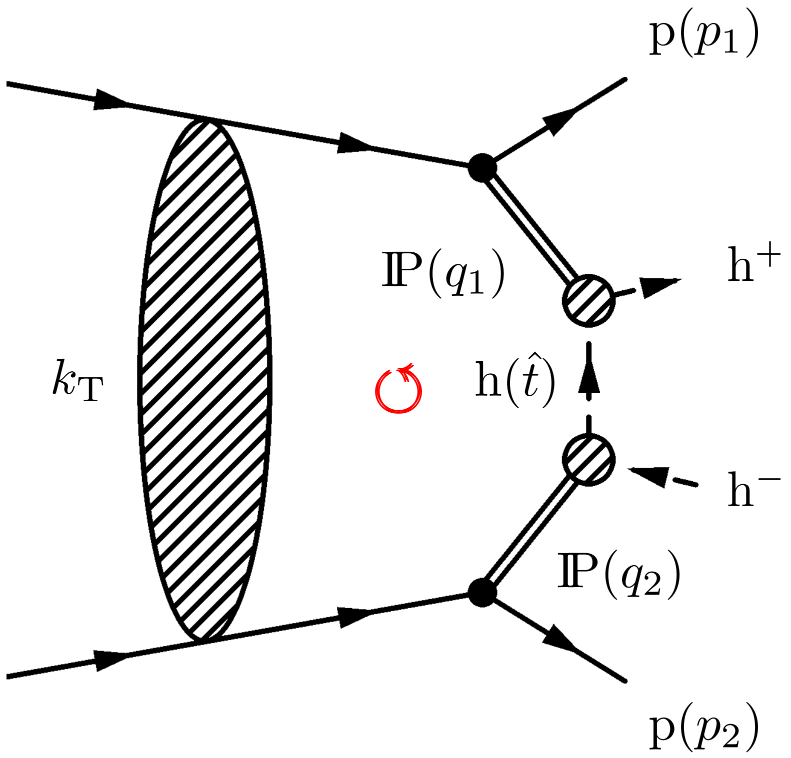
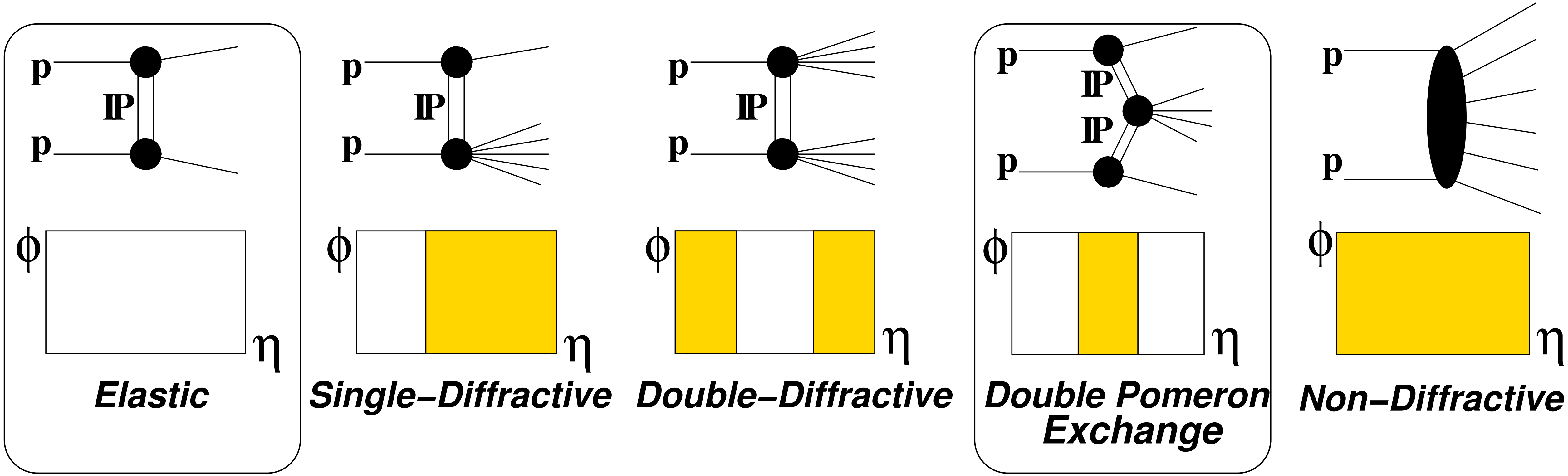


CMS+TOTEM results on central exclusive production (nonresonant processes)

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

EMMI Workshop "Forward Physics in ALICE 3"
Heidelberg, October 19, 2023

Proton-proton collisions

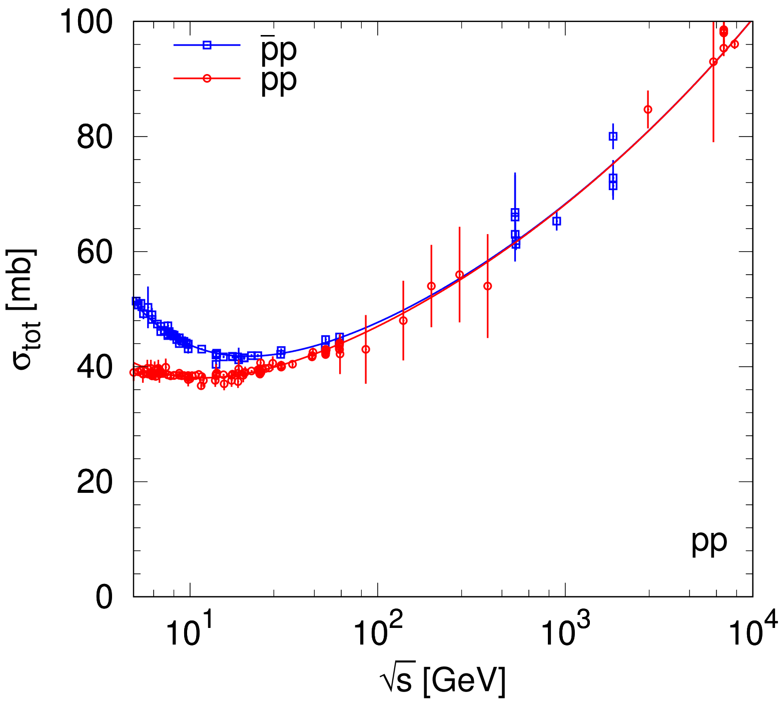


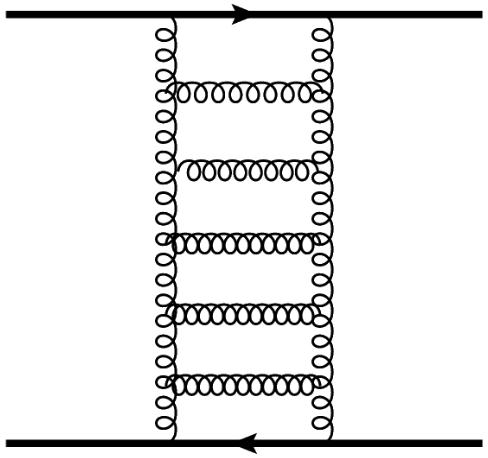
- Types
  - elastic: no additional particles
  - diffractive: one or both protons are excited and dissociate
  - what is the exchanged particle? actually, is it a particle?

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

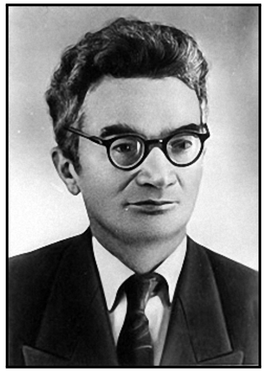
Physics Analysis Summary at: https://cds.cern.ch/record/2867988

Pomeron ($\mathbb{P}$)



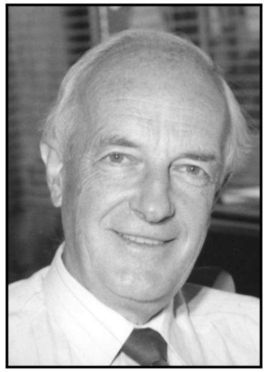


- Problems
  - – the pp and $\bar{\mathrm{p}}$p cross sections are similar
  - – they keep rising; exchange?
  - – force carrier must have zero charges
  - – gluon ladder? nonperturbative



Isaak Pomeranchuk

Vladimir Gribov



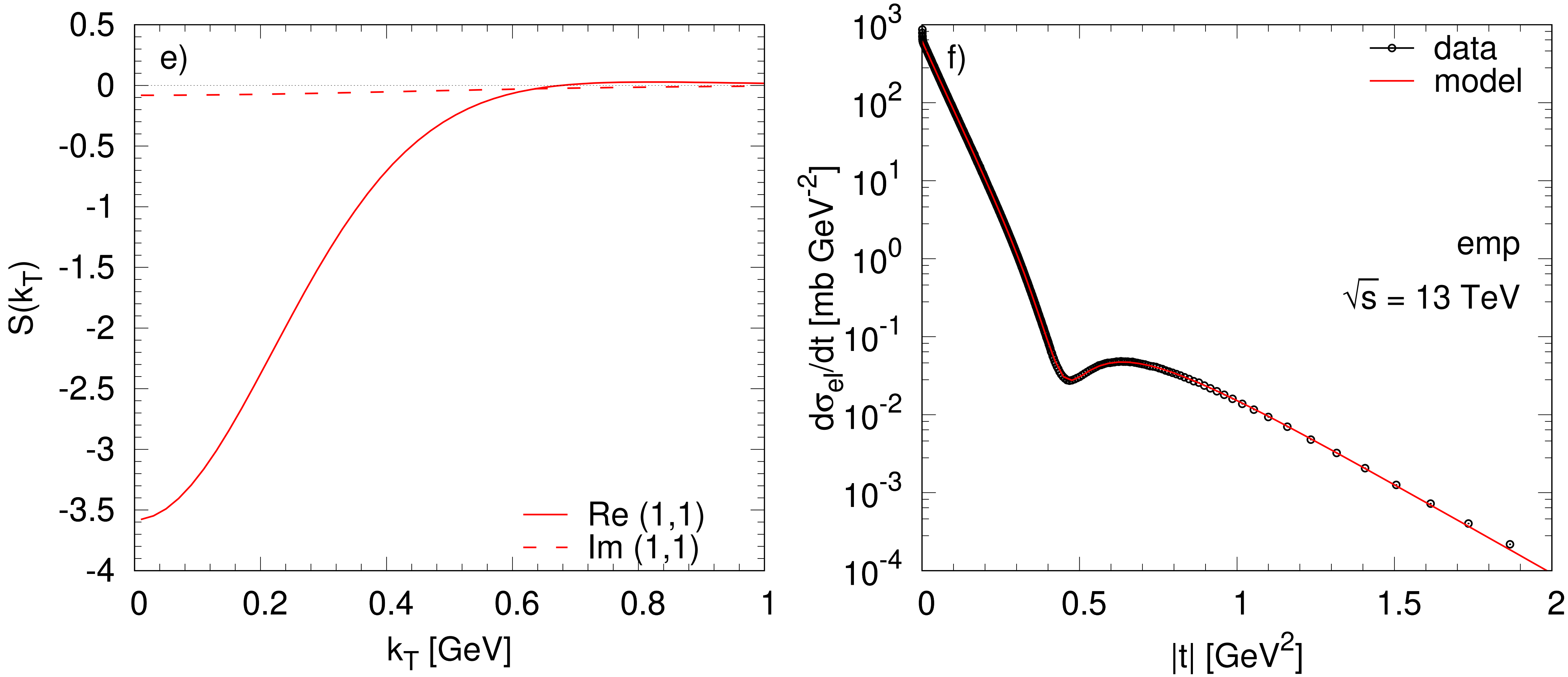
Sandy Donnachie

Peter Landshoff

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

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

Theory – elastic differential cross section

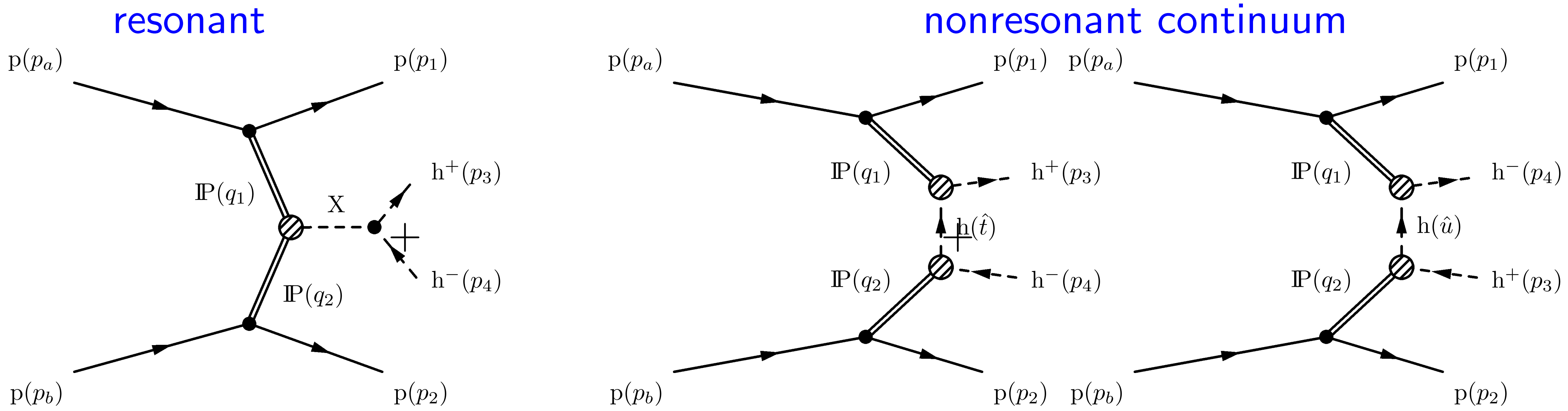


TOTEM Coll., EPJC **79** (2019) 785 and 861
Fagundes et al, PRD **88** (2013) 094019

Get it from $S(k_\mathrm{T}) = T_\mathrm{el}(k_\mathrm{T})/(2\pi)^2$ where $T_\mathrm{el}(t) = i\left[G(t)\sqrt{A}e^{Bt/2} + e^{i\phi}\sqrt{C}e^{Dt/2}\right]$

Empirical parametrisation of TOTEM data (Phillips-Barger model)

