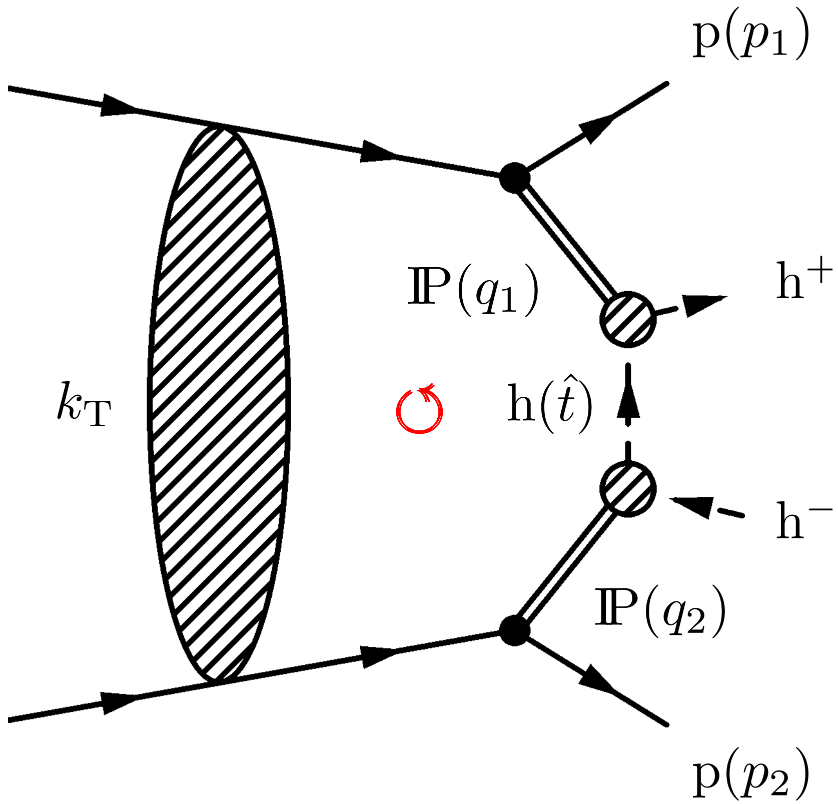


Central exclusive production (nonresonant processes)

Ferenc Siklér

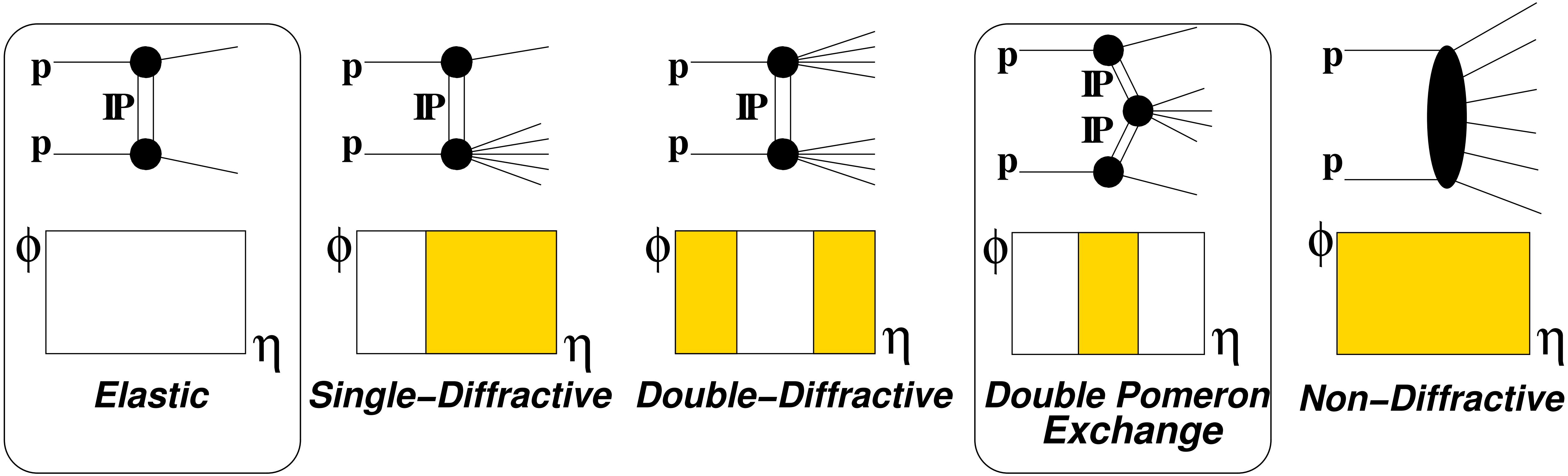
Wigner Research Centre for Physics, Budapest

for the CMS and TOTEM Collaborations

Low-x 2023, Leros, Greece

September 4, 2023

Proton-proton collisions

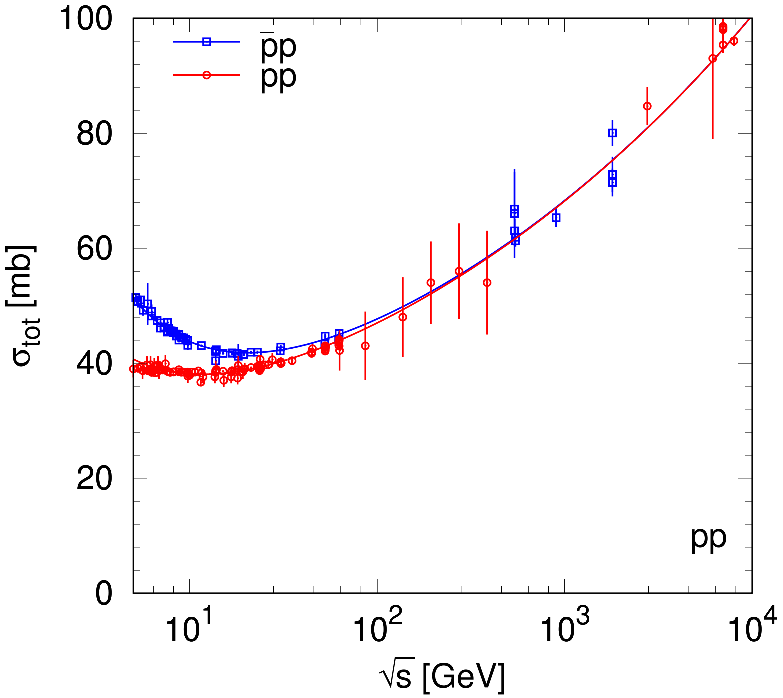


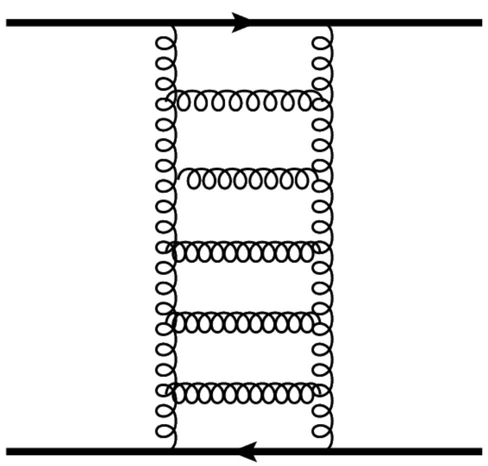
- Types
  - elastic: no additional particles
  - diffractive: one or both protons are excited and dissociate
  - what is the exchanged particle? actually, is it a particle?

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

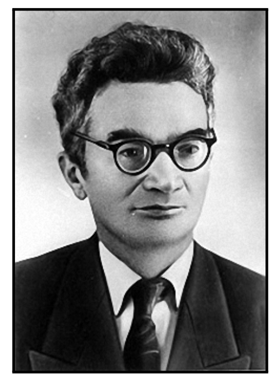
Physics Analysis Summary at: https://cds.cern.ch/record/2867988

Pomeron ($\mathbb{P}$)



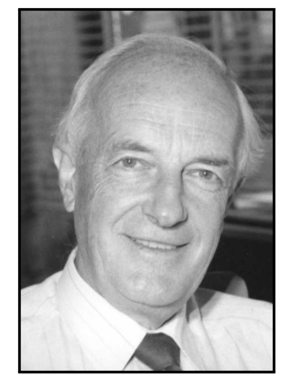


- Problems
  - the pp and $\bar{p}p$ cross sections are similar
  - they keep rising; exchange?
  - force carrier must have zero charges
  - gluon ladder? nonperturbative

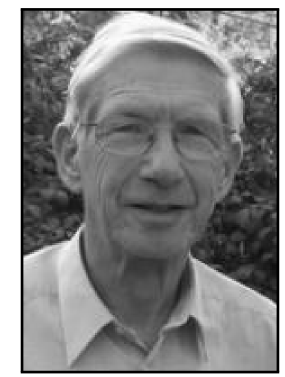


Isaak Pomeranchuk

Vladimir Gribov



Sandy Donnachie

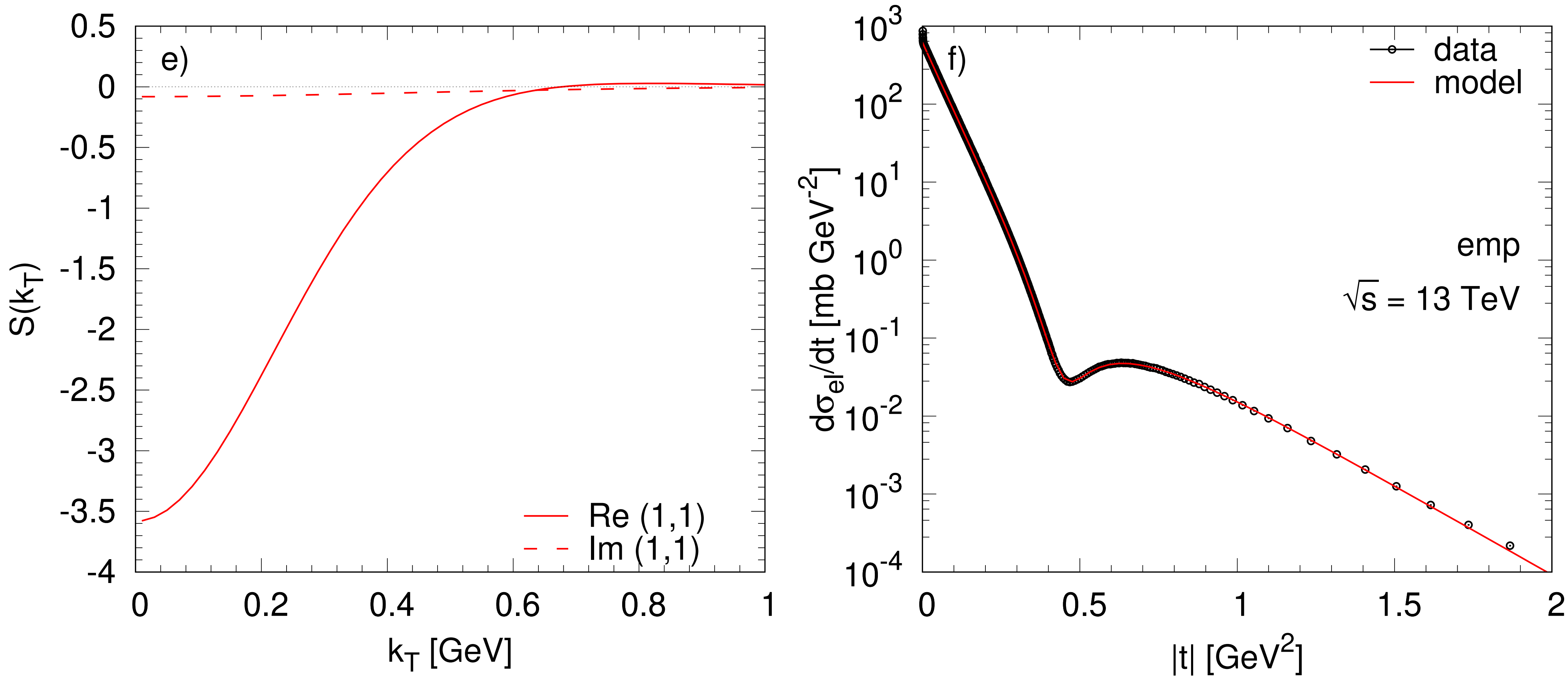


Peter Landshoff

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

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

Theory – elastic differential cross section



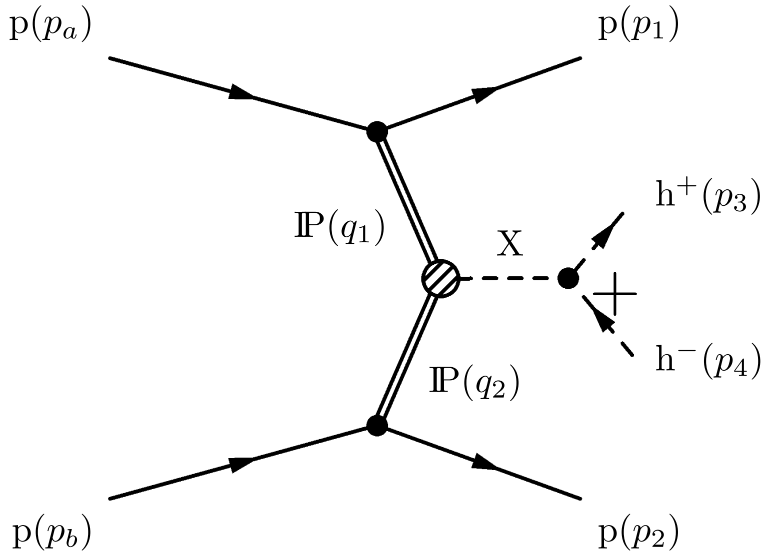
TOTEM Coll., EPJC **79** (2019) 785 and 861
Fagundes et al, PRD **88** (2013) 094019

