with electric charge (...

Summary and conclusions



- Analysis
  - double pomeron exchange, charged hadron pairs, 13 TeV
  - now the $\pi^+\pi^-$ final state, resonance-free region
  - differential cross sections in bins of $(p_{1,\mathrm{T}}, p_{2,\mathrm{T}})$
  - azimuthal angle ϕ between the surviving protons
- Results
  - rich structure of nonperturbative interactions
  - **parabolic minimum in the distribution of ϕ** (first)
  - **interference** of the bare and the rescattered amplitudes
  - **model tuning: pomeron-related quantities** (first)
  - good quality fits, **choices of form factors** tested

Physics Analysis Summary at: https://cds.cern.ch/record/2867988

More to come ($\pi^+\pi^-$ and $\mathrm{K}^+\mathrm{K}^-$ resonances!)