Theory – resonances vs background


resonant

nonresonant continuum

- Nonresonant continuum

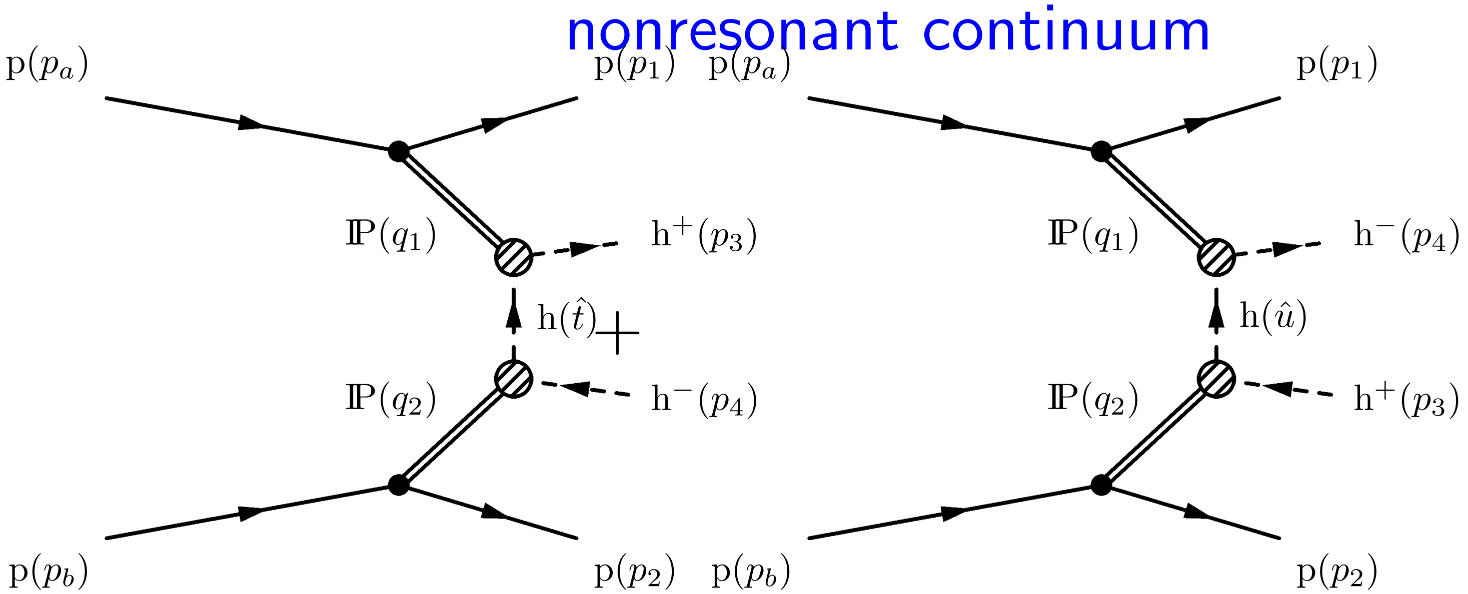
The matrix element for the nonresonant continuum process is

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

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

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

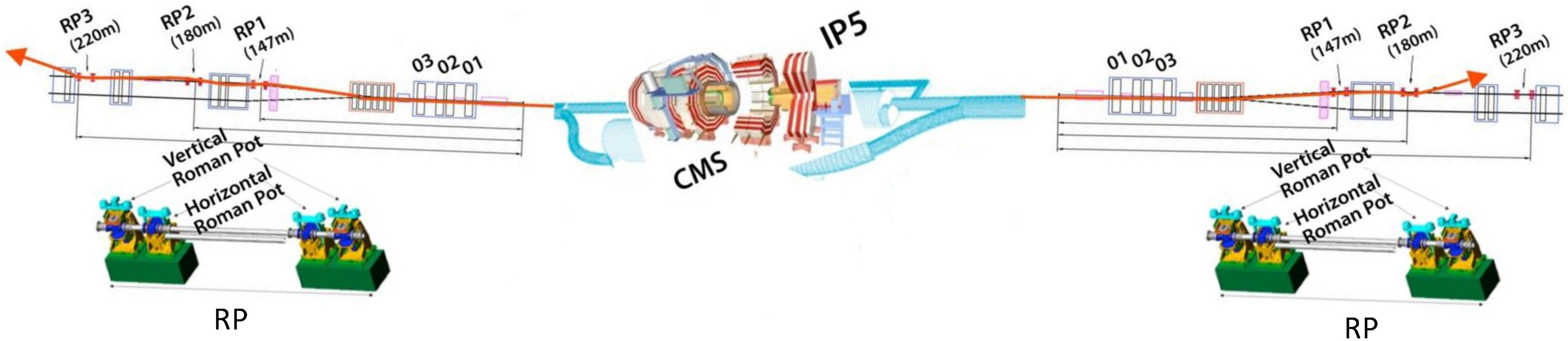
  $$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} \exp\left(\frac{B_{\mathbb{P}}}{2} t_i\right)$$

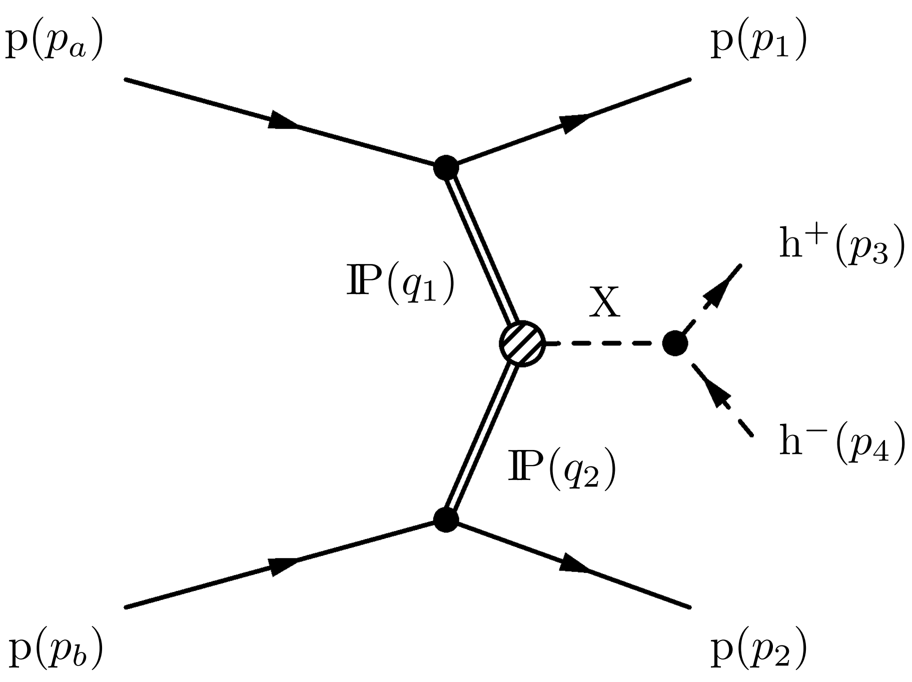
  Taking into account the reggeon exchange as well

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

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

Central exclusive production – data

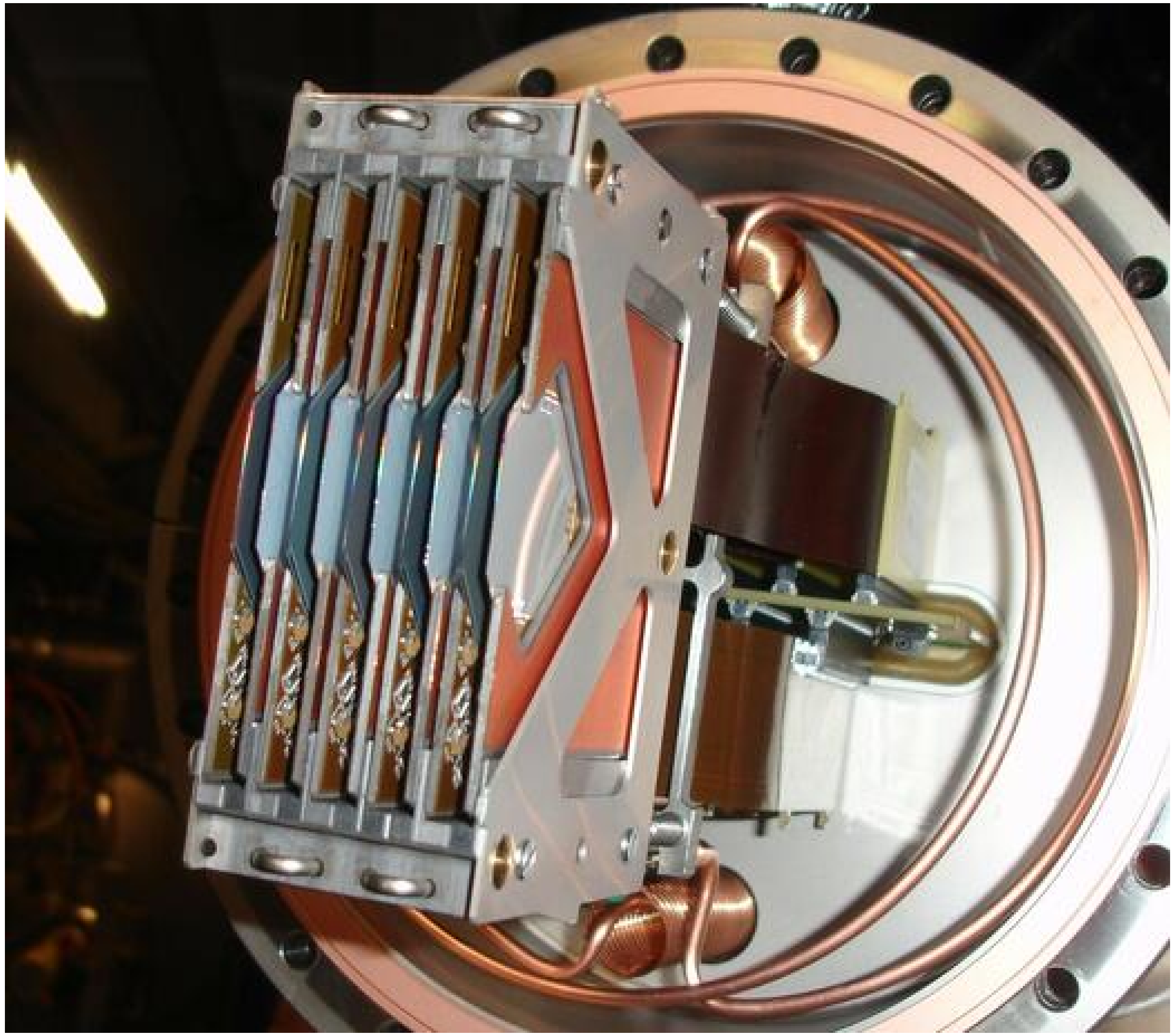




- CMS+TOTEM dataset ($\beta^* = 90\,\mathrm{m}$, 2018)
  - about 80 M events with **two scattered protons** and only **two reconstructed central tracks**
  - part of those is double pomeron exchange (DPE), where a central system (X) was created
  - decayed to particle-antiparticle pair $\mathrm{h^+h^-}$,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