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

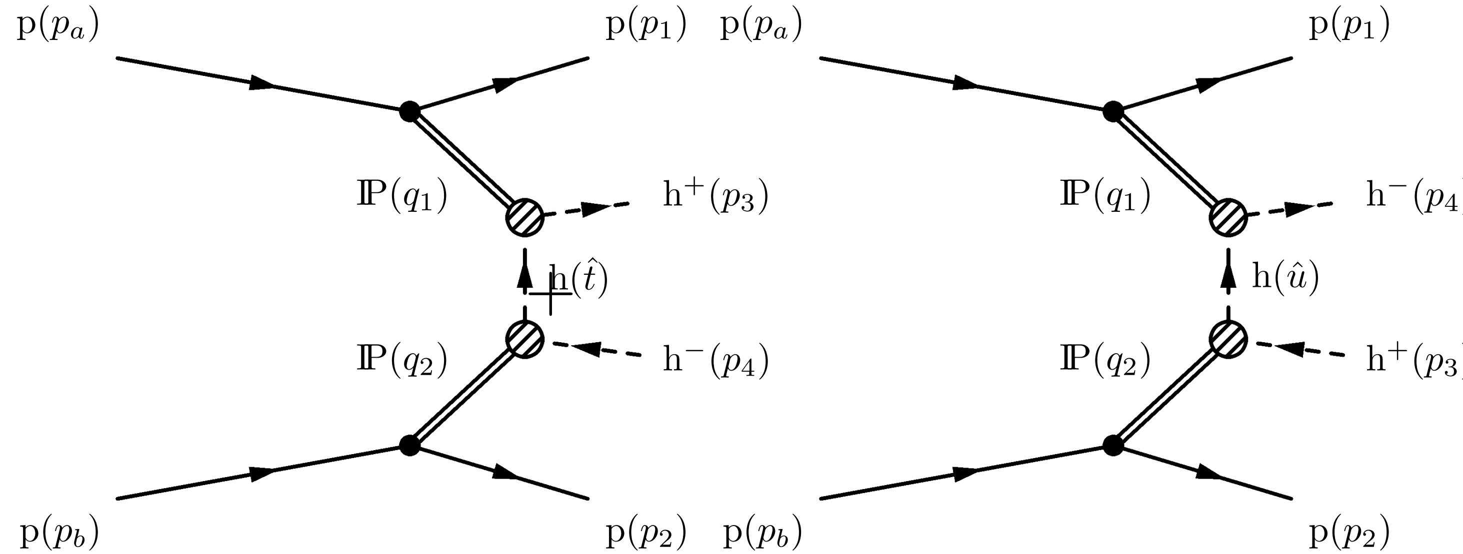
Empirical parametrisation of TOTEM data (Phillips-Barger model)

Theory – resonances vs background

resonant



nonresonant continuum



- Nonresonant continuum

  The matrix element for the nonresonant continuum process is

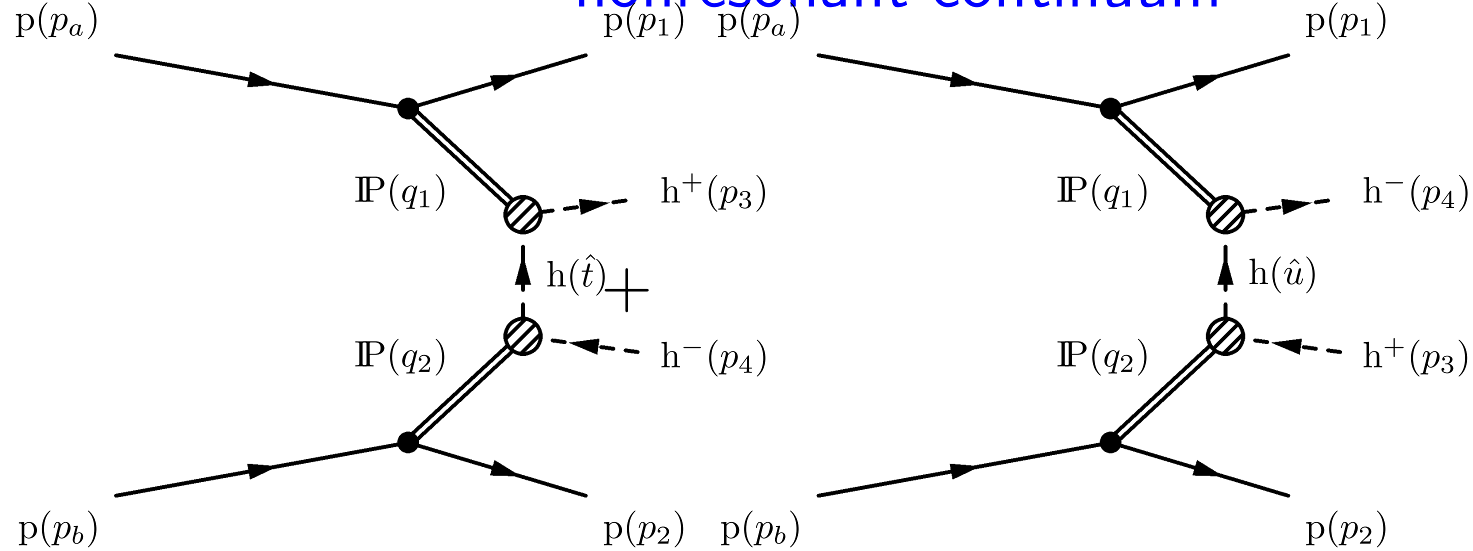
  $$\mathcal{M} = M_{13}(t_1, s_{13})\frac{F_m^2(\hat{t})}{\hat{t}-m^2}M_{24}(t_2, s_{24}) + M_{14}(t_1, s_{14})\frac{F_m^2(\hat{u})}{\hat{u}-m^2}M_{23}(t_2, s_{23})$$

  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



- Nonresonant continuum

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

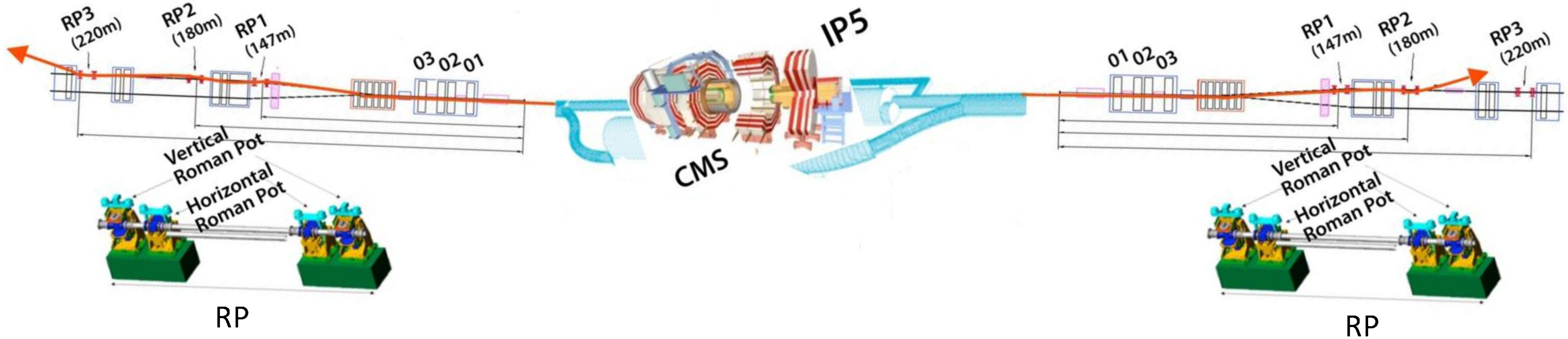
  $$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} \exp\left(\frac{B_{\mathbb{P}}}{2} t_i\right)$$

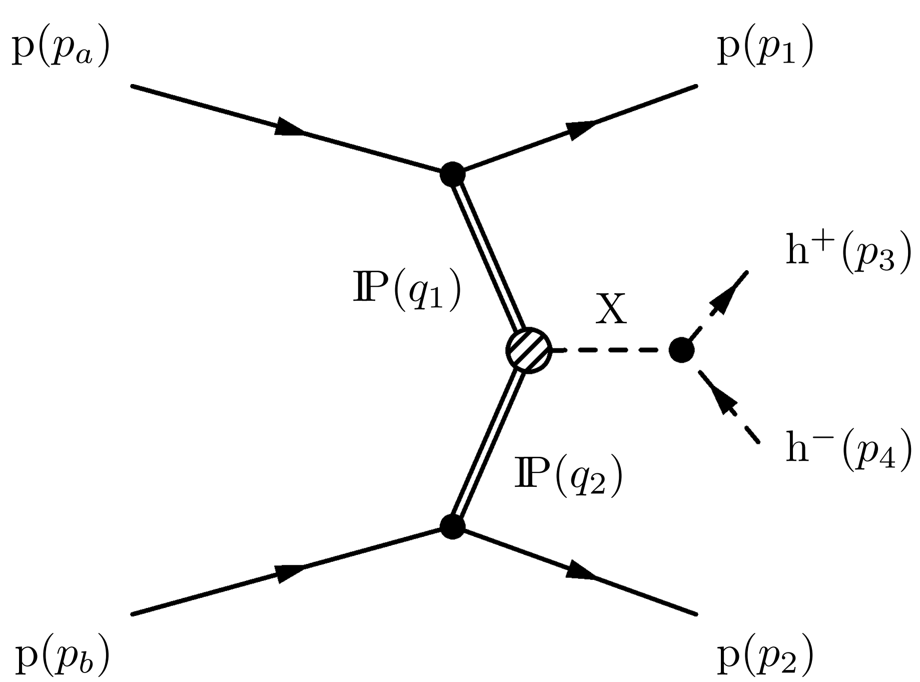
  Taking into account the reggeon exchange as well