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

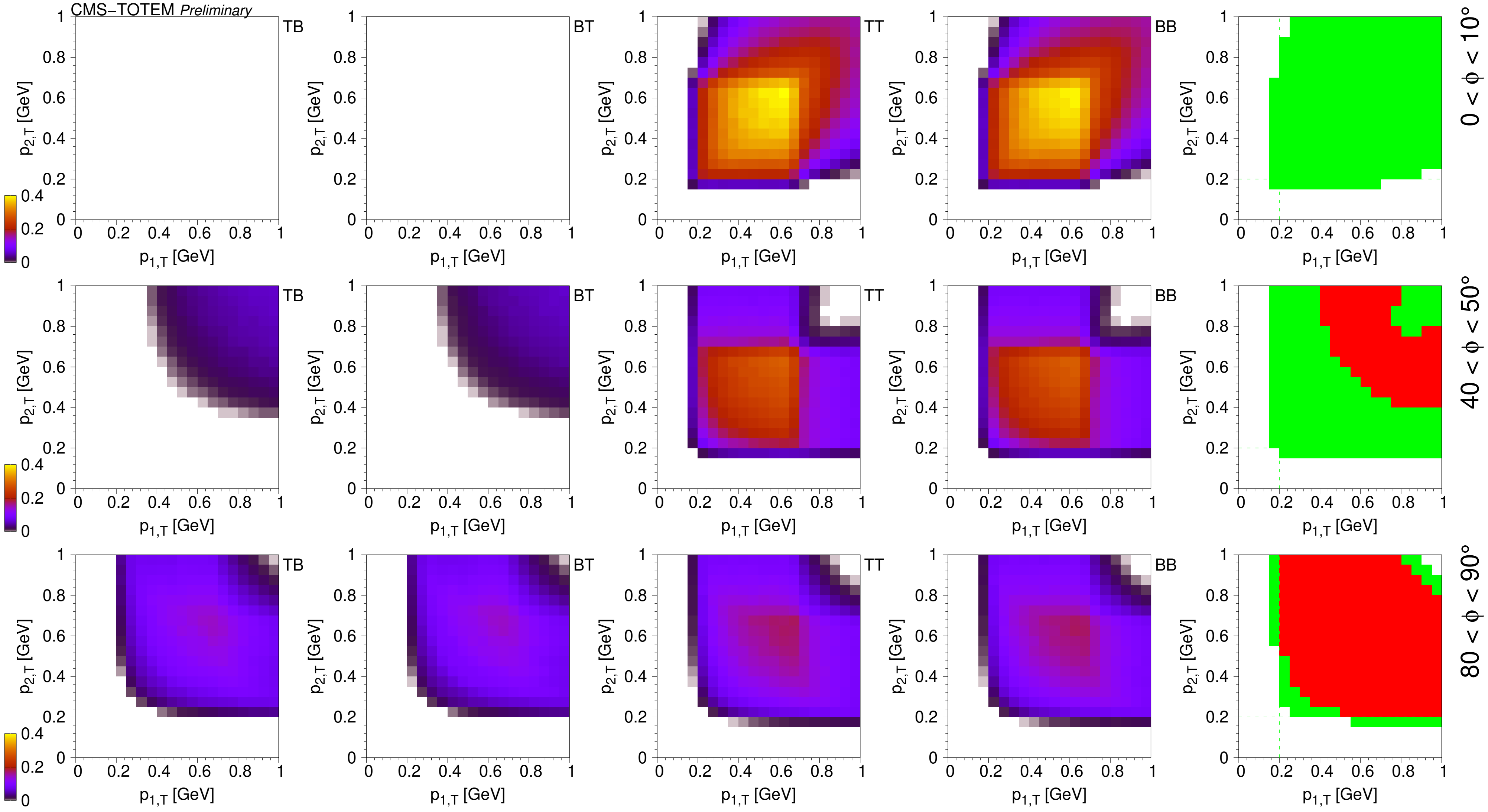
Scattered protons – roman pots



- 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

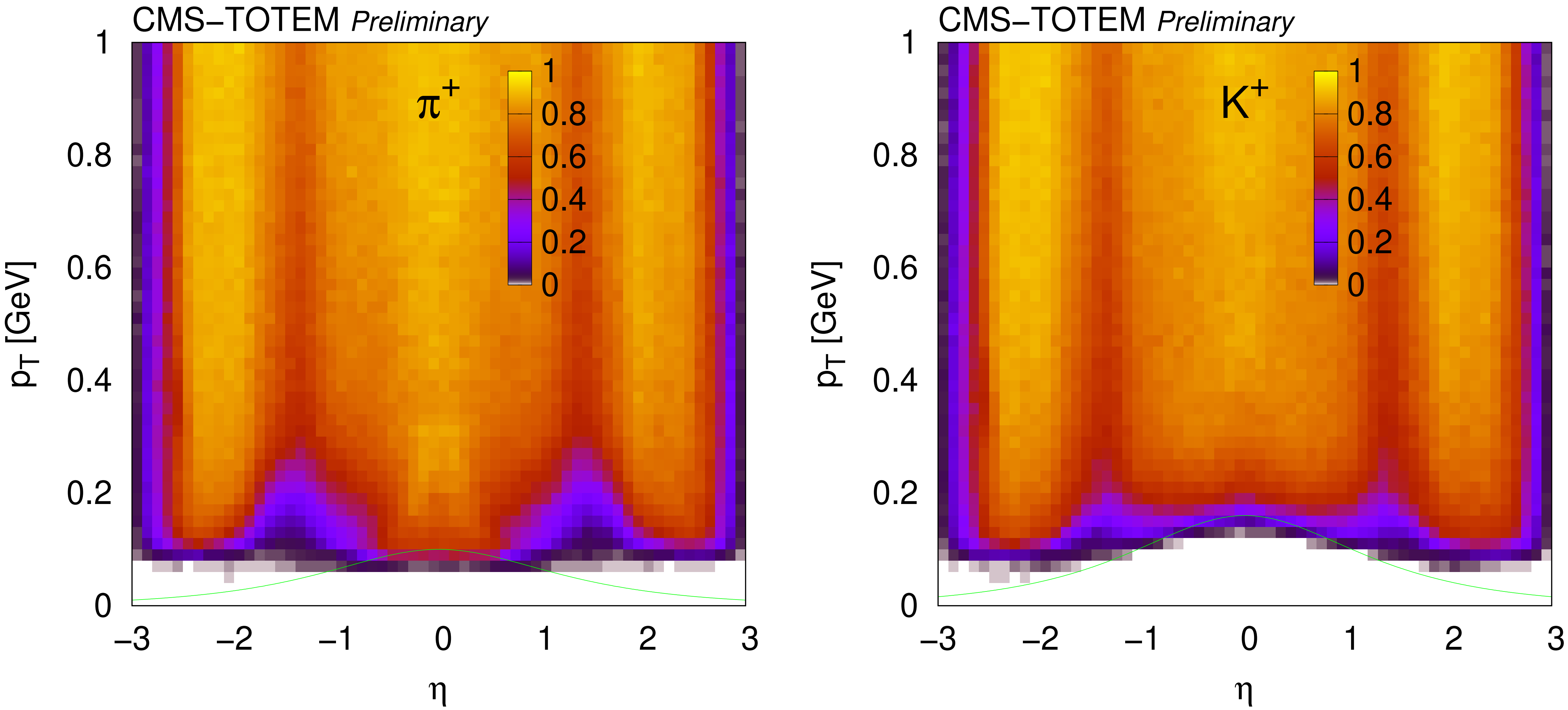
Novel tracklet fits, relative alignment of planes, strip-level efficiencies

Roman pots – proton-pair acceptance and coverage vs ϕ



Calculated detection efficiencies for the pair of scattered protons
as a function of their transverse momenta $(p_{1,\mathrm{T}}, p_{2,\mathrm{T}})$

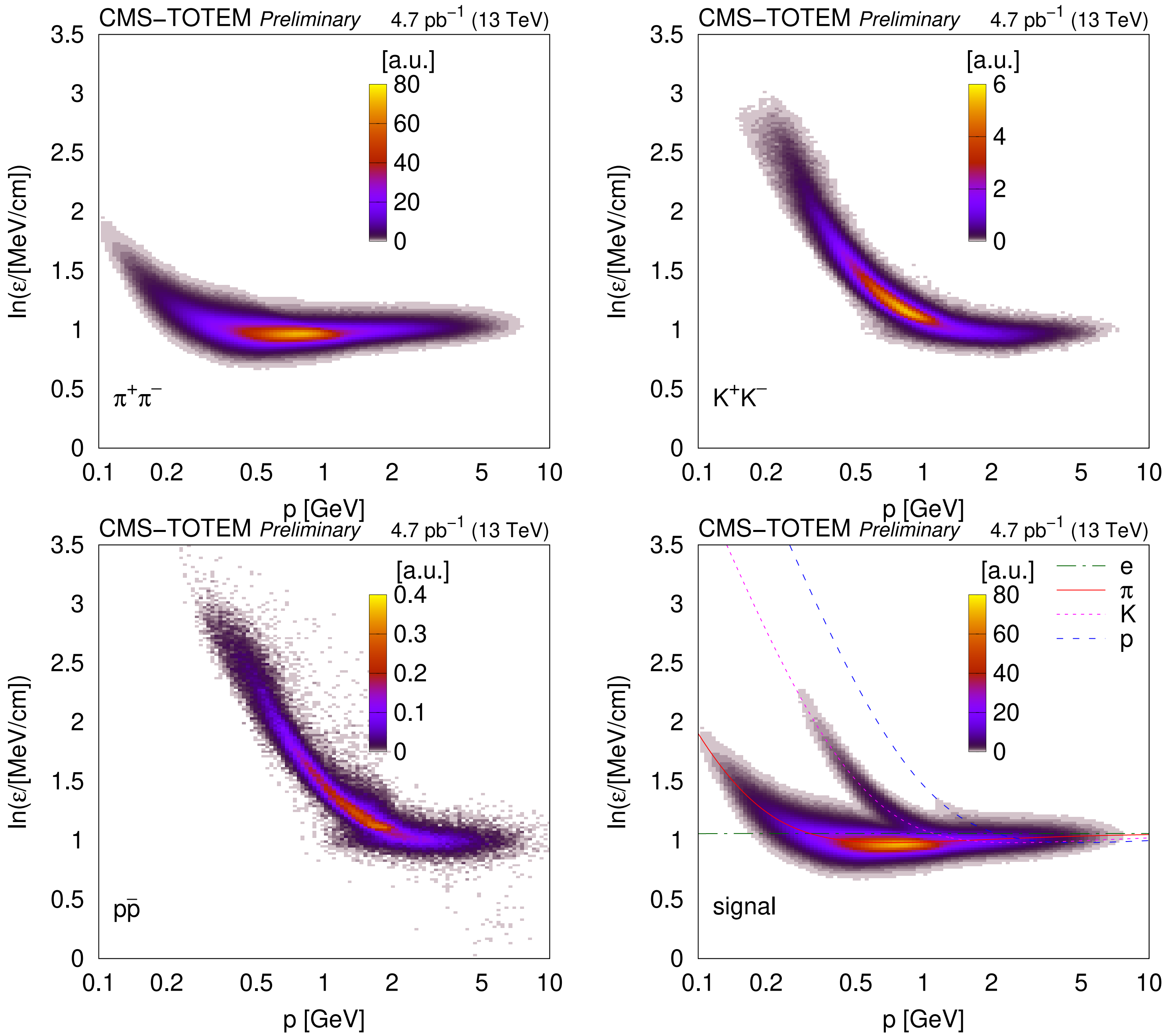
Central hadrons – tracking and HLT efficiencies



At least 5 pixel clusters and at least 3 layers in barrel pixel, or at least one pixel track