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

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

Central exclusive production – data

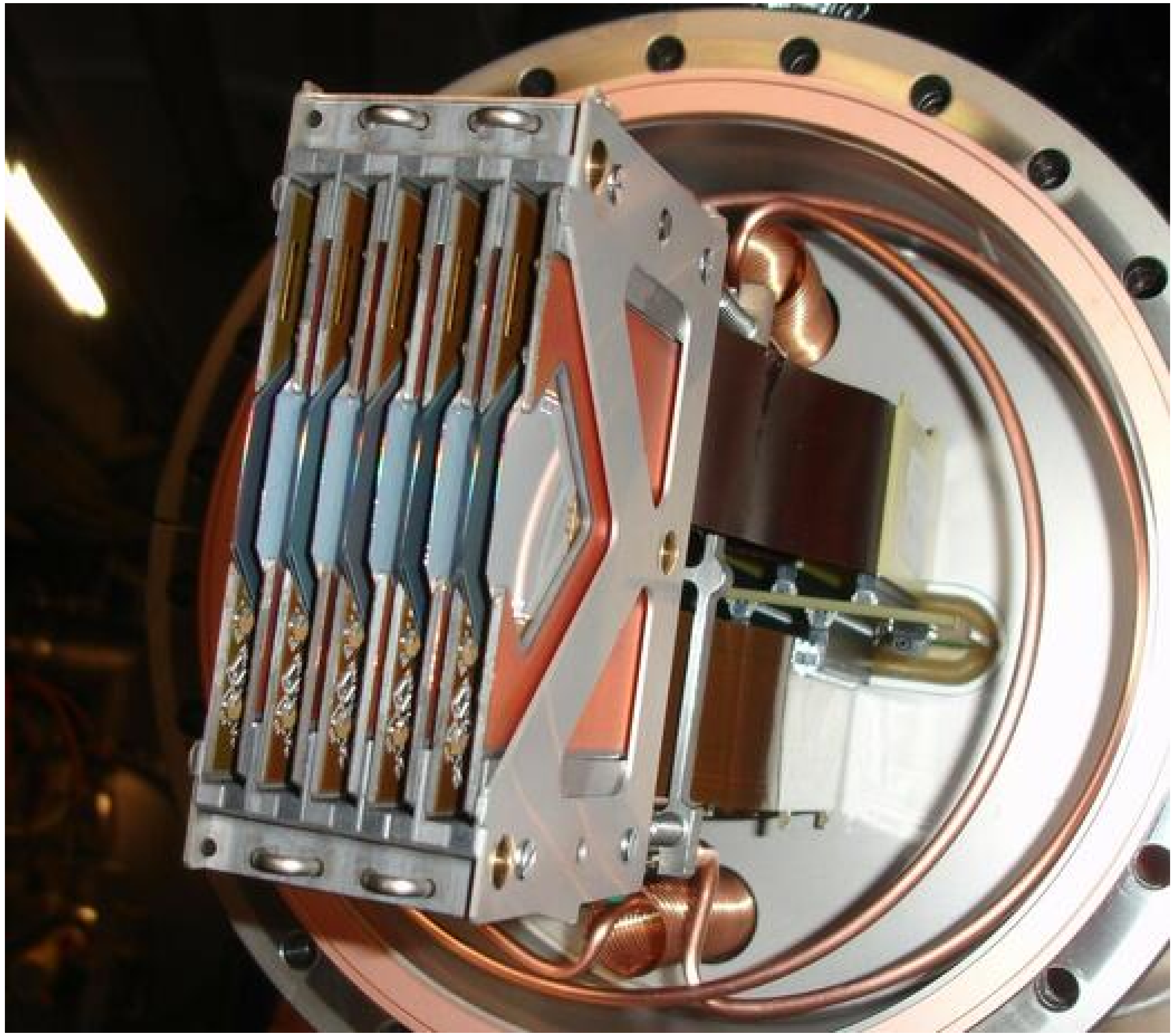




- CMS+TOTEM dataset ($\beta^* = 90$ m, 2018)
  - about 80 M events with **two scattered protons** and only **two reconstructed central tracks**
  - part of those is double pomeron exchange (DPE), where a central system (X) was created
  - decayed to particle-antiparticle pair $\mathrm{h^+h^-}$, mostly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

$\mathbb{PP}$ collider $\rightarrow$ gluon-rich initial state

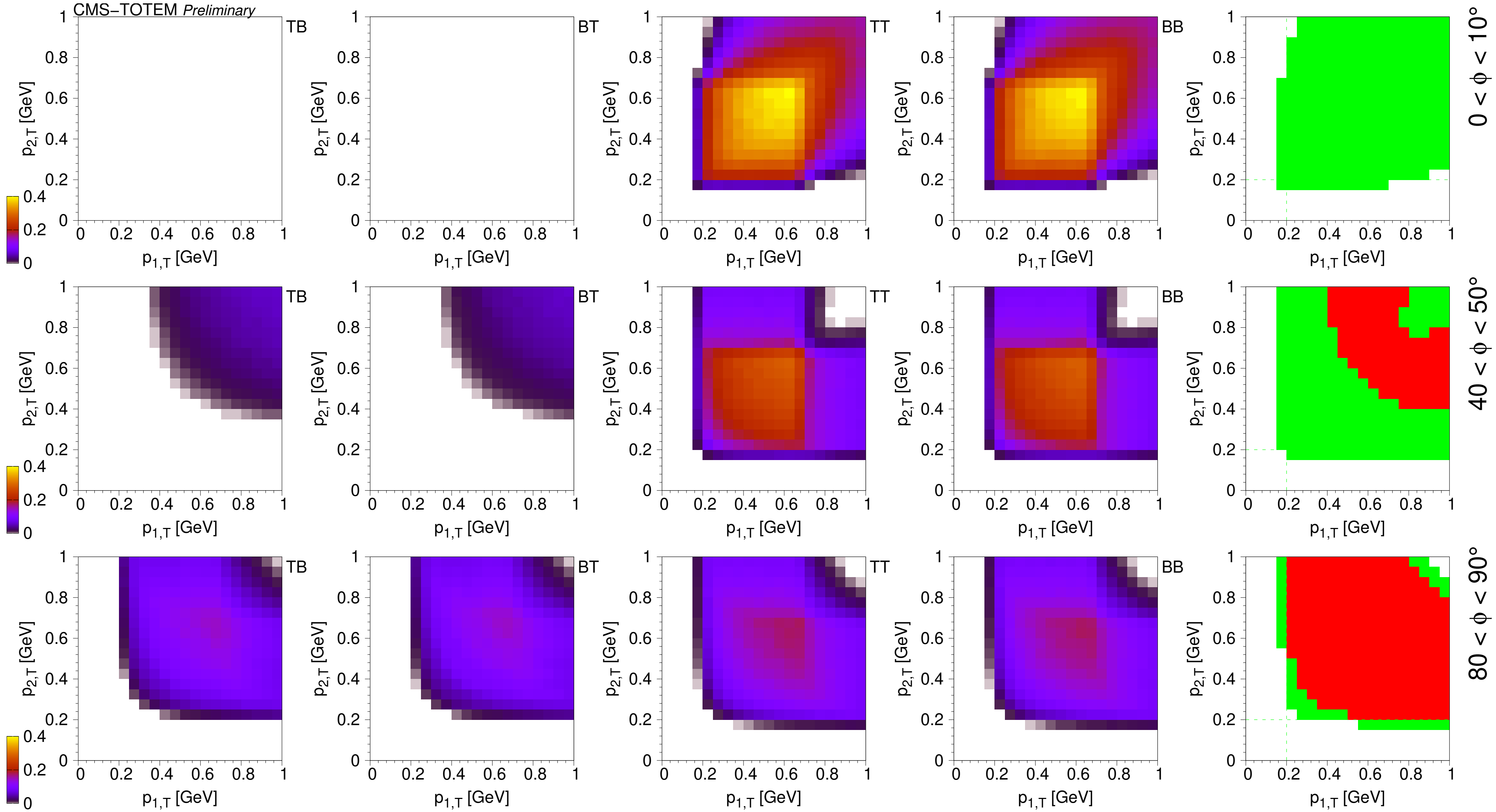
Scattered protons – roman pots



- 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

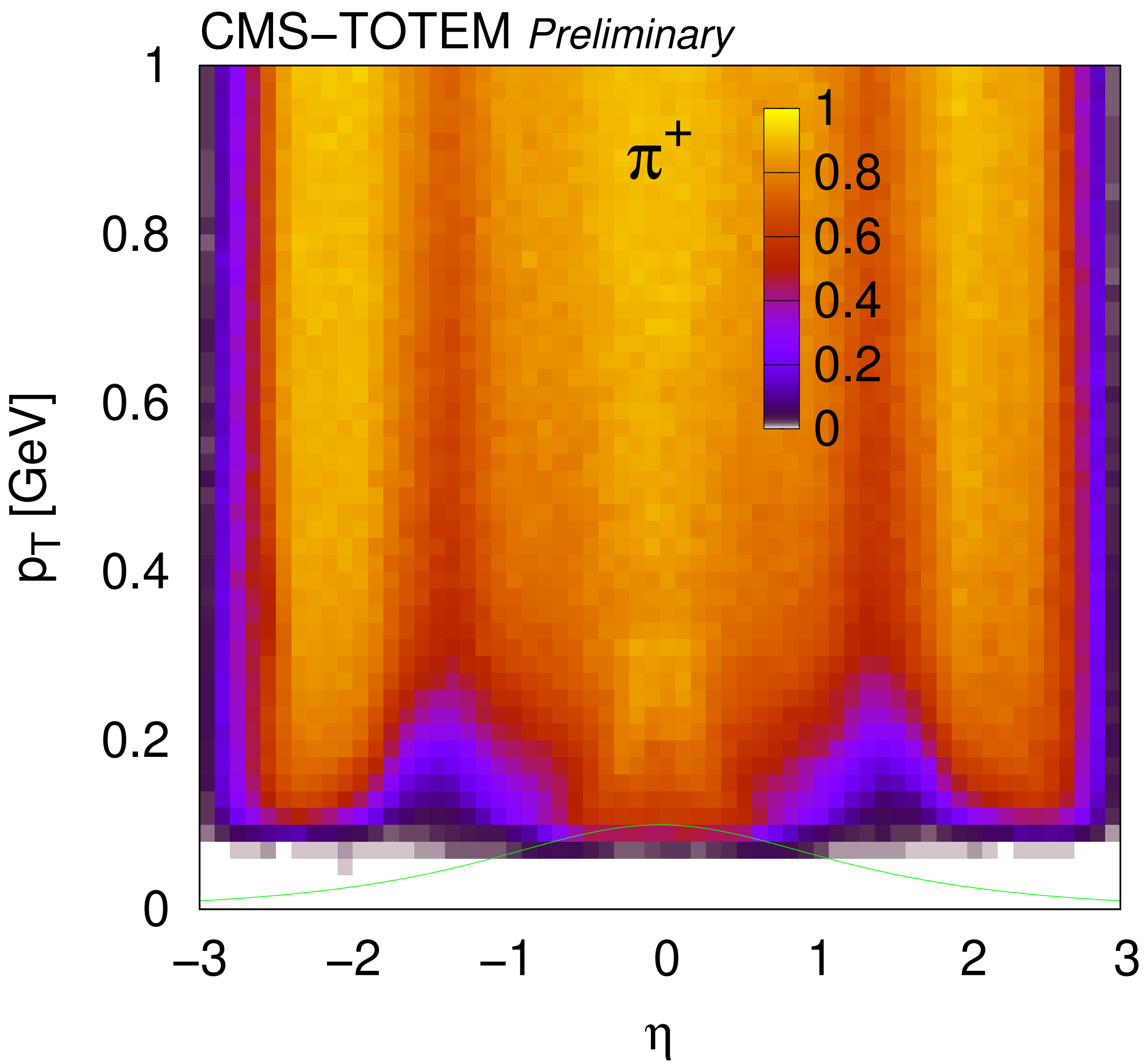
Novel tracklet fits, relative alignment of planes, strip-level efficiencies

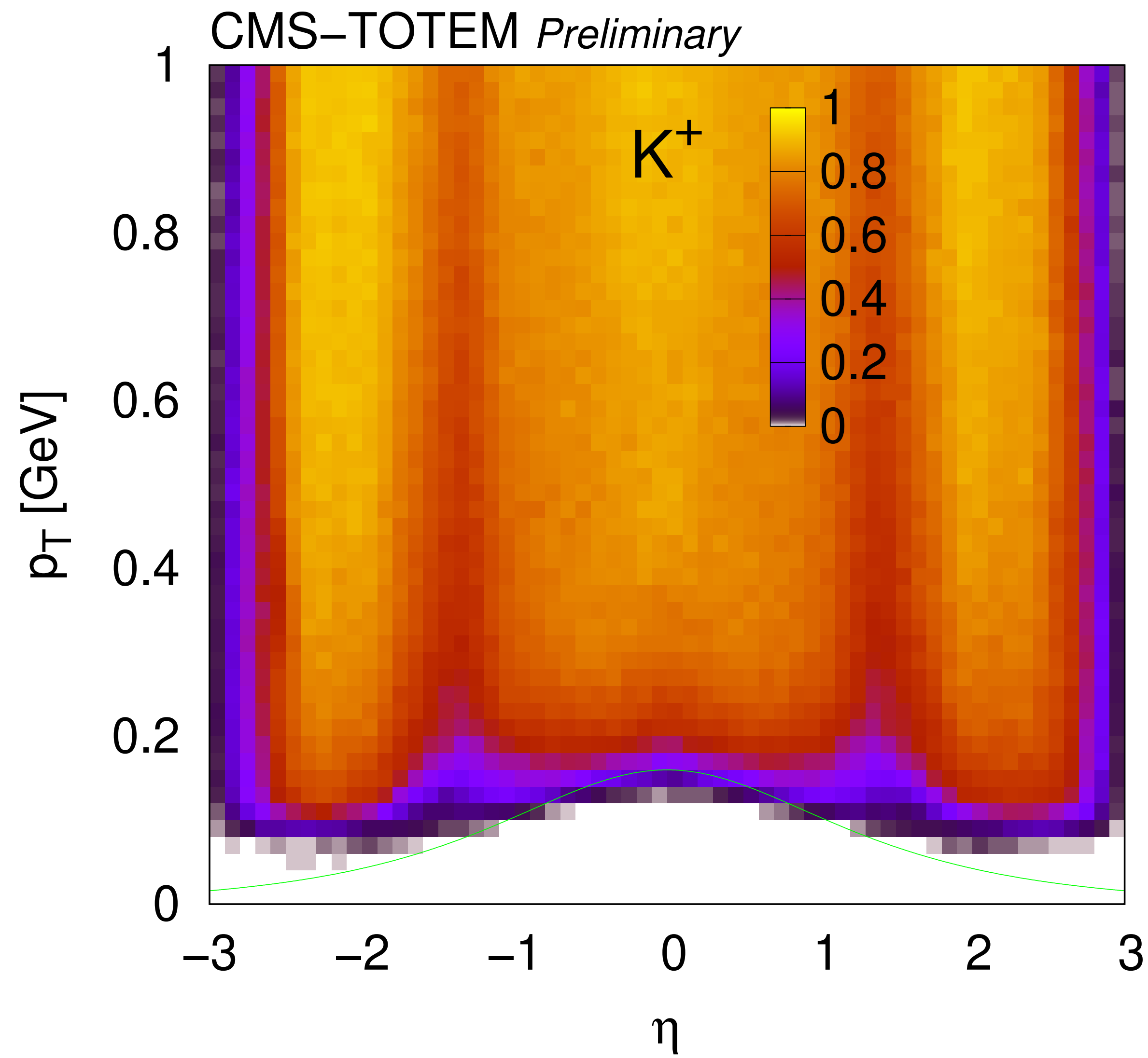
Roman pots – proton-pair acceptance and coverage vs ϕ



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

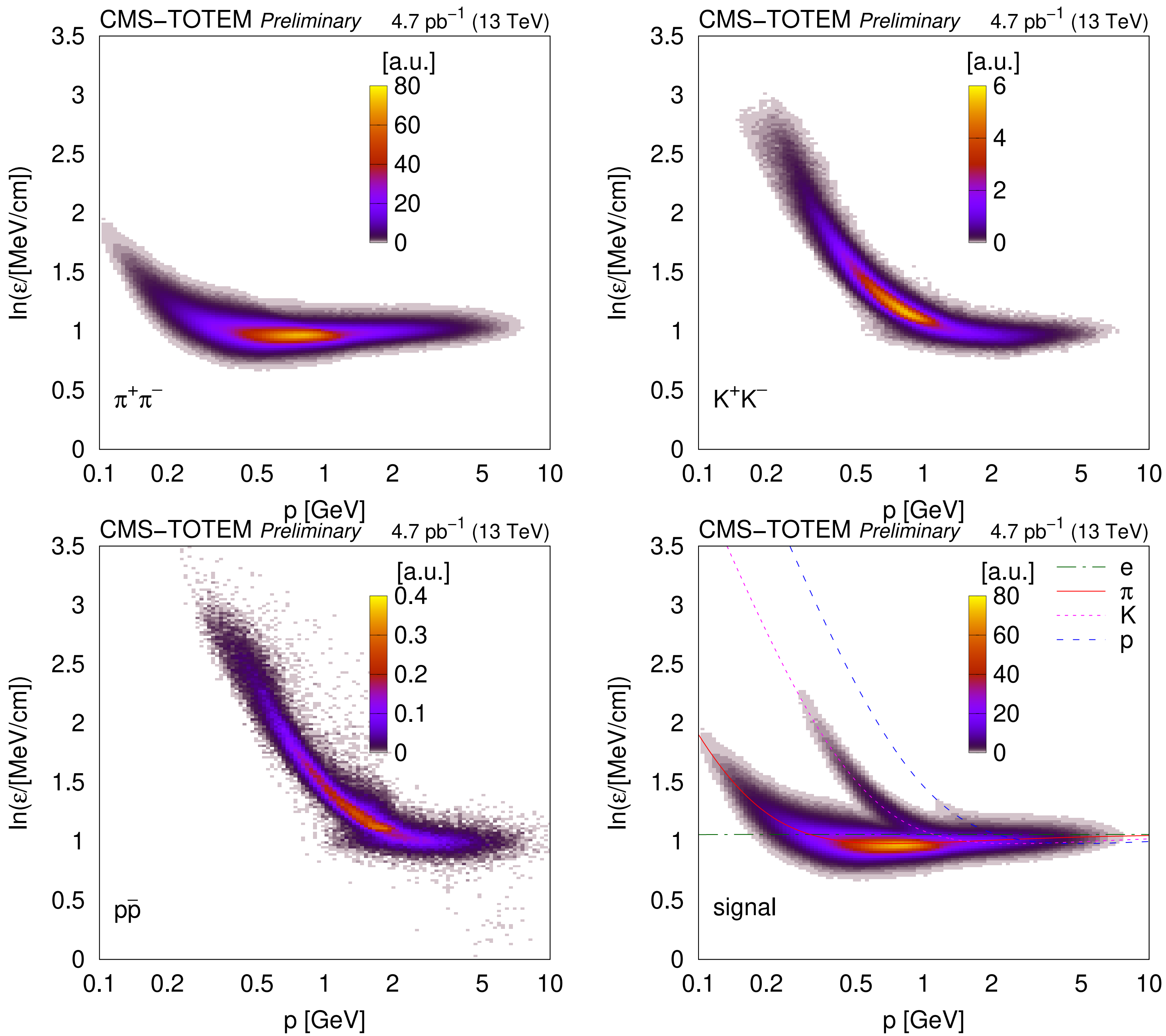




At least 5 pixel clusters and at least 3 layers in barrel pixel, or at least one pixel track