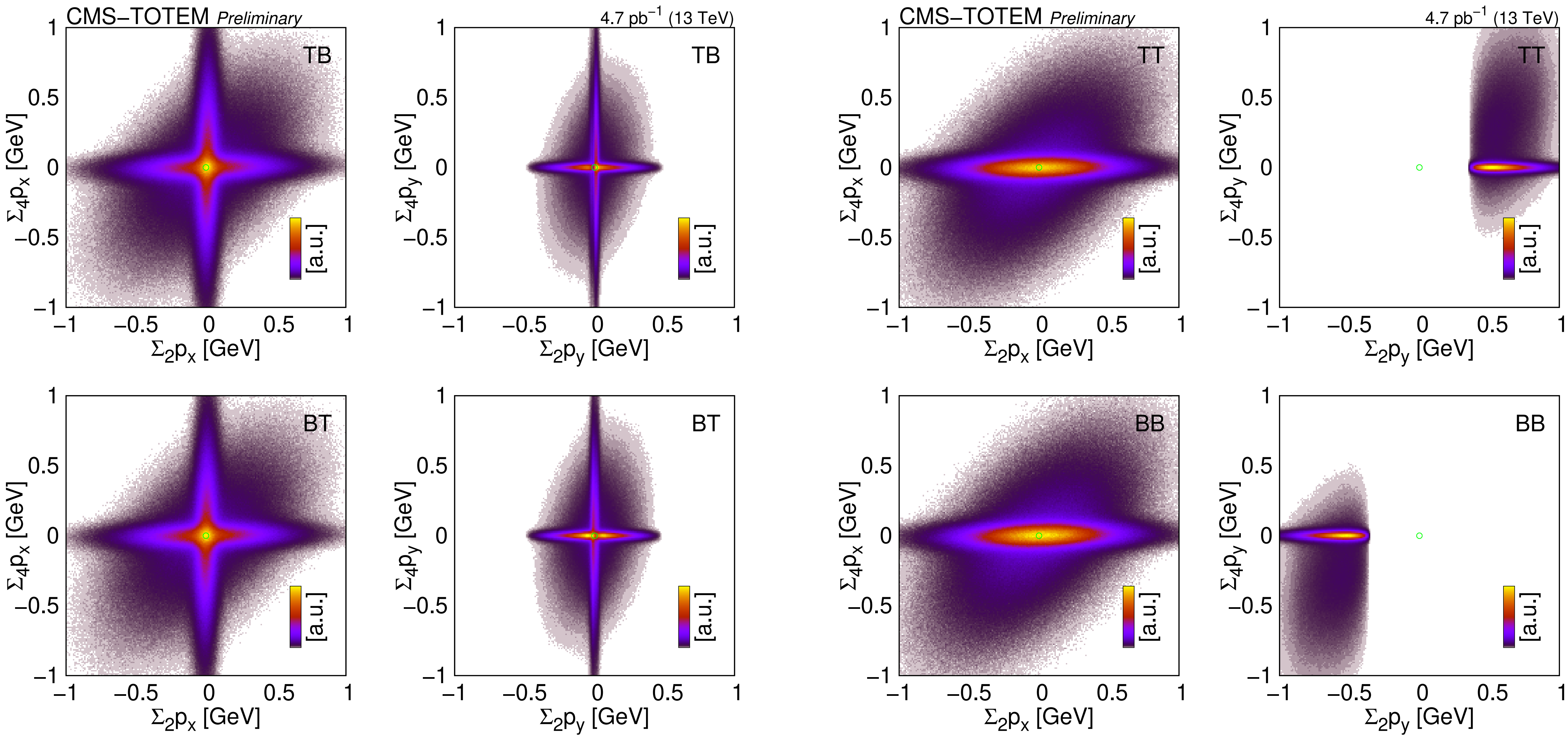
Inefficiencies, valleys to be corrected

Central hadrons – particle identification through dE/dx



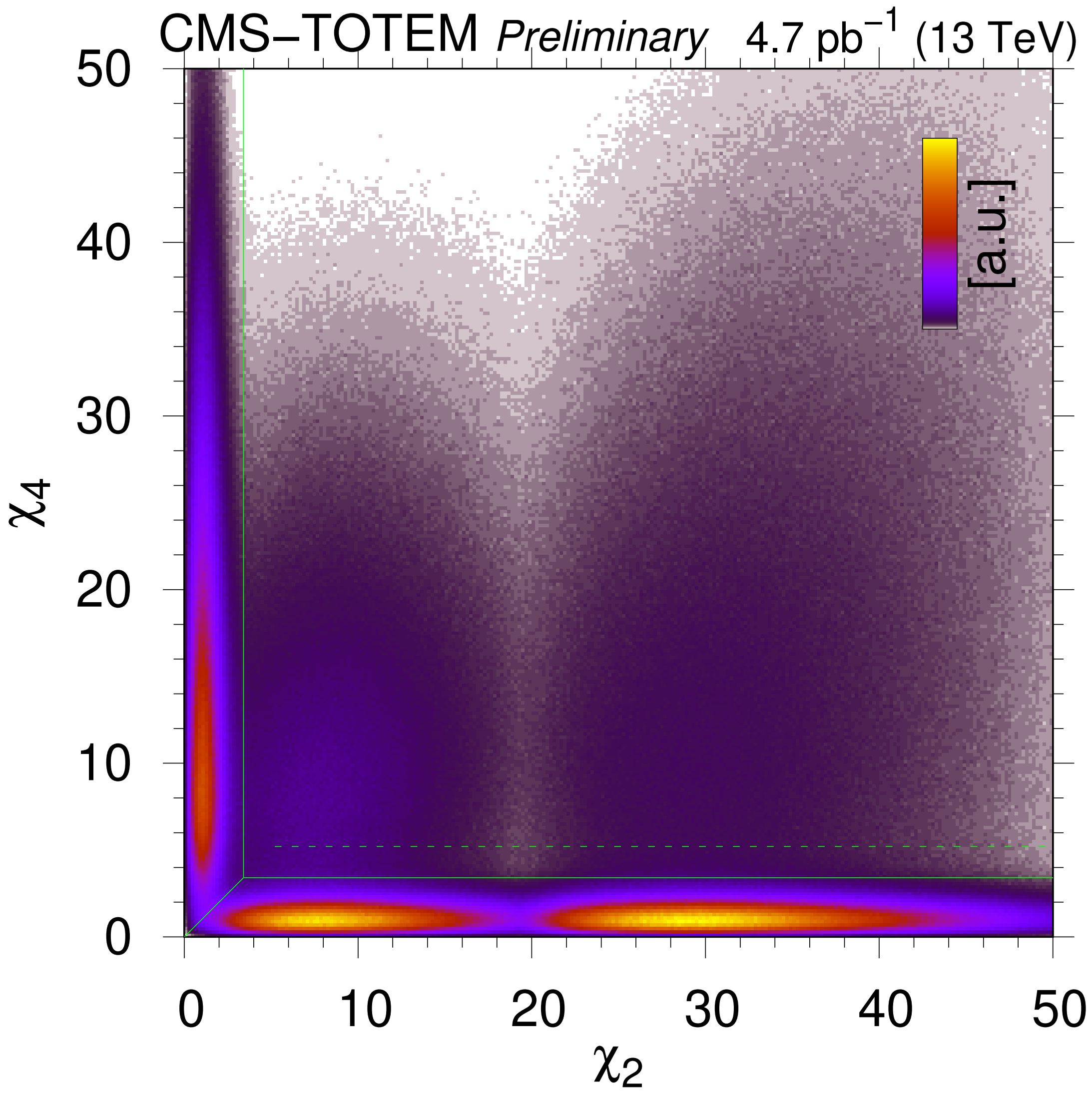
- Particle pair
  - identified as type $\mathrm{h}^+\mathrm{h}^-$ if $P_{1,\mathrm{h}}P_{2,\mathrm{h}} > 10 \cdot P_{1,i}P_{2,i}$ for all $i \neq h$
- Proof of exclusivity
  - $\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$, and $\mathrm{p\bar{p}}$ pairs
  - conservation laws at work: charge, strangeness, baryon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

Event classification – true exclusive or pileup?

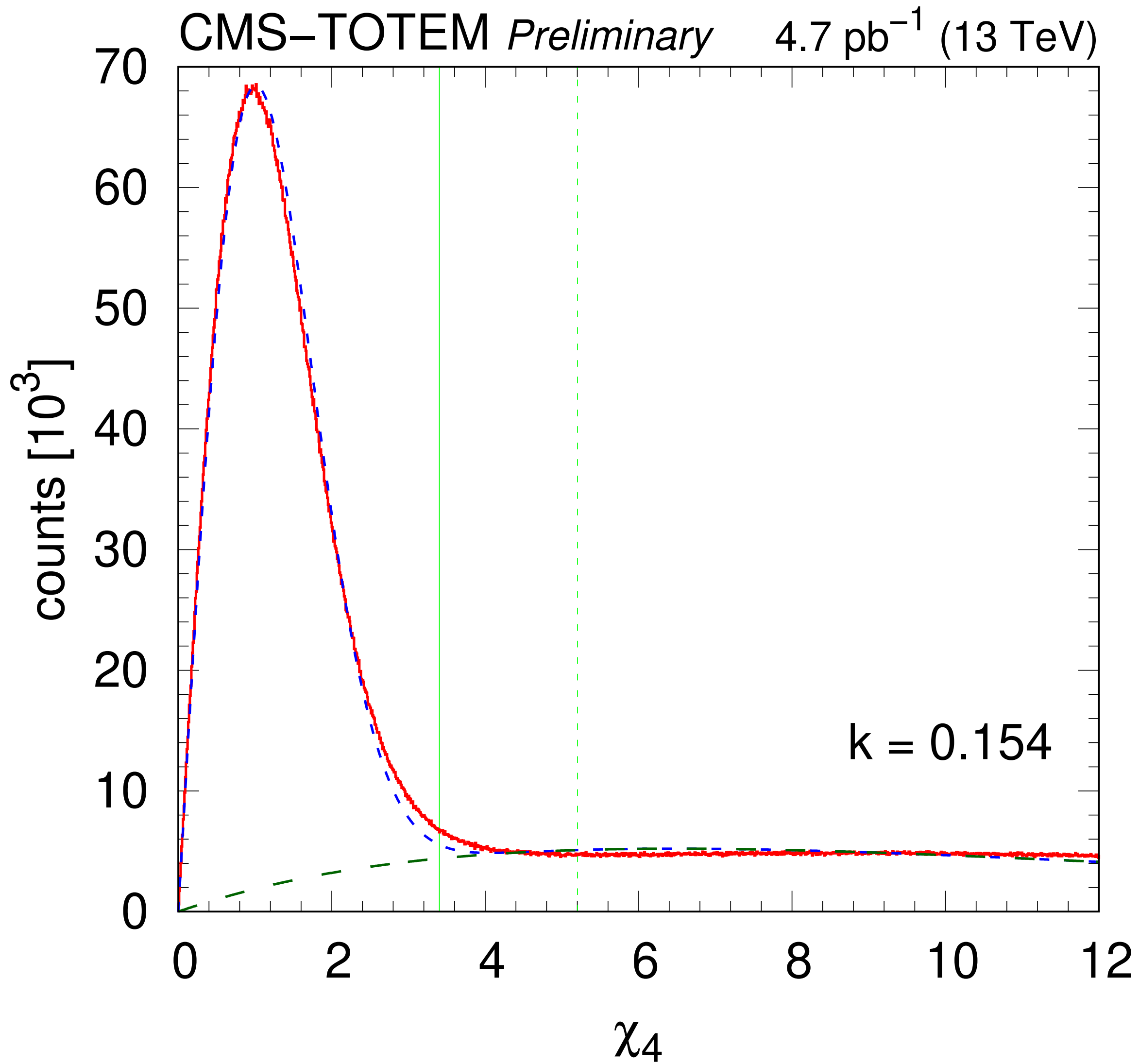


Based on $(\sum_4 p_x$ vs $\sum_2 p_x$, $\sum_4 p_y$ vs $\sum_2 p_y)$

Event classification – χ_4 – signal and sideband



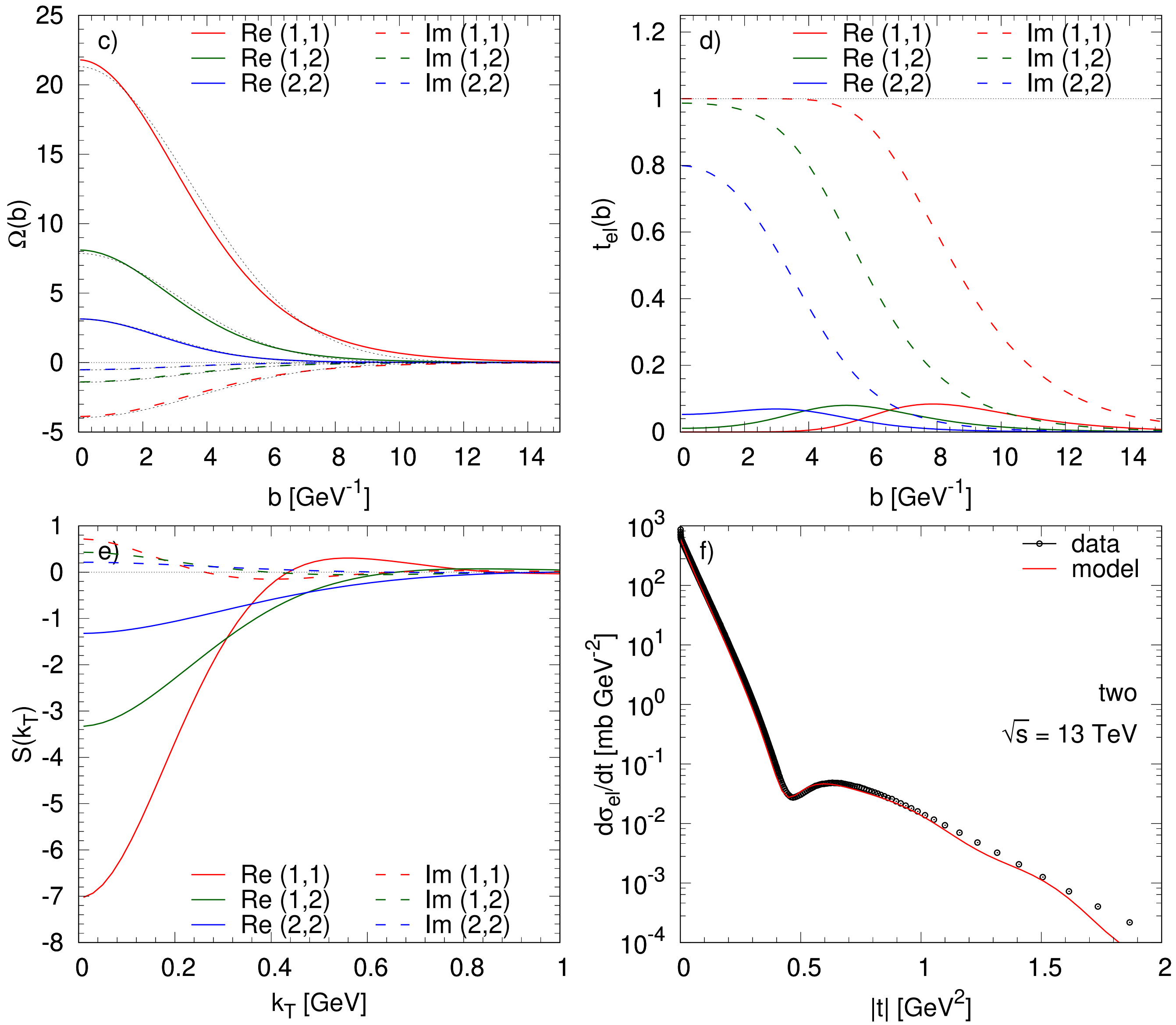
Mahalanobis distance $\chi(\mathbf{s}) = (\mathbf{s}^T V^{-1} \mathbf{s})^{1/2}$



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

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

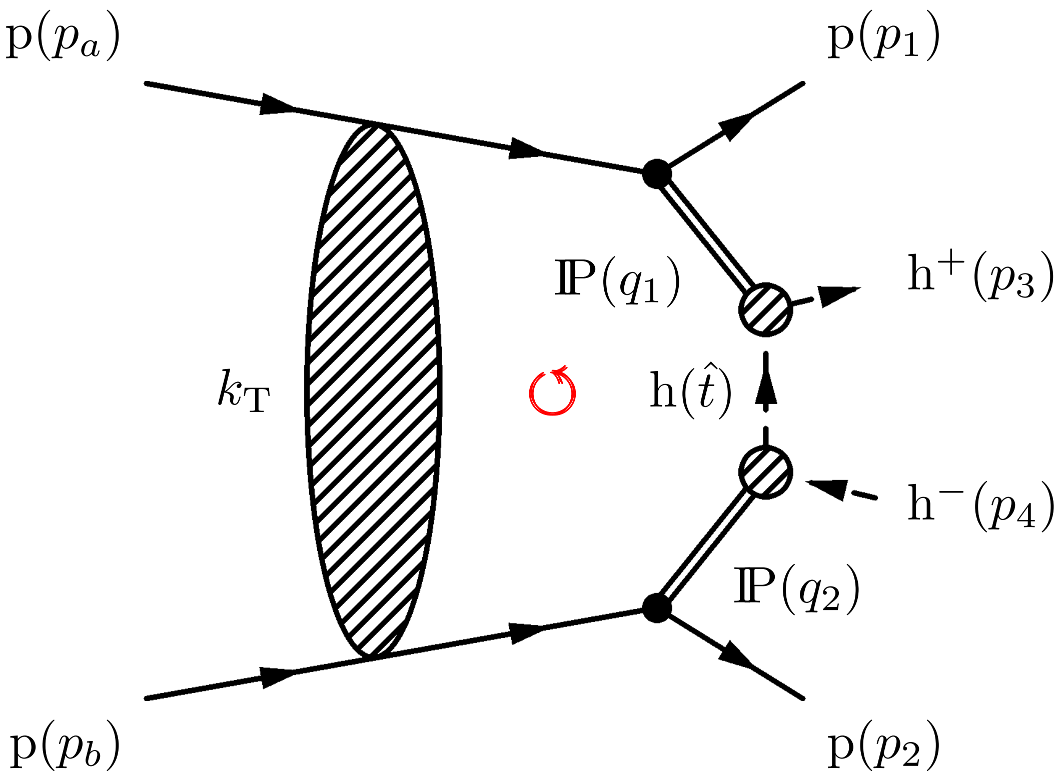
Theory – elastic screening – two-channel



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 $d\sigma_{\text{el}}/dt$, **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
  $\mathcal{M}(\mathbf{p_1}, \mathbf{p_2}) = \mathcal{M}_0(\mathbf{p_1}, \mathbf{p_2}) + \int d^2\mathbf{k}_T T_{\text{el}}(k_T) \mathcal{M}_0(\mathbf{p_1} - \mathbf{k}_T, \mathbf{p_2} + \mathbf{k}_T)$
  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	
b_2 [GeV^{-2}]	4.5	6	3.8	4.2	pomeron coupling to eigenstates
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