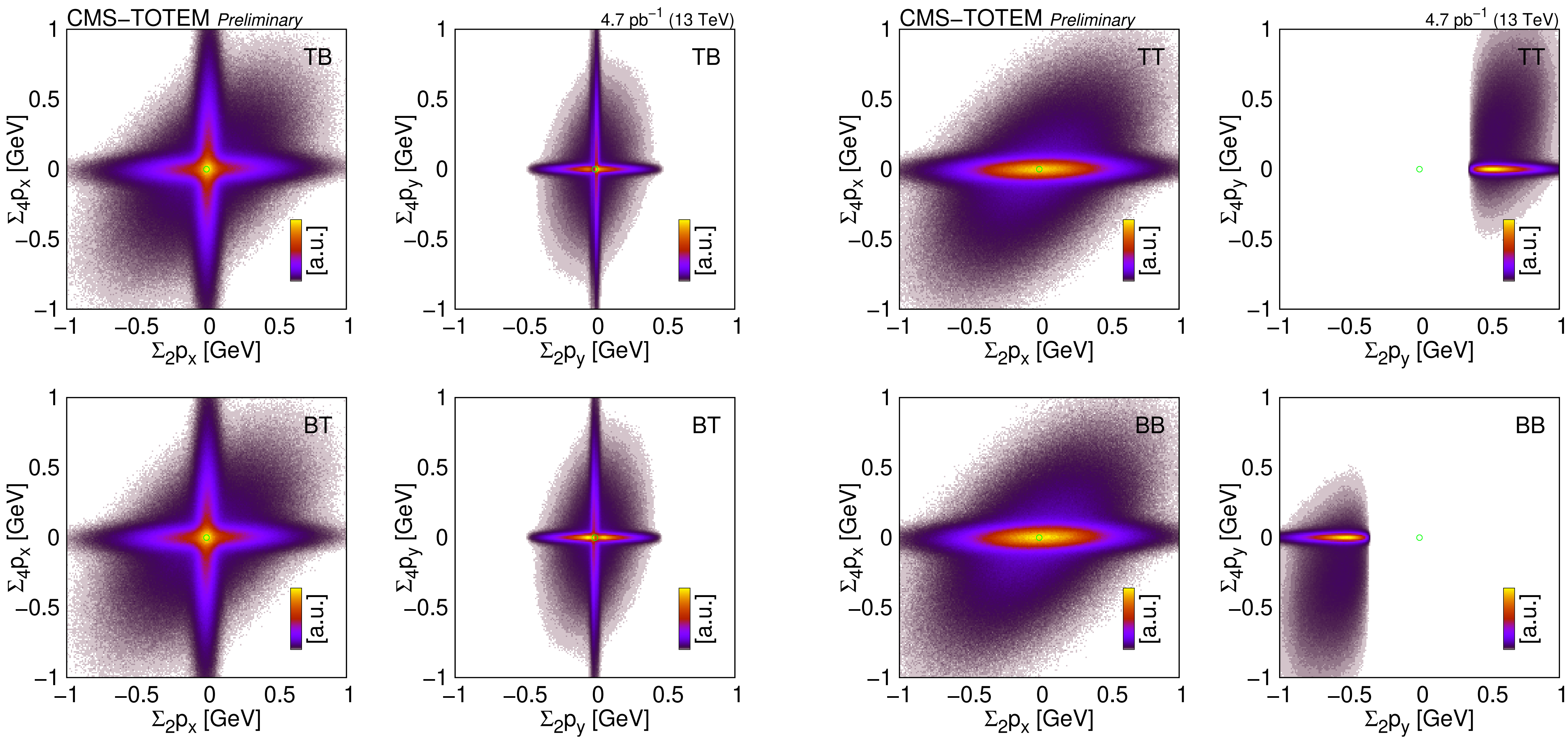
Inefficiencies, valleys to be corrected

Central hadrons – particle identification through dE/dx



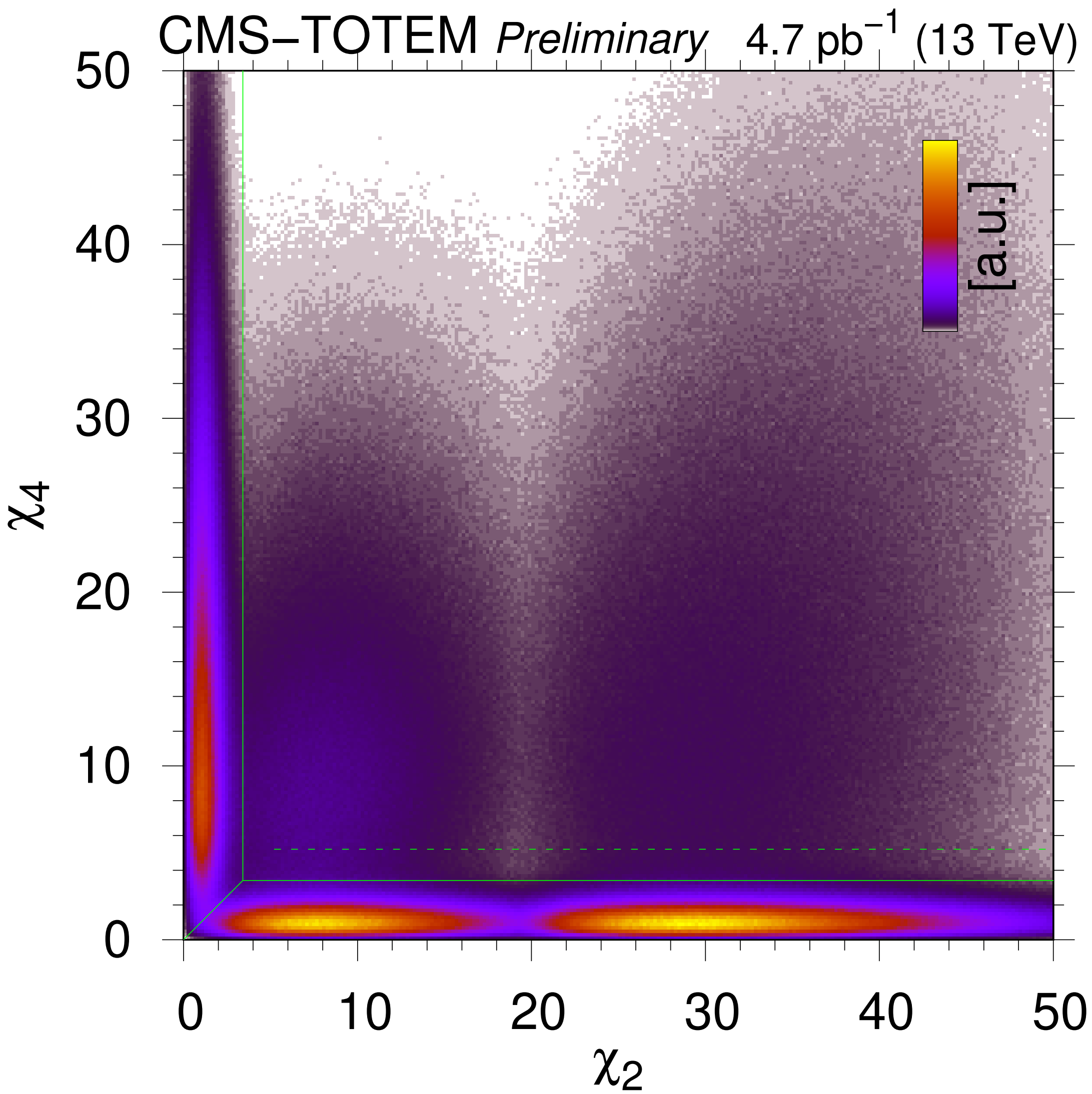
- Particle pair
  - identified as type $\mathrm{h}^+\mathrm{h}^-$ if $P_{1,\mathrm{h}}P_{2,\mathrm{h}} > 10 \cdot P_{1,i}P_{2,i}$ for all $i \neq h$
- Proof of exclusivity
  - $\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$, and $\mathrm{p}\bar{\mathrm{p}}$ pairs
  - conservation laws at work: charge, strangeness,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

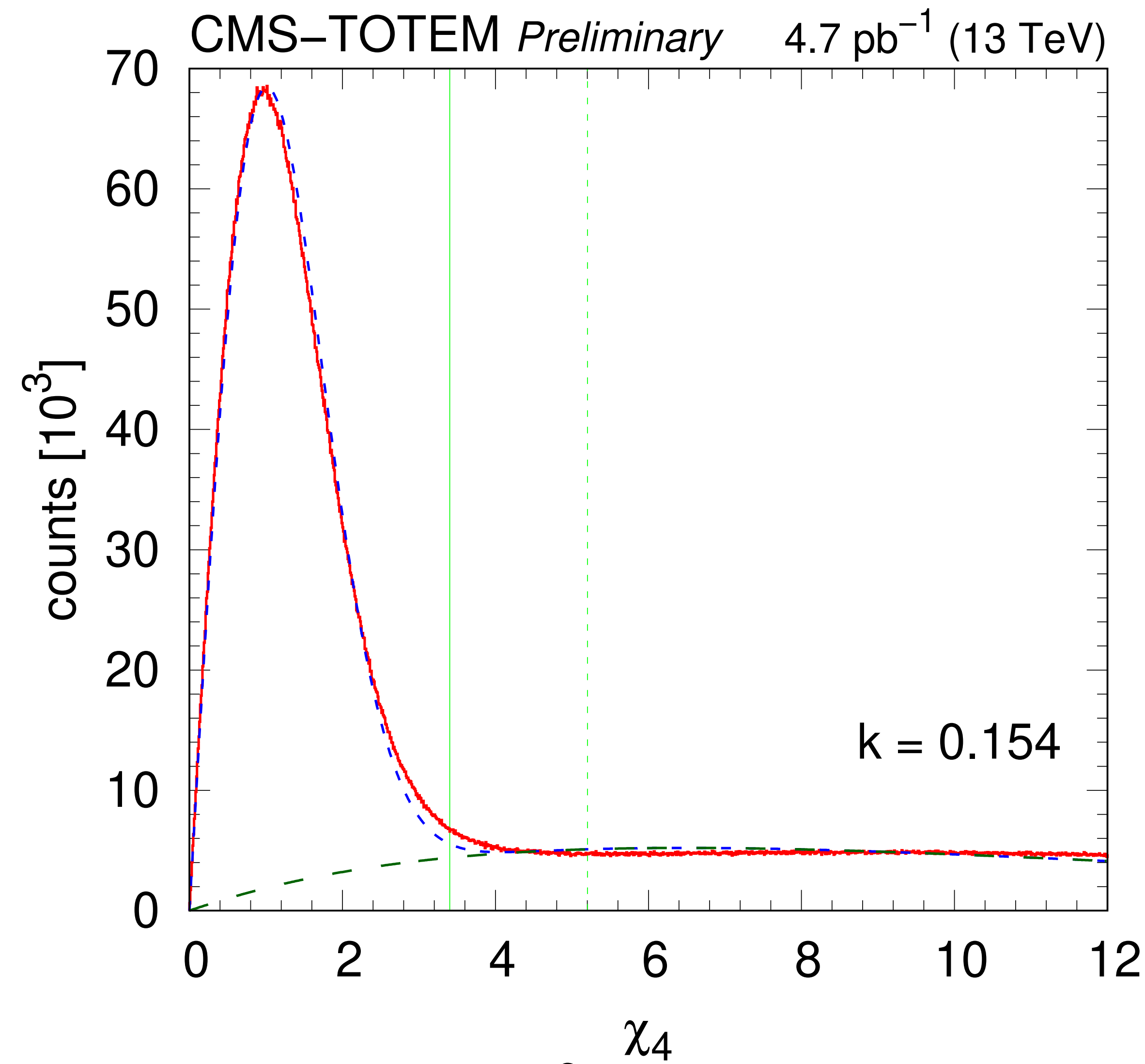
Event classification – true exclusive or pileup?



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



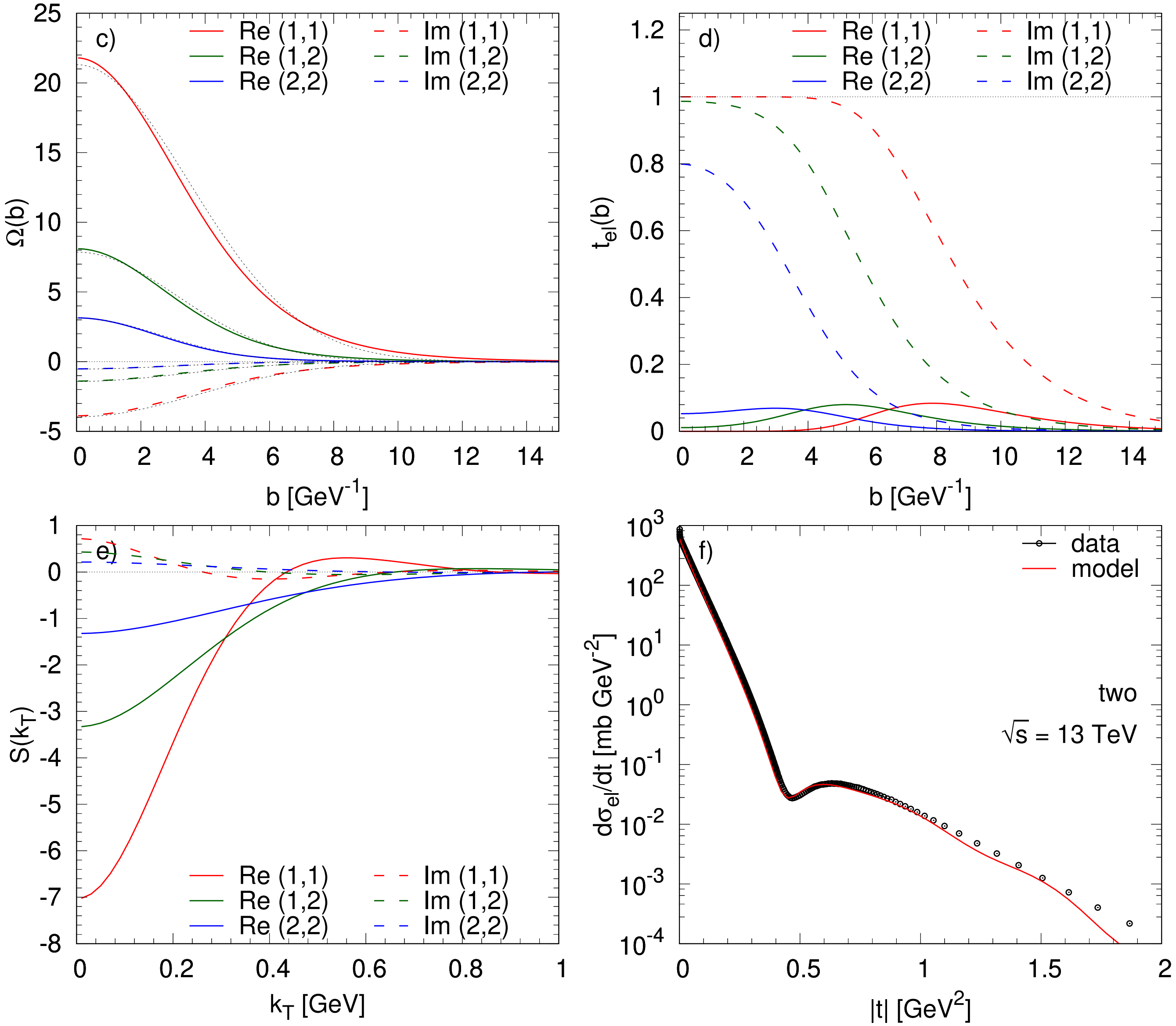


Mahalanobis distance $\chi(\mathbf{s}) = (\mathbf{s}^T V^{-1} \mathbf{s})^{1/2}$

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

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

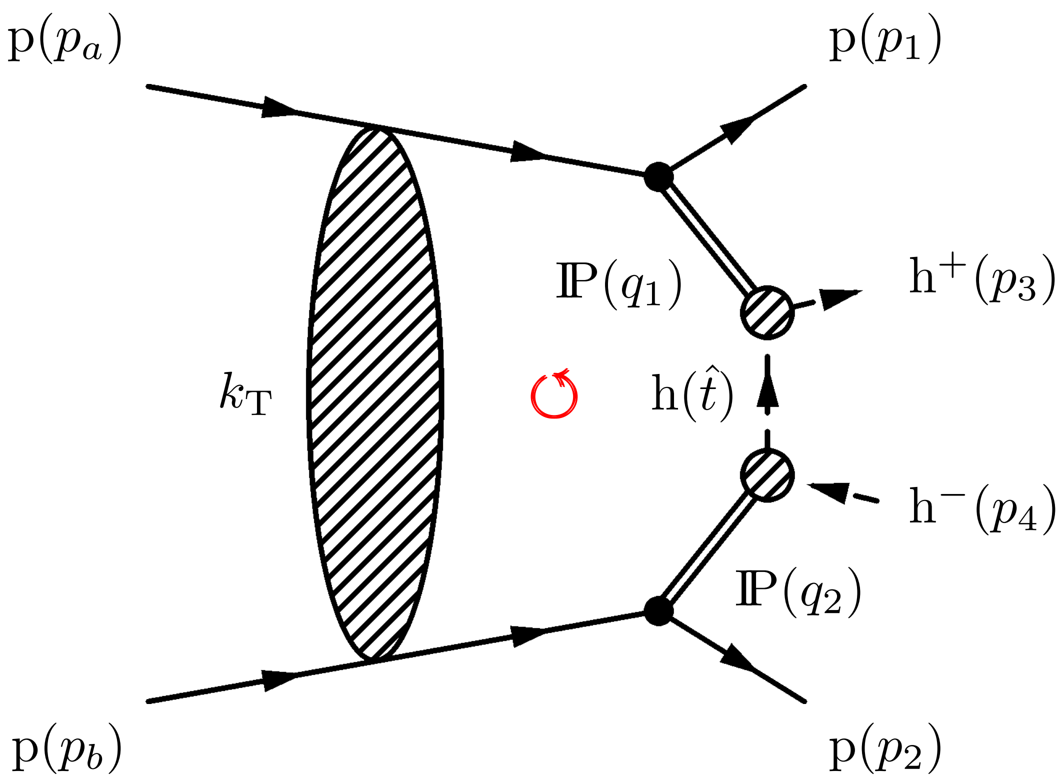
Theory – elastic screening – two-channel



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 $\mathrm{d}\sigma_\mathrm{el}/\mathrm{d}t$, **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
  $\mathcal{M}(\mathbf{p_1}, \mathbf{p_2}) = \mathcal{M}_0(\mathbf{p_1}, \mathbf{p_2}) + \int \mathrm{d}^2\mathbf{k}_\mathrm{T} T_\mathrm{el}(k_\mathrm{T}) \mathcal{M}_0(\mathbf{p_1} - \mathbf{k}_\mathrm{T}, \mathbf{p_2} + \mathbf{k}_\mathrm{T})$
  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
$2\ \|a_i\|^2$	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 – 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

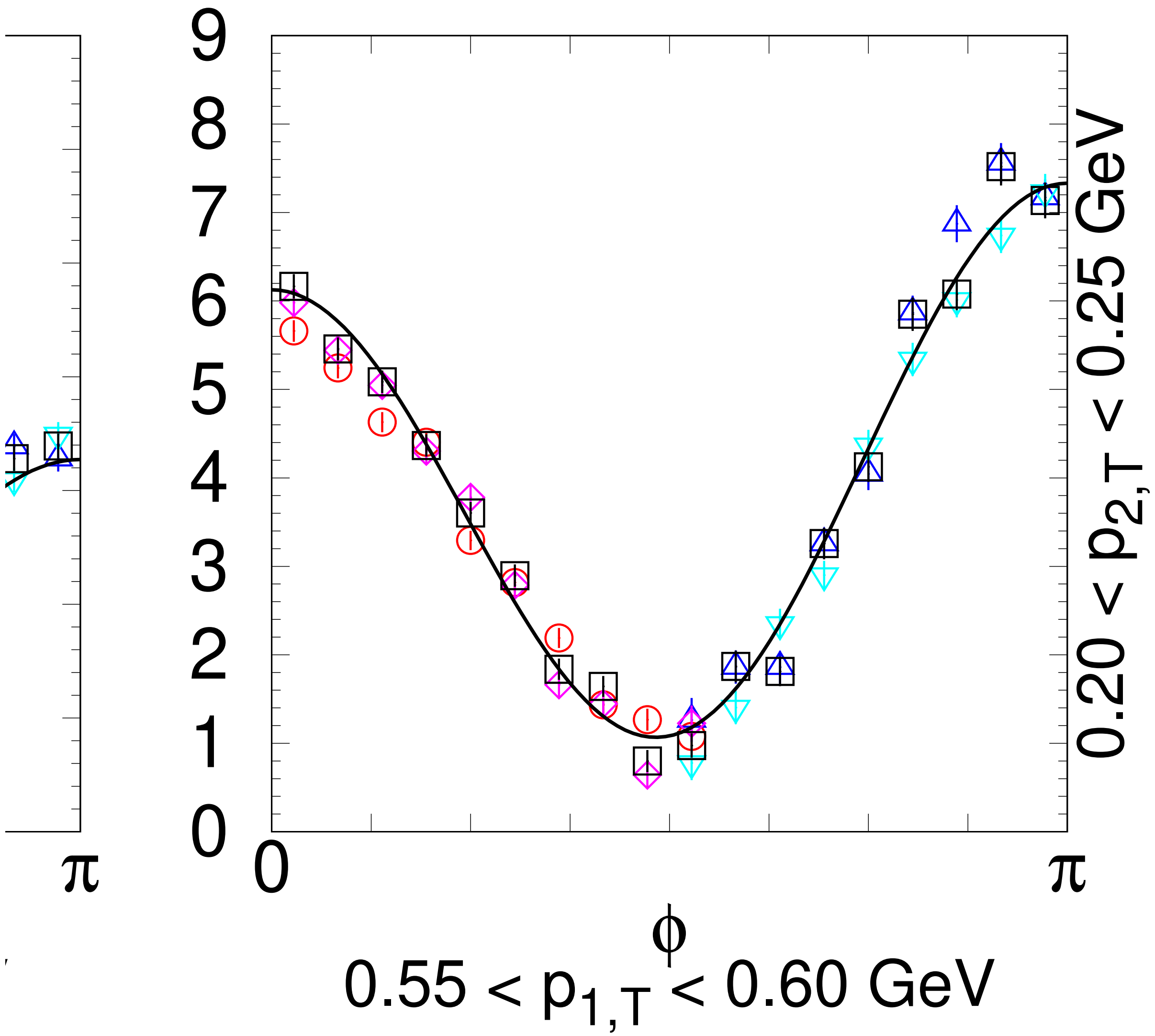
- Proton-pomeron(eigenstate) coupling
  - One-channel model: $F_p(t) = \exp(B_{\mathbb{P}}/2 \cdot t)$
  - Two-channel model:
    $F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$

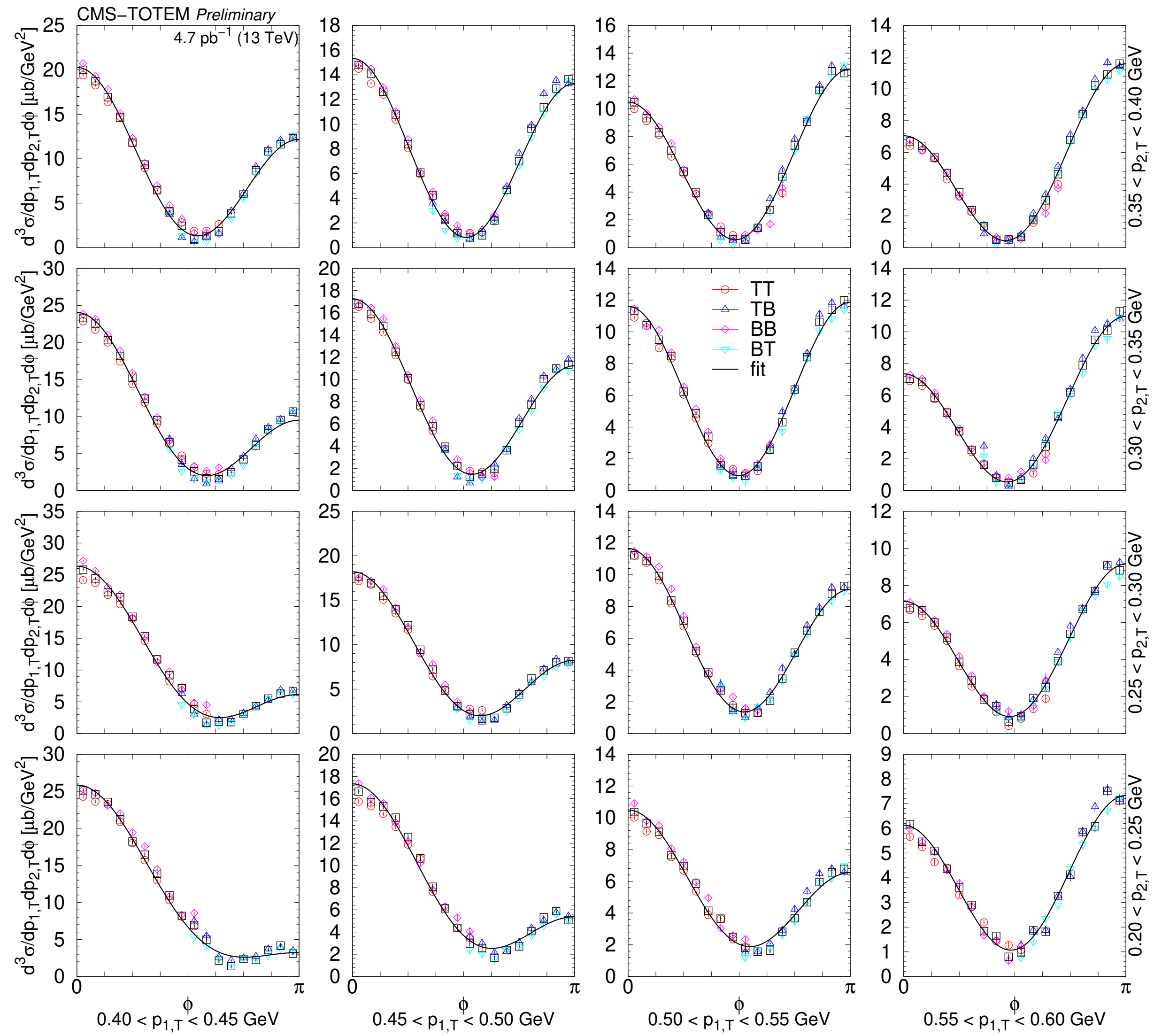
- Pomeron-meson coupling

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

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

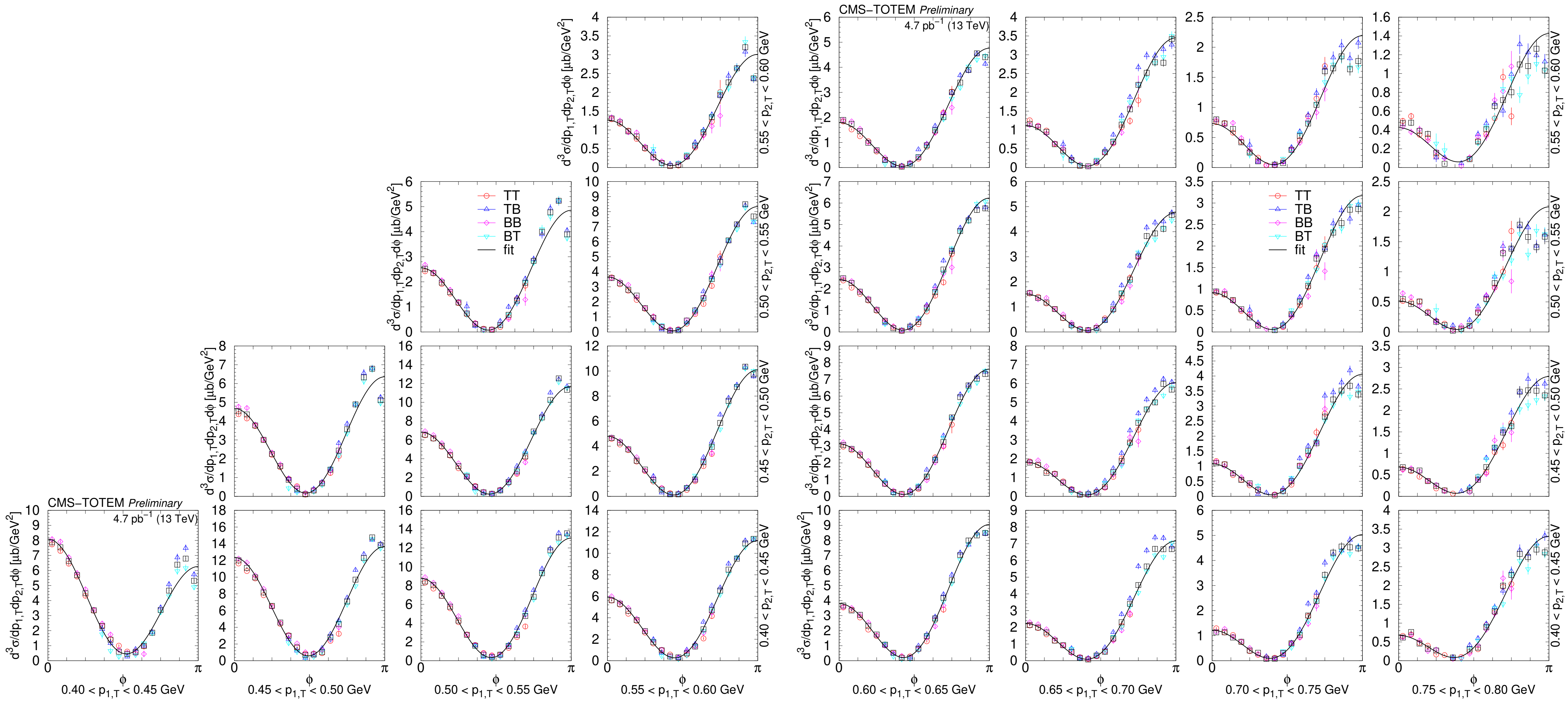
Measurements – nonresonant $d^3\sigma/dp_{1,T}dp_{2,T}d\phi$