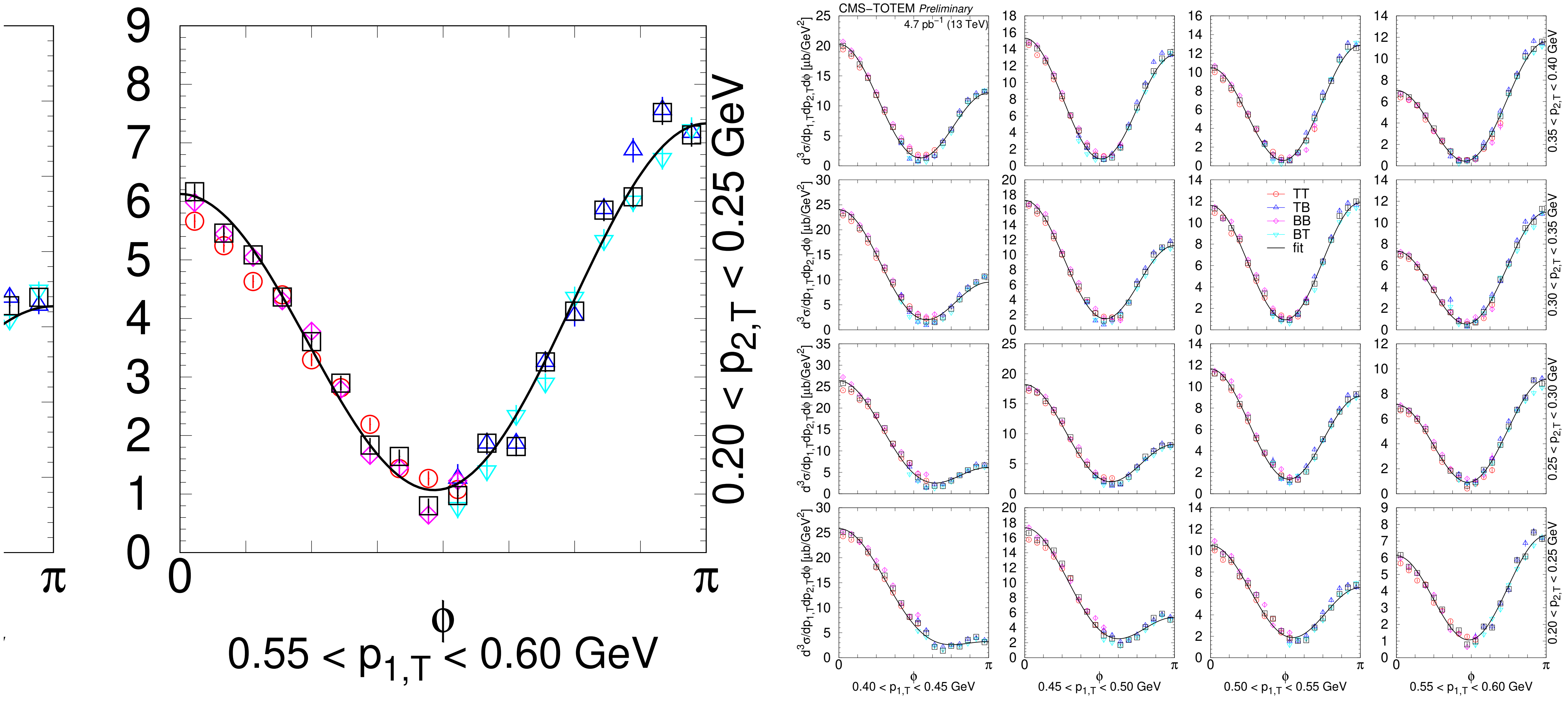
- Proton-pomeron(eigenstate) coupling
  - One-channel model: $F_p(t) = \exp(B_{\mathbb{P}}/2 \cdot t)$
  - Two-channel model:
    $F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$

- Pomeron-meson coupling

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

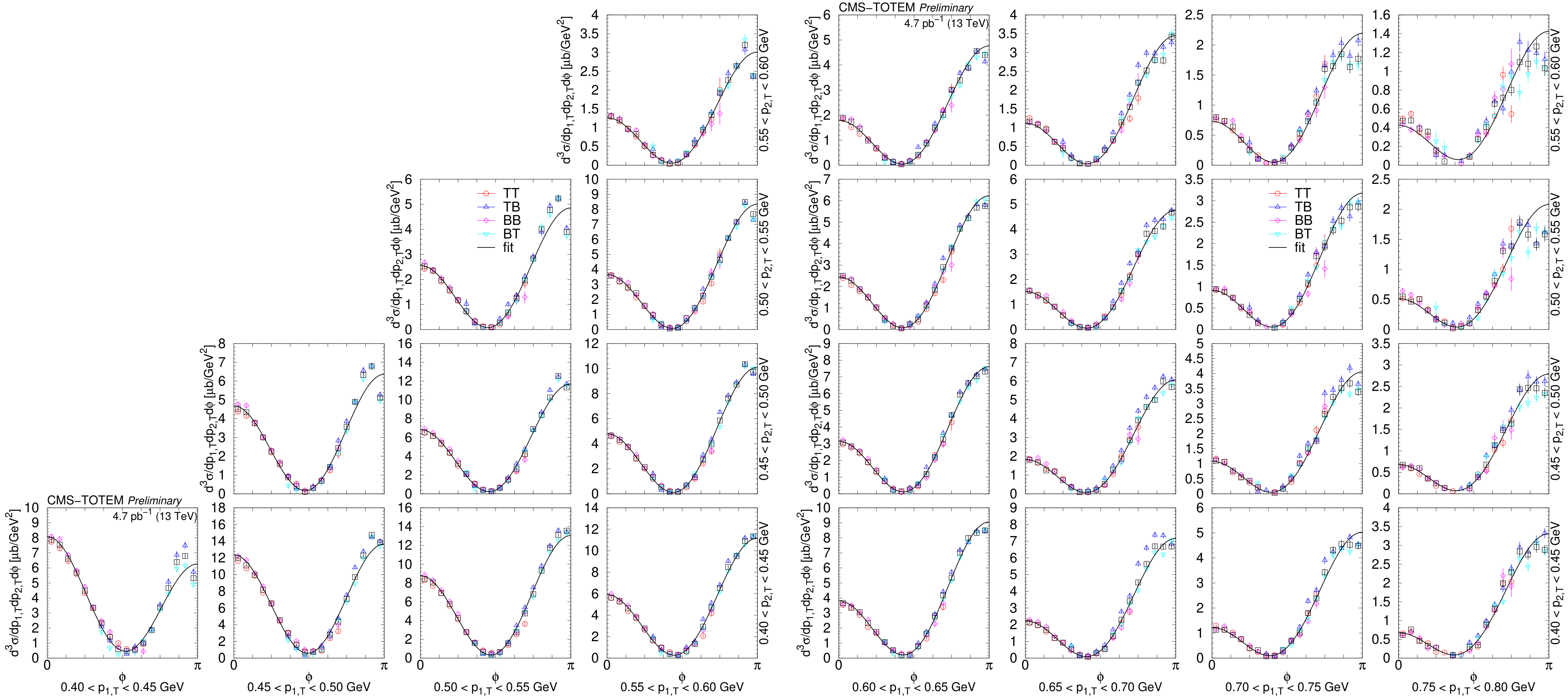
Now using a new generator with proper physics content, from scratch

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 $0.35 < m_{\pi\pi} < 0.65\,\mathrm{GeV}$

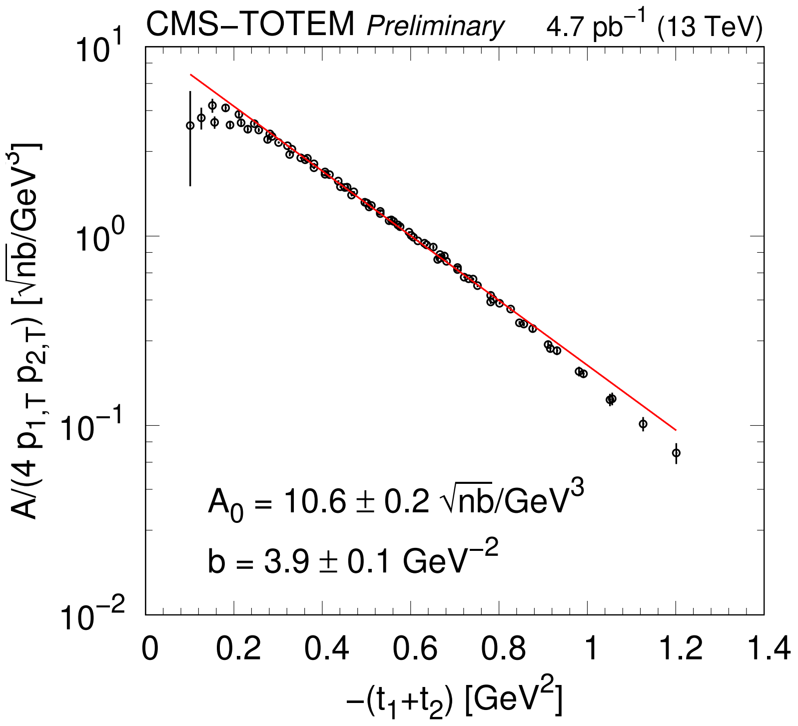
Measurements – nonresonant $\mathrm{d}^3\sigma/\mathrm{d}p_{1,T}\mathrm{d}p_{2,T}\mathrm{d}\phi$

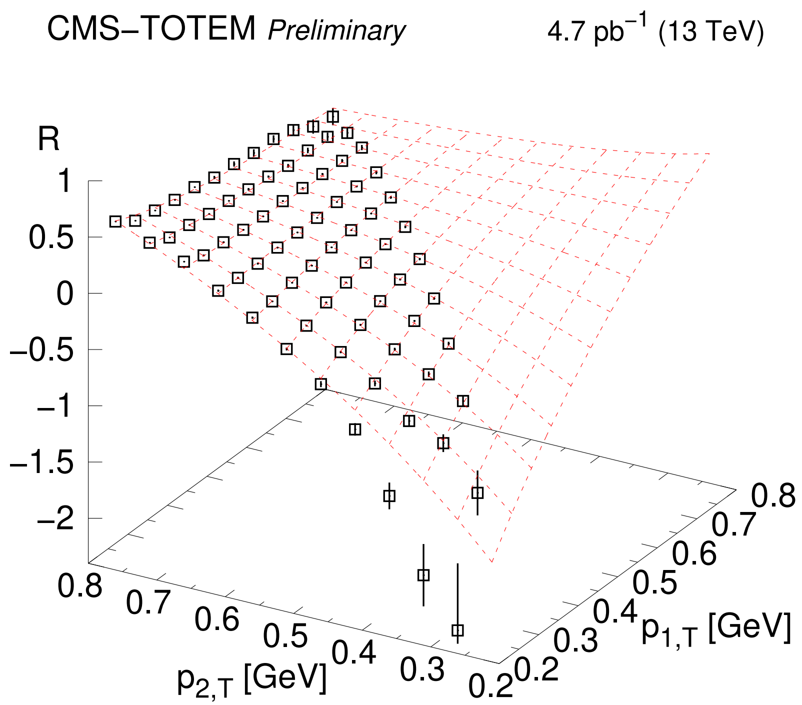


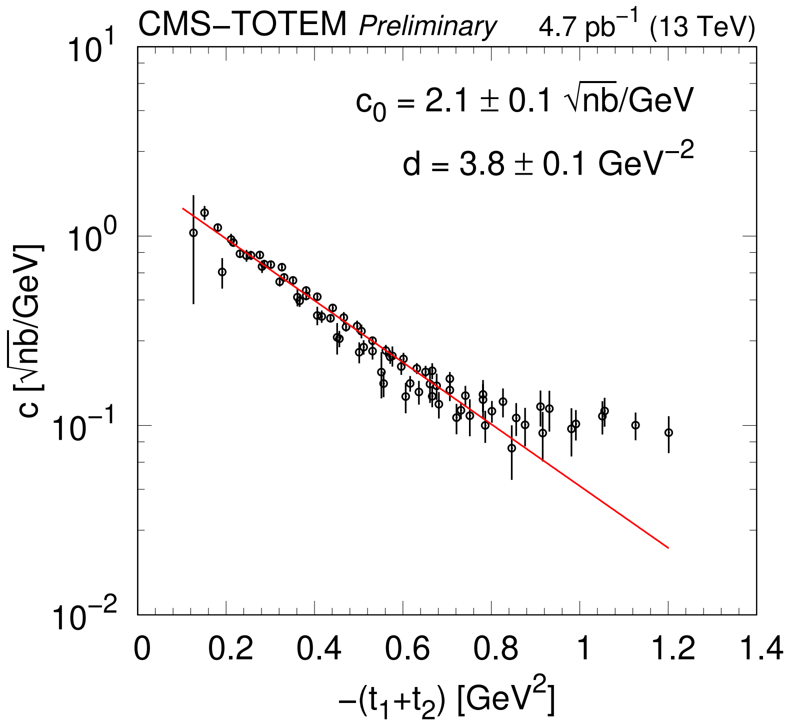
Curves of a phenomenology-motivated fits with the form $[A(R - \cos\phi)]^2 + c^2$ are plotted

(Close, Kirk, Schuler)

Parameter dependencies – A, R, c







Scaling described by theory-motivated functional forms

$$A(t_1,t_2) = 4\sqrt{t_1 t_2} \cdot A_0 e^{b(t_1+t_2)} \qquad R(t_1,t_2) \approx \frac{1.2(\sqrt{-t_1}+\sqrt{-t_2}) - 1.6\sqrt{t_1 t_2} - 0.8}{\sqrt{t_1 t_2}+0.1},$$

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

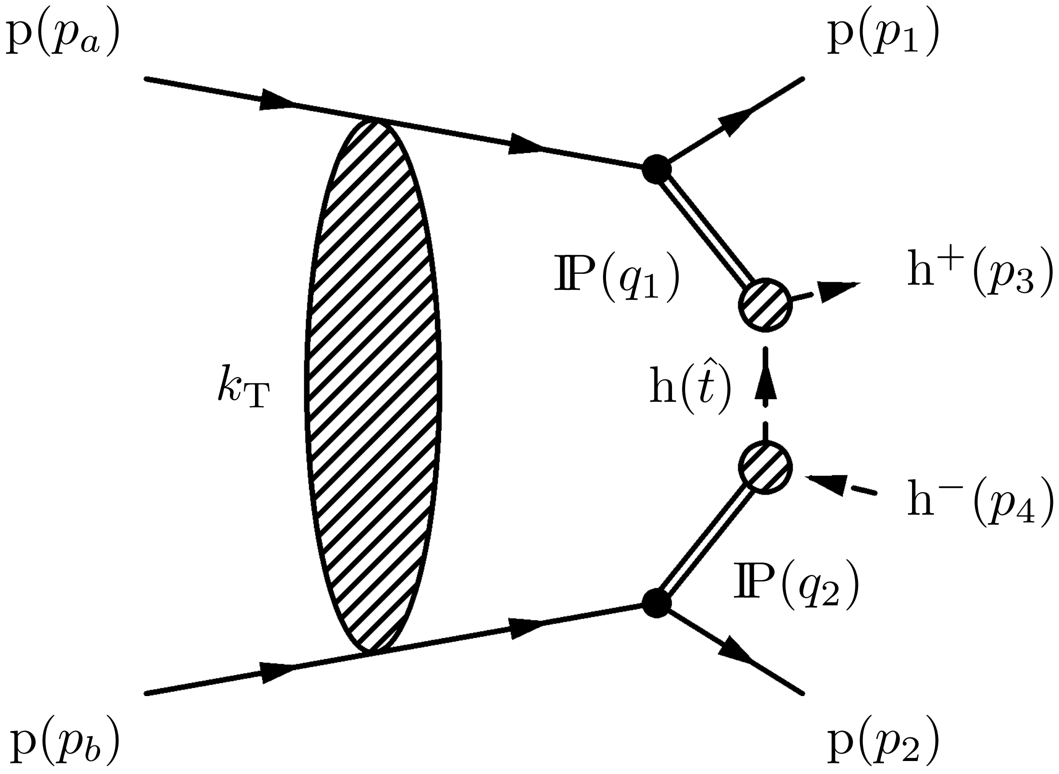
Model tuning with PROFESSOR (version 2.3.3) ⇒