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

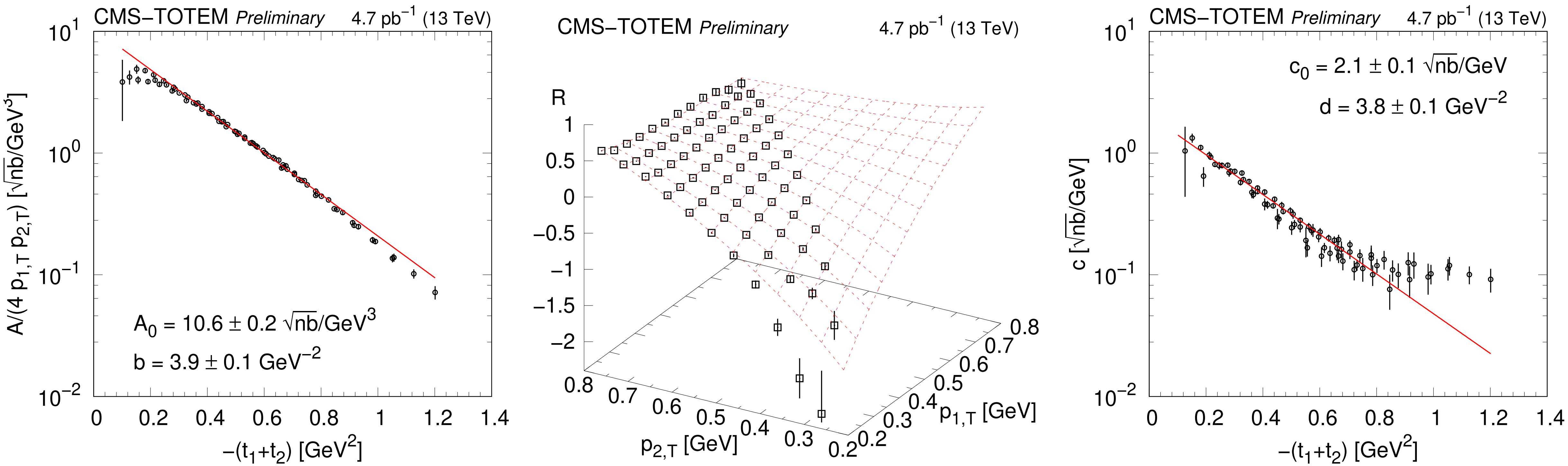
Measurements – nonresonant $\mathrm{d}^3\sigma/\mathrm{d}p_{1,T}\mathrm{d}p_{2,T}\mathrm{d}\phi$



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

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

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

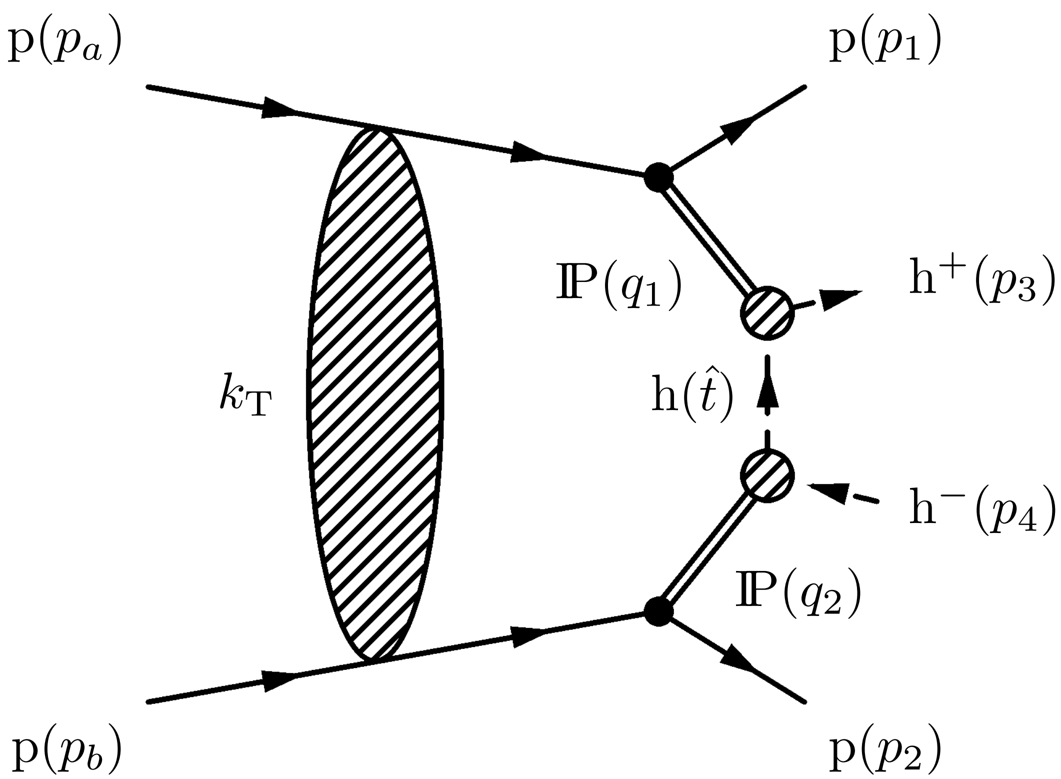
Model tuning with PROFESSOR (version 2.3.3) ⇒

Systematics

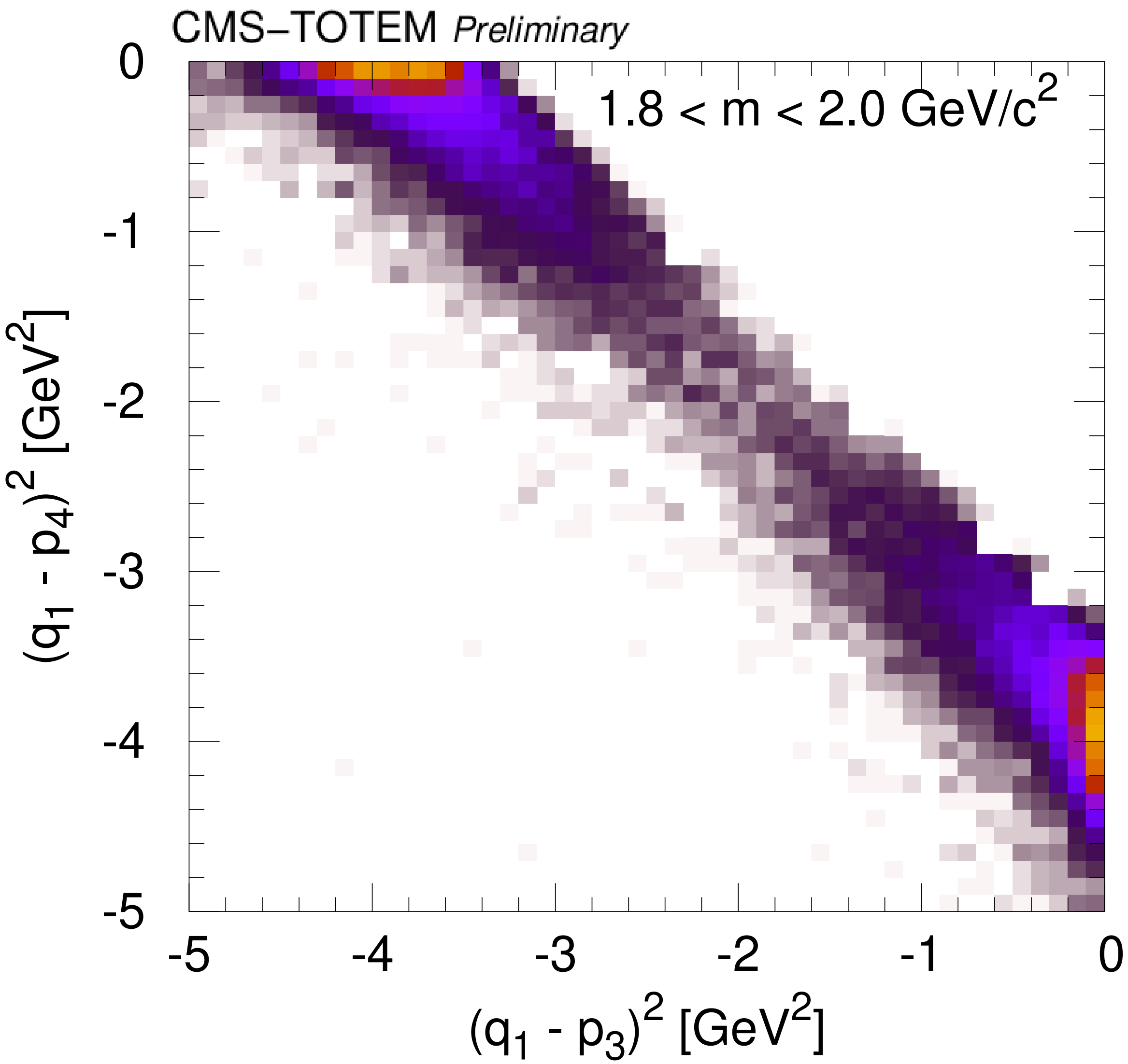
Source	Value	Remark
Pileup correction	1.0%	through visible cross section (σ_{vis})
Lumisections with reduced RP availability	0.5%	
Integrated luminosity (L_{int})	2.5%	
HLT efficiency	small	neglected
Total normalisation-type	2.7%	
Roman pot efficiency	$\approx 3.0\%$	to be taken twice
Background removal	$< 0.5\%$	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