Systematics

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%	

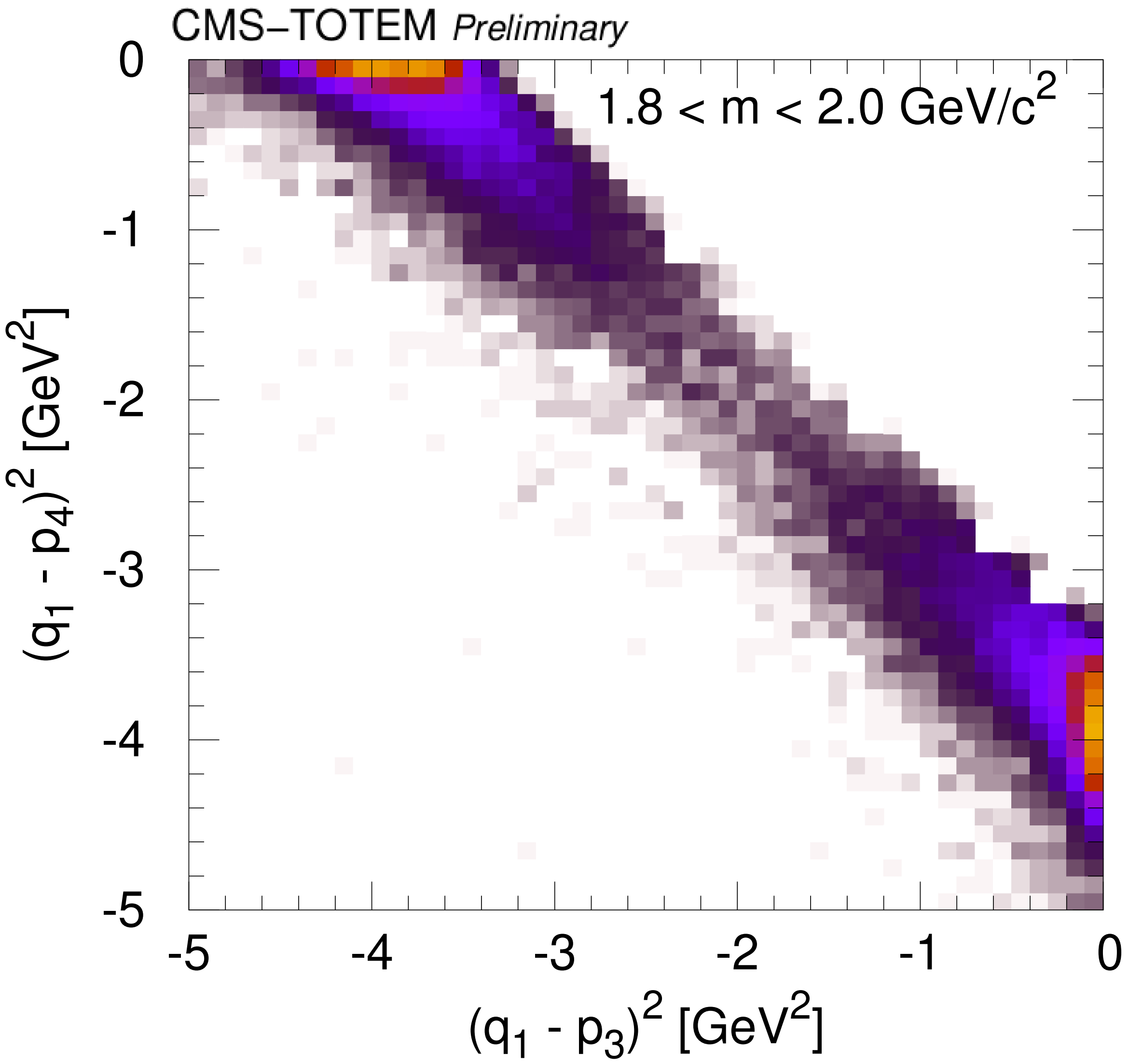
Several sources, reasonable systematics $\sim 5\%$

Virtual hadron – proof



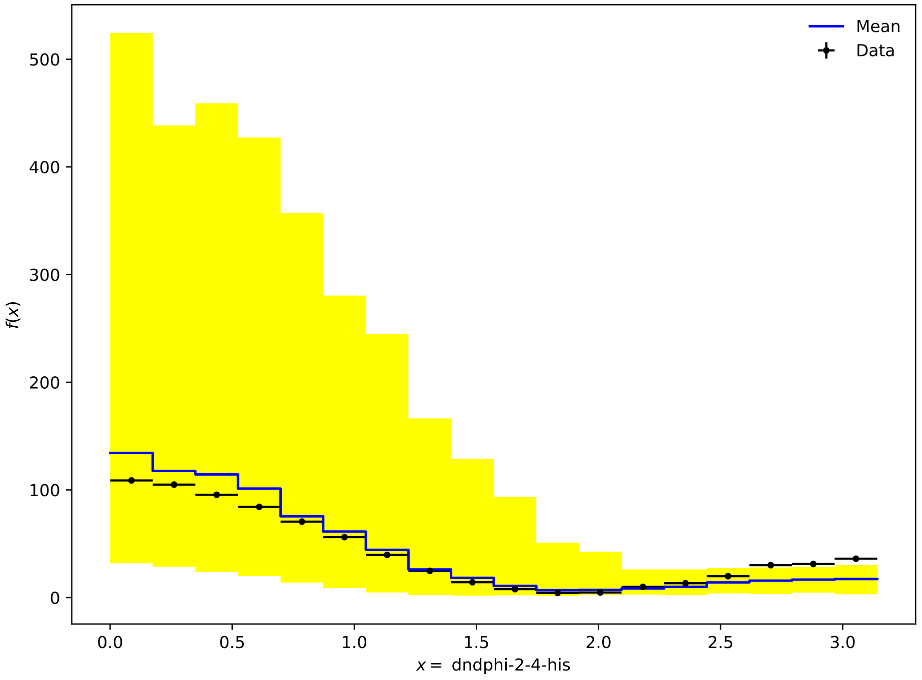
Propagator of virtual hadron:

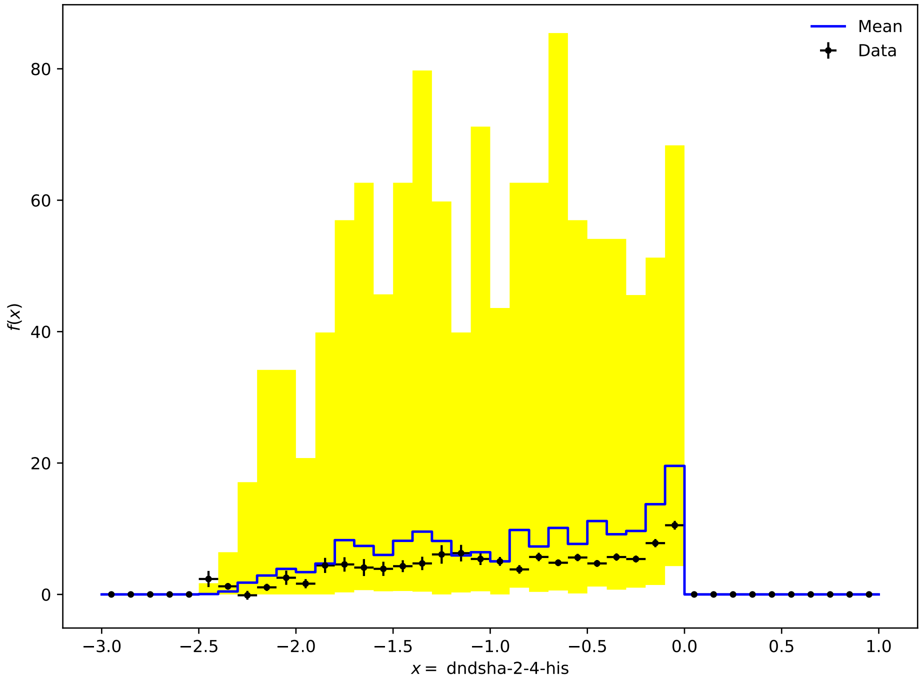
$$1/(\hat{t} - m^2)$$



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

Tuning with PROFESSOR (version 2.3.3)





- The tool, the tuning
  - parametrises the per-bin generator response to variations, numerical optimisation
  - reduces the exponentially expensive brute-force tuning to a scaling closer to a power-law
  - the parameter space is up to 12 dimensional; the envelopes well cover the data points
  - 400 generator runs are performed, each with 500 thousand generated events each

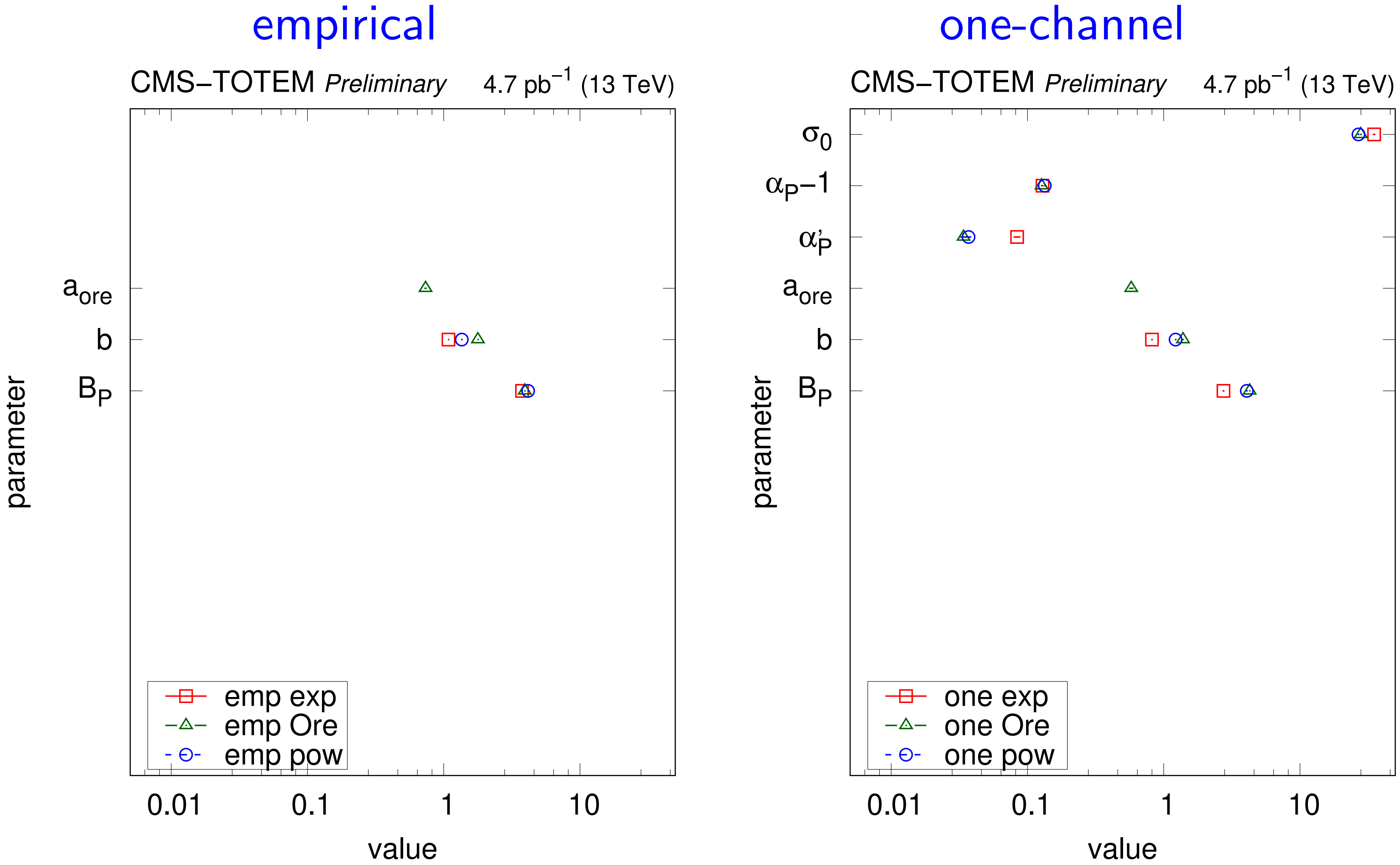
Tuned separately for different parametrisations of the $\mathbb{P}$-meson form factor

Model tuning – result

Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{\text{exp/ore/pow}}$[$\text{GeV}^{-2 \text{ or } -1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{I\!P}$ [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	—	
$b_{\text{exp/ore/pow}}$[$\text{GeV}^{-2 \text{ or } -1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{I\!P}$ [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	—	
$b_{\text{exp/ore/pow}}$[$\text{GeV}^{-2 \text{ or } -1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\lvert a\rvert^2$	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

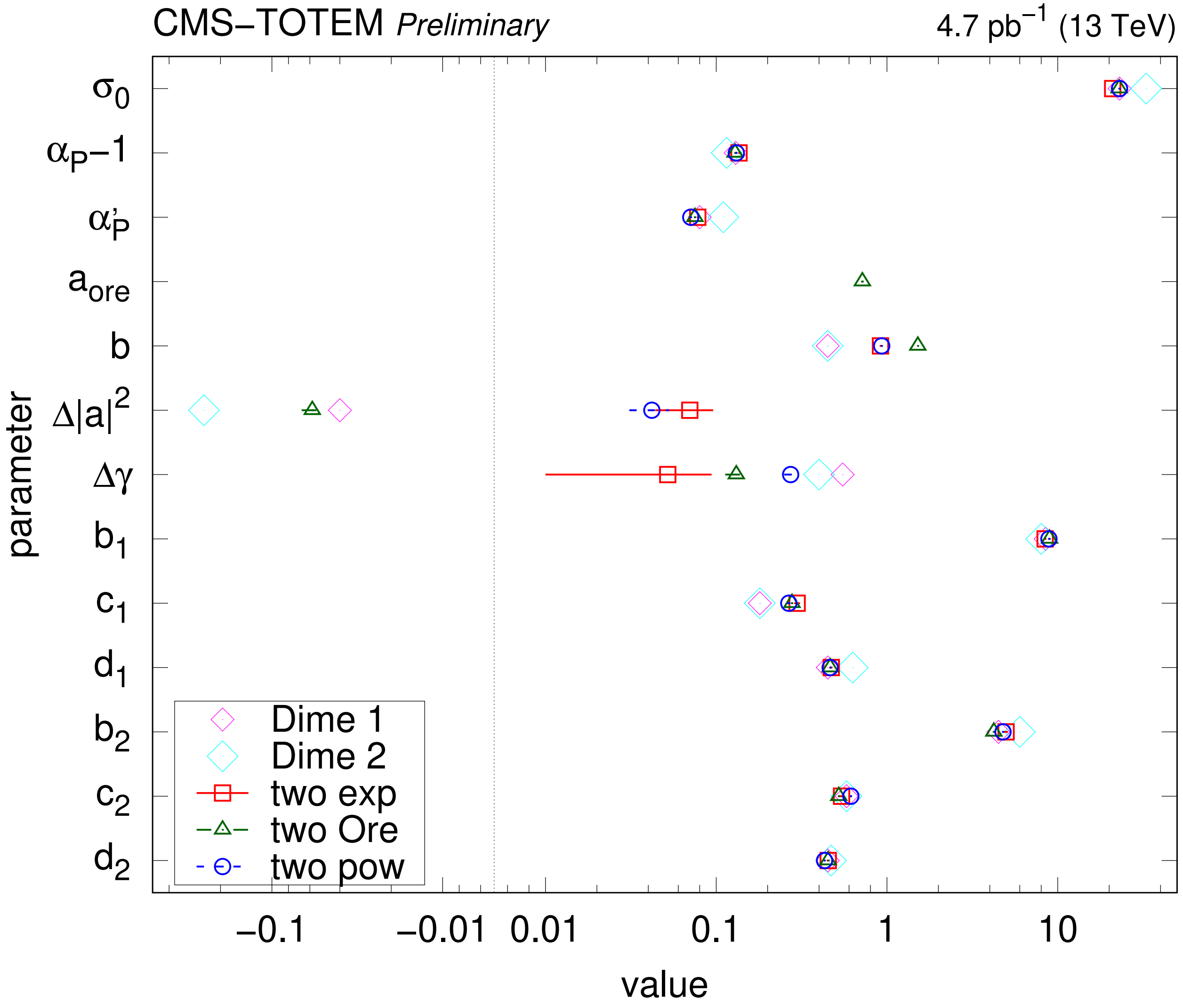
Model tuning – result



Best fit with two-channel exponential, others are also close

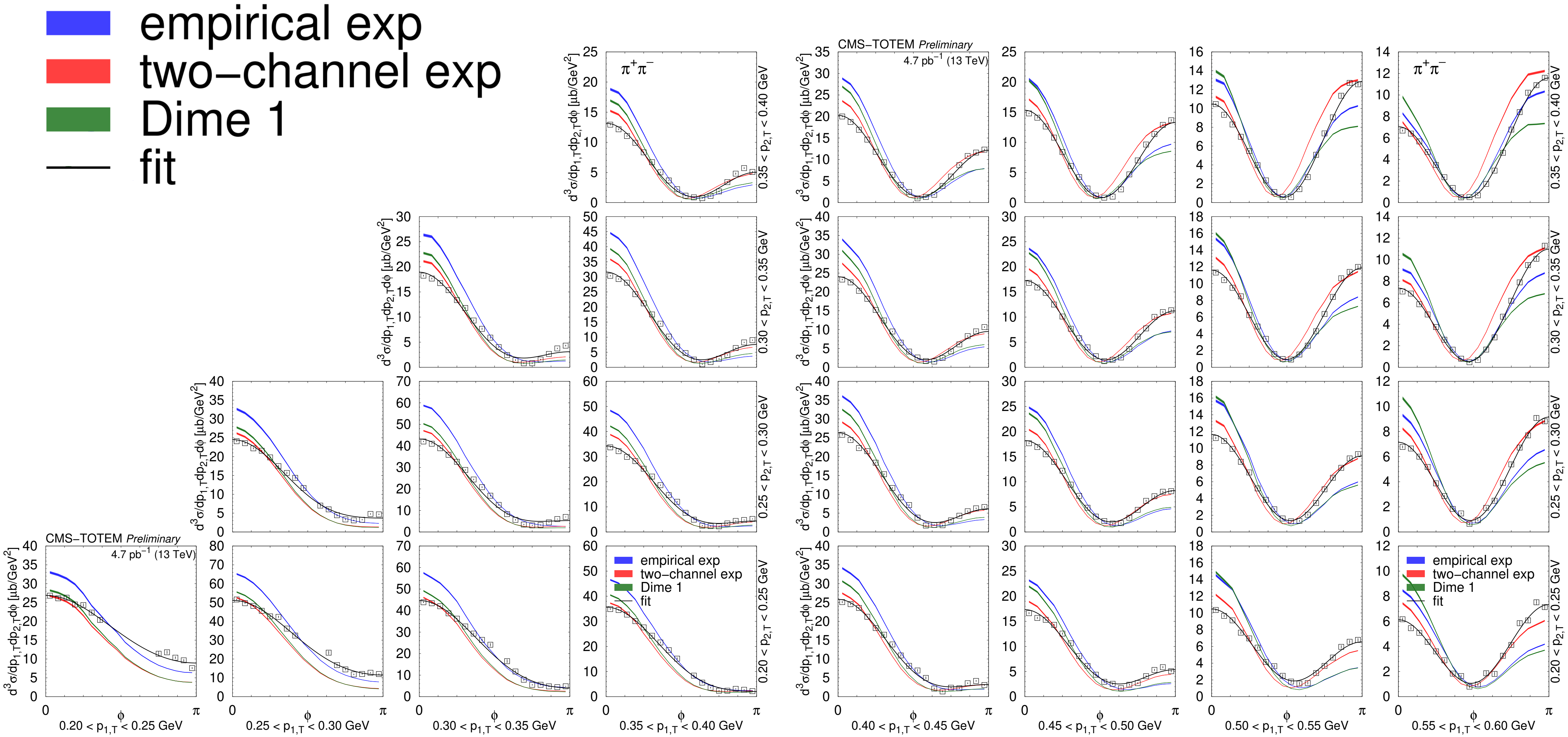
Model tuning – result

two-channel



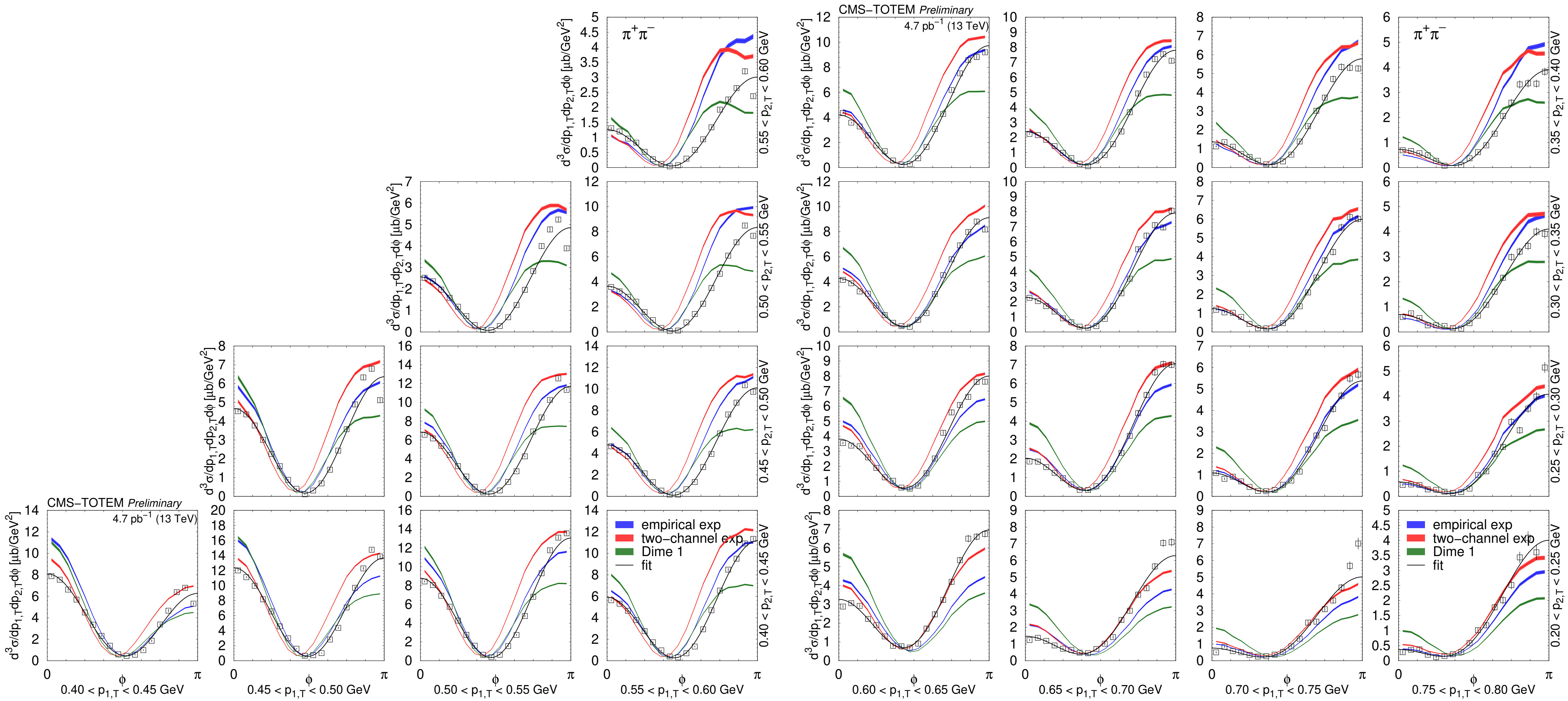
Remarkable agreement with Dime (“soft model 1”), although with unexpected eigenstate weights ($a_1 \approx a_2$) and eigenstate-pomeron coupling ($\gamma_1 \approx \gamma_2$)!

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



Good quality

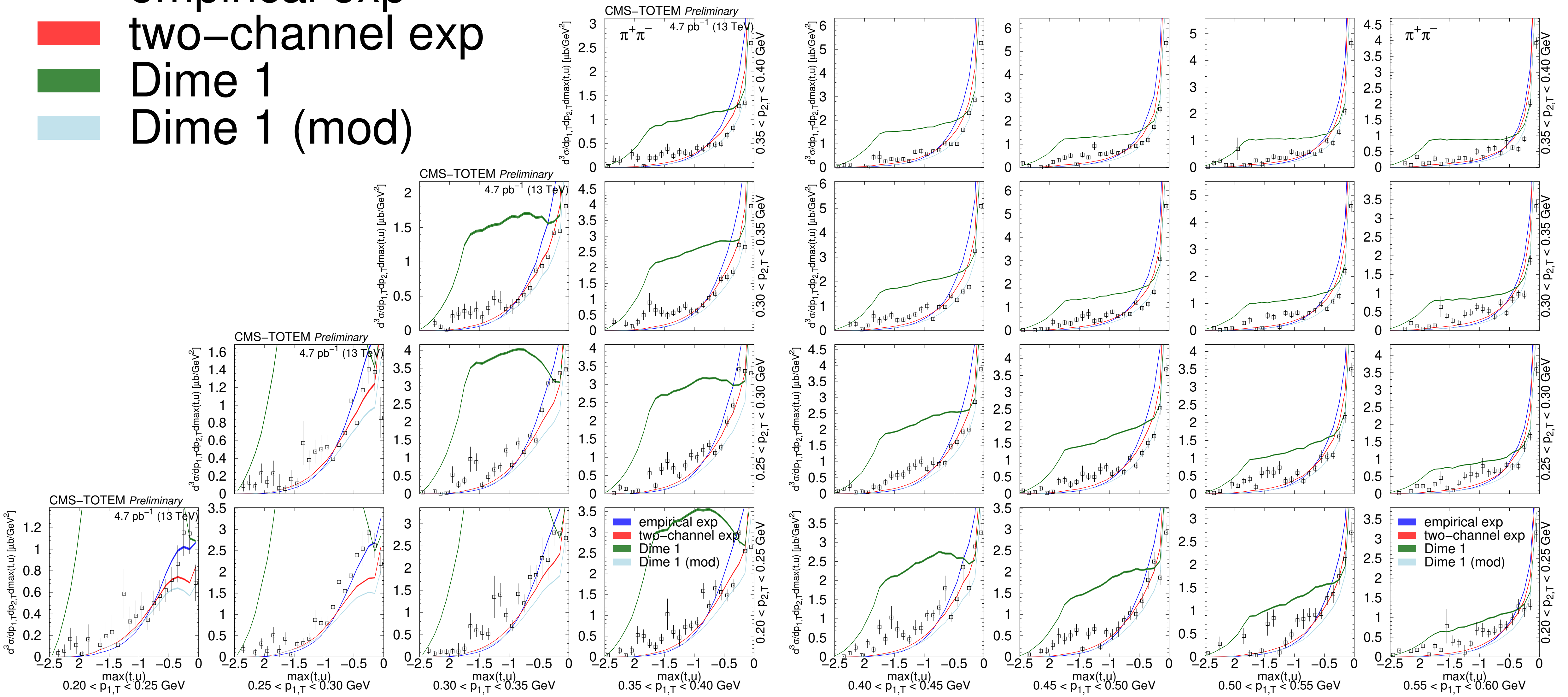
$\mathrm{d}\sigma/\mathrm{d}\phi$ – $\pi^+\pi^-$



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

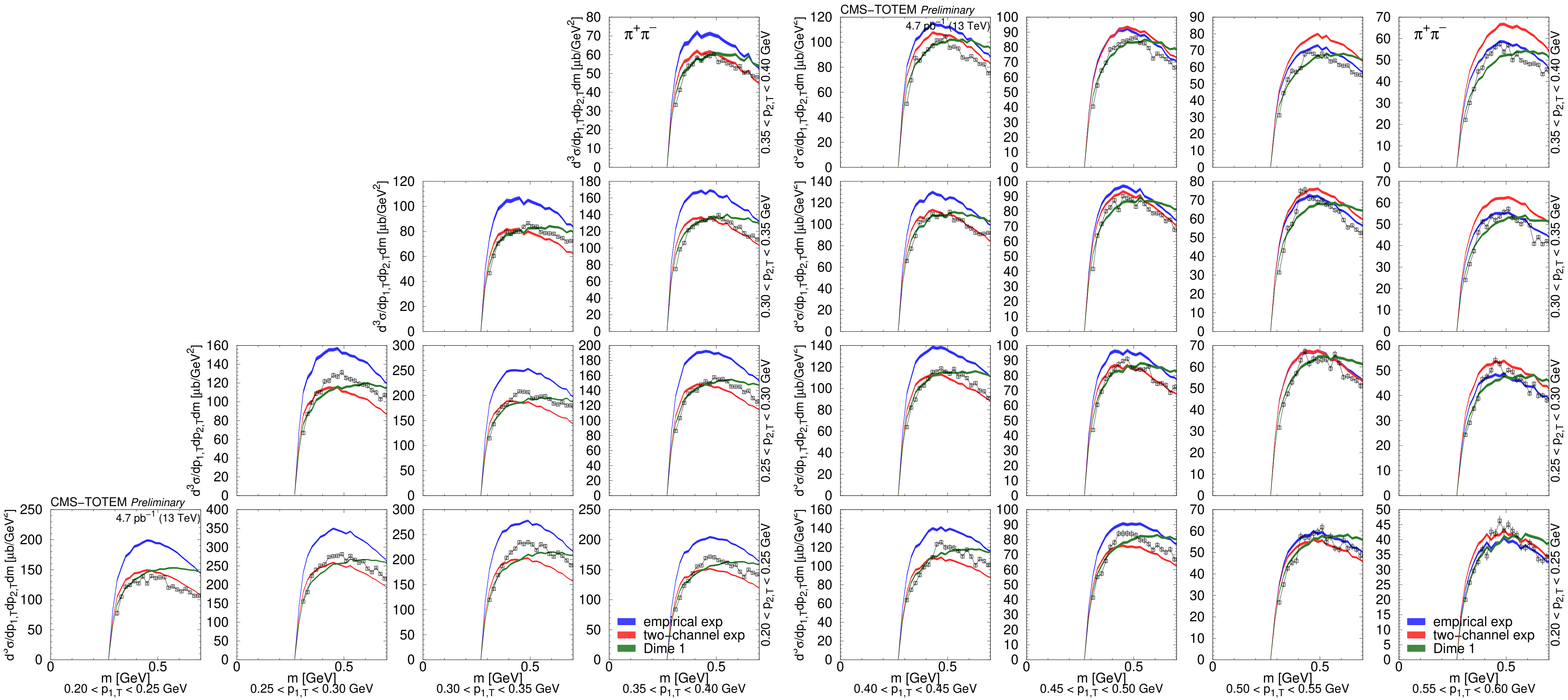
$d\sigma/d\max(\hat{t},\hat{u})\ -\ \pi^+\pi^-$

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



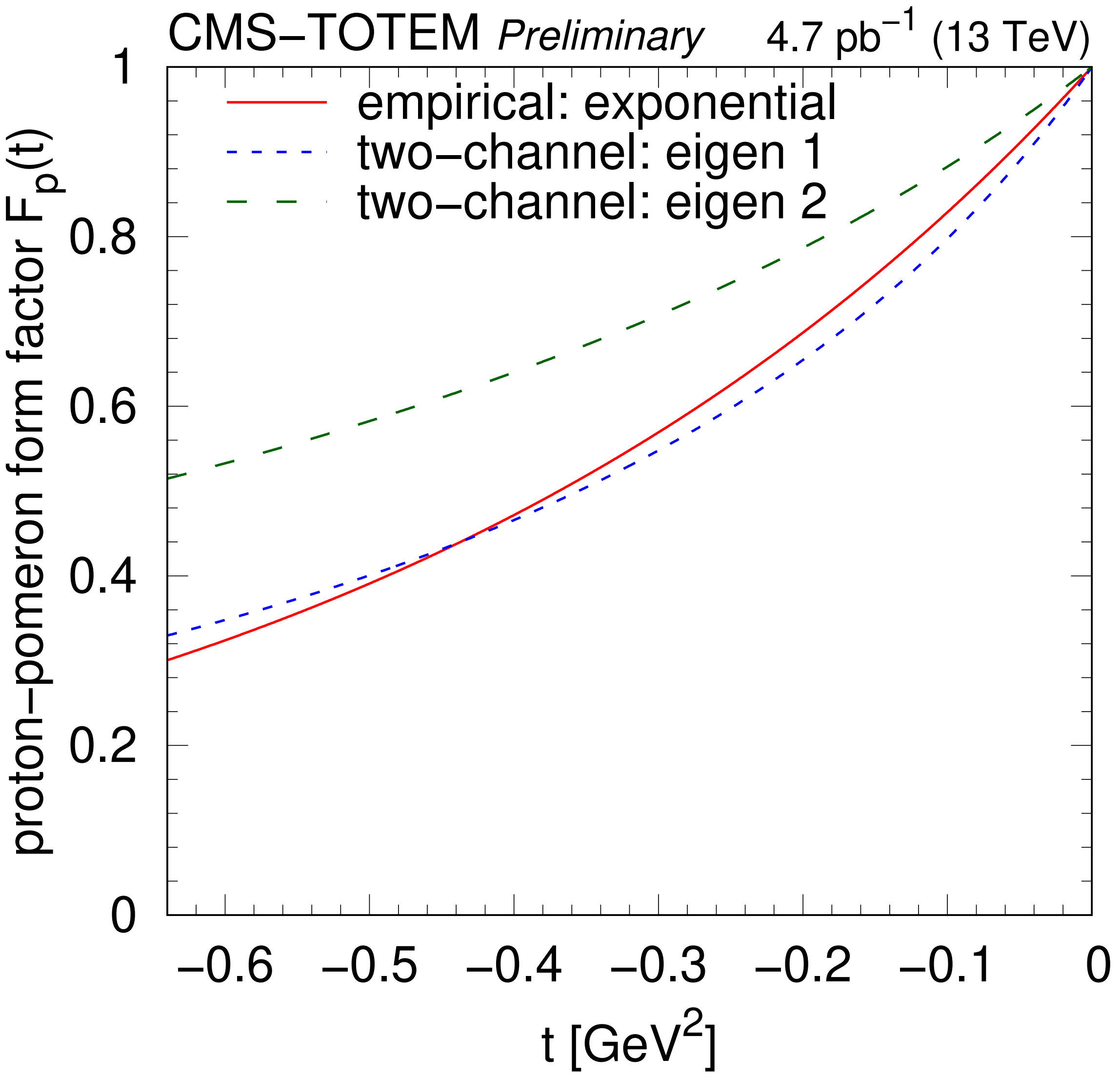
Virtual hadrons – important to fix the value of b_{exp} $(0.45 \to 0.9\,\text{GeV}^{-2})$

$d\sigma/dm$ – $\pi^+\pi^-$

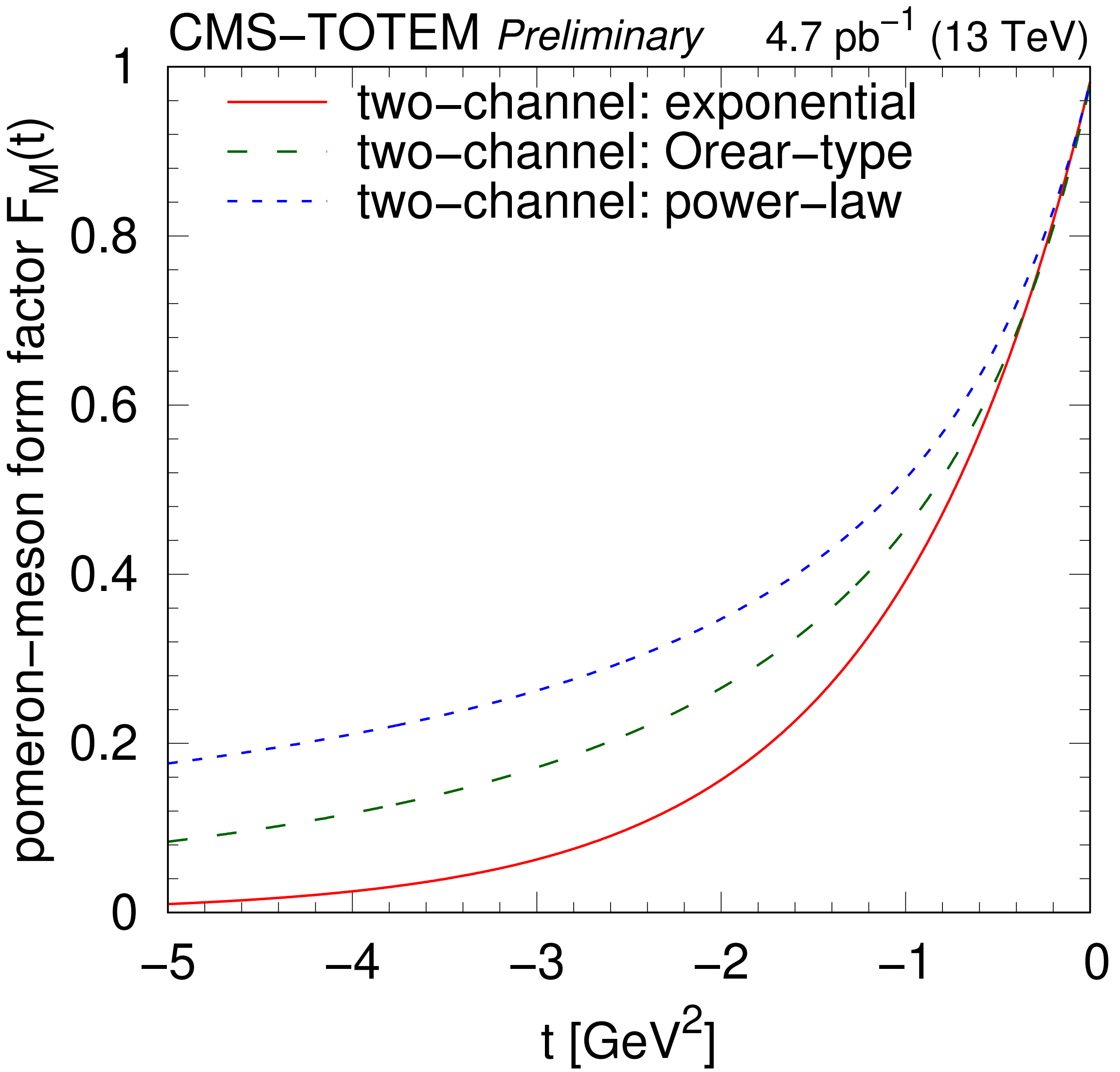


Invariant mass spectra of the central two-hadron system

Form factors – t-dependence

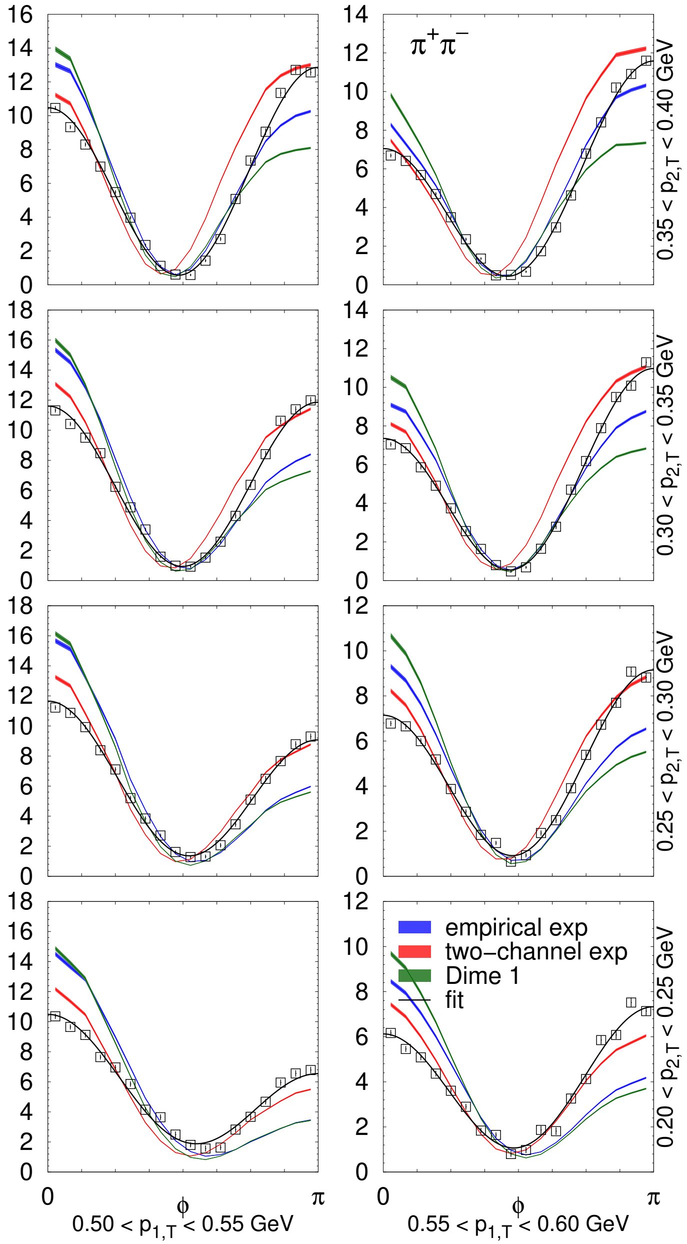


proton-pomeron



pomeron-meson

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!)