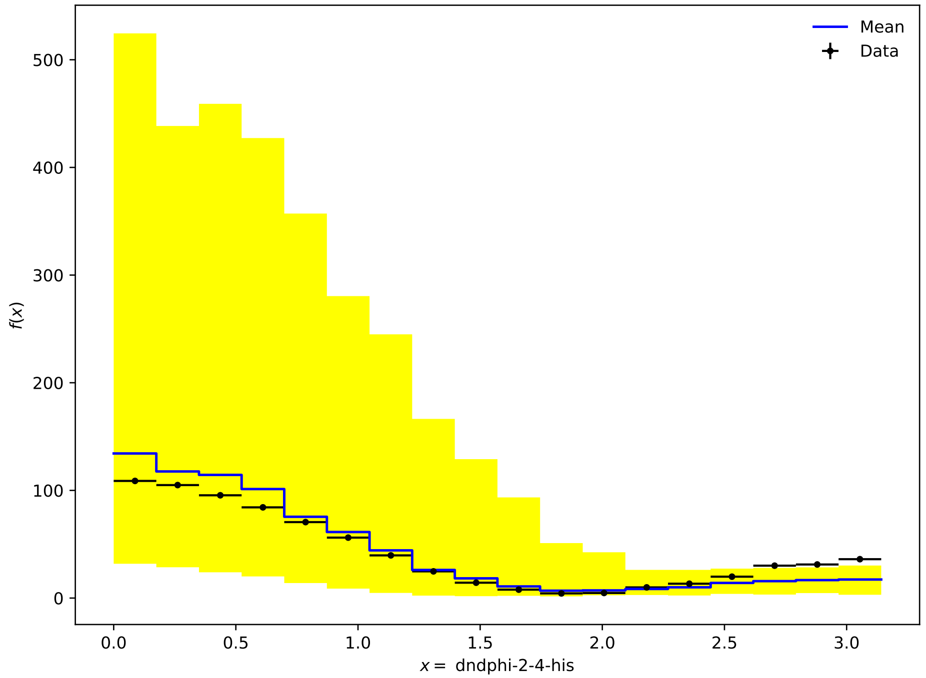


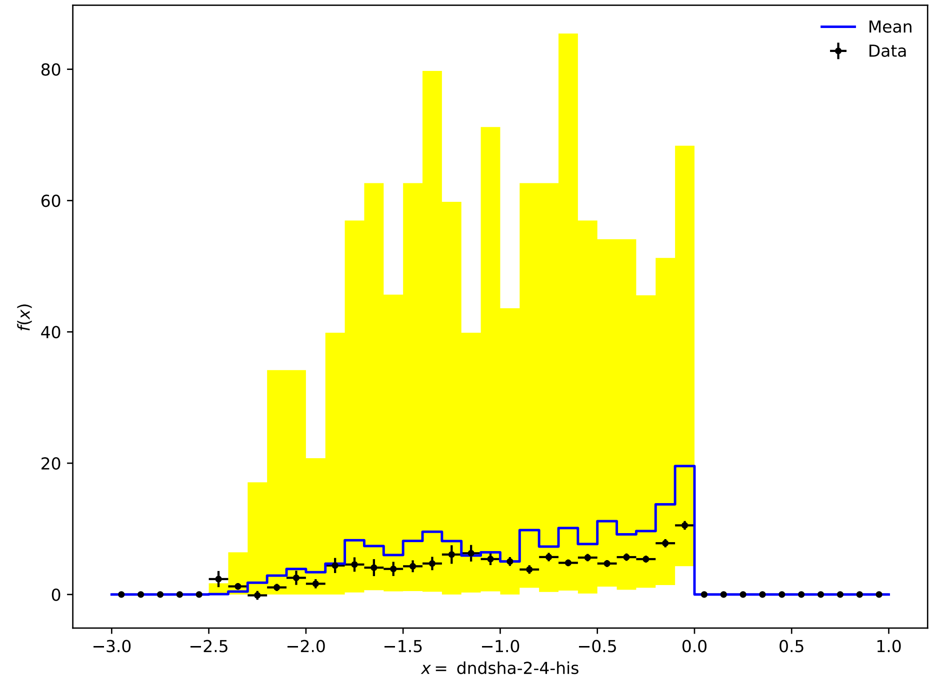
Propagator of virtual hadron:
$1/(\hat{t} - m^2)$



The squared four-momentum differences between IP and the hadrons $h^\pm$

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

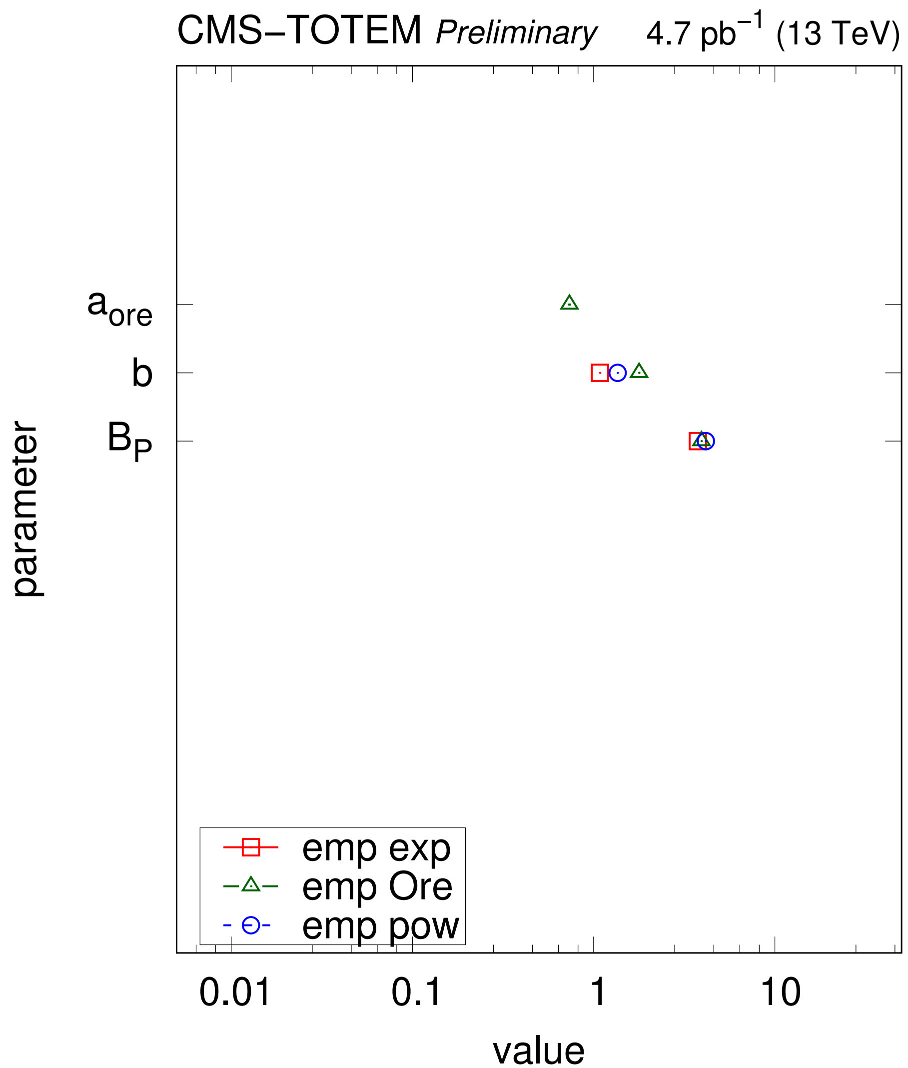
Model tuning – result

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

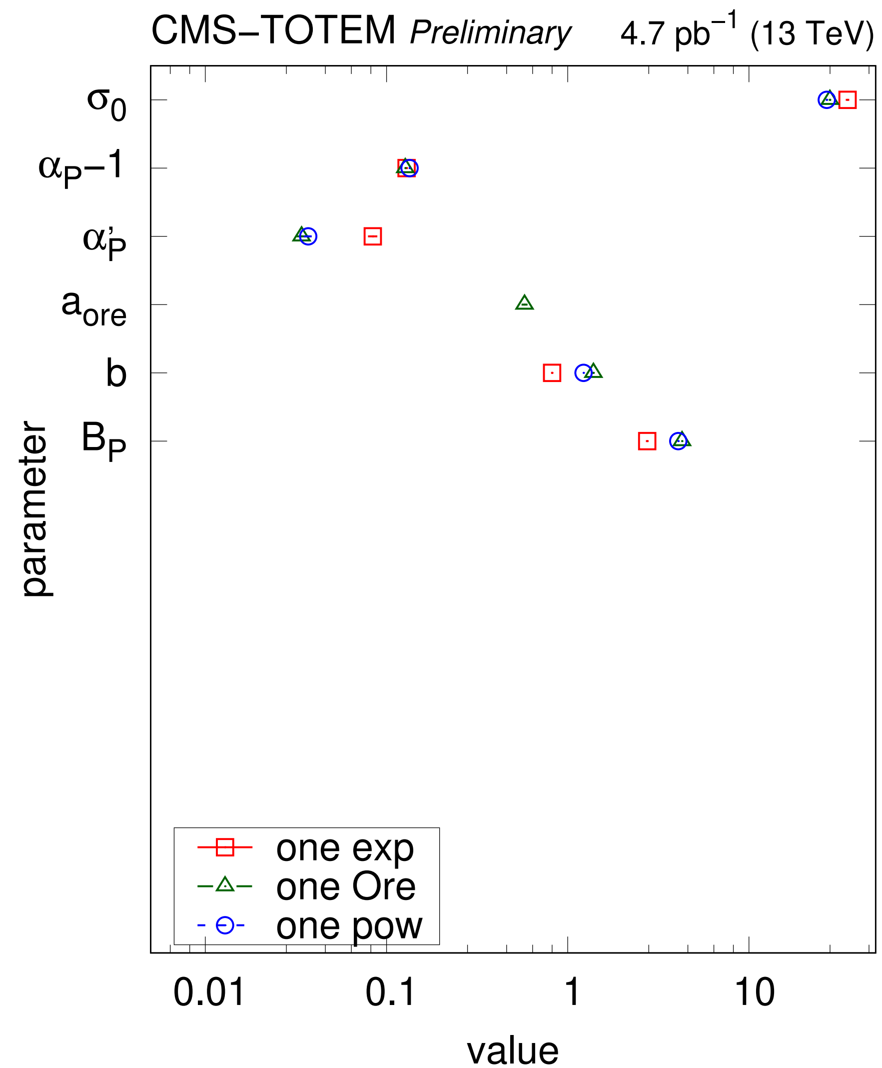
- Models
  - empirical (measured elastic diff cross section)
  - one-channel (proton in ground state)
  - two-channel (two diff eigenstates of the proton)
- Form factors
  - pomeron-meson (exponential, Orear-type, power-law)
  - proton-pomeron

Model tuning – result

empirical



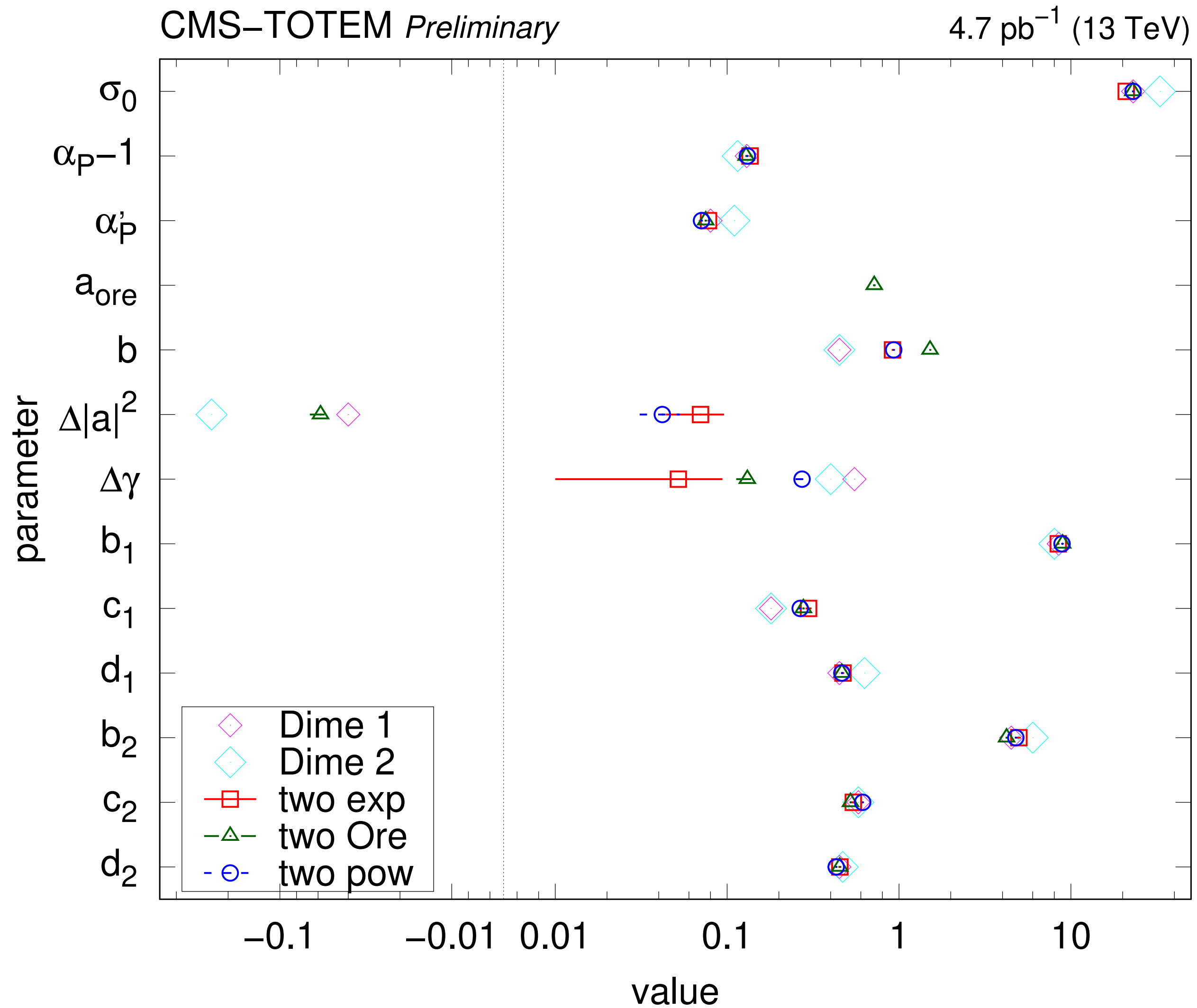
one-channel



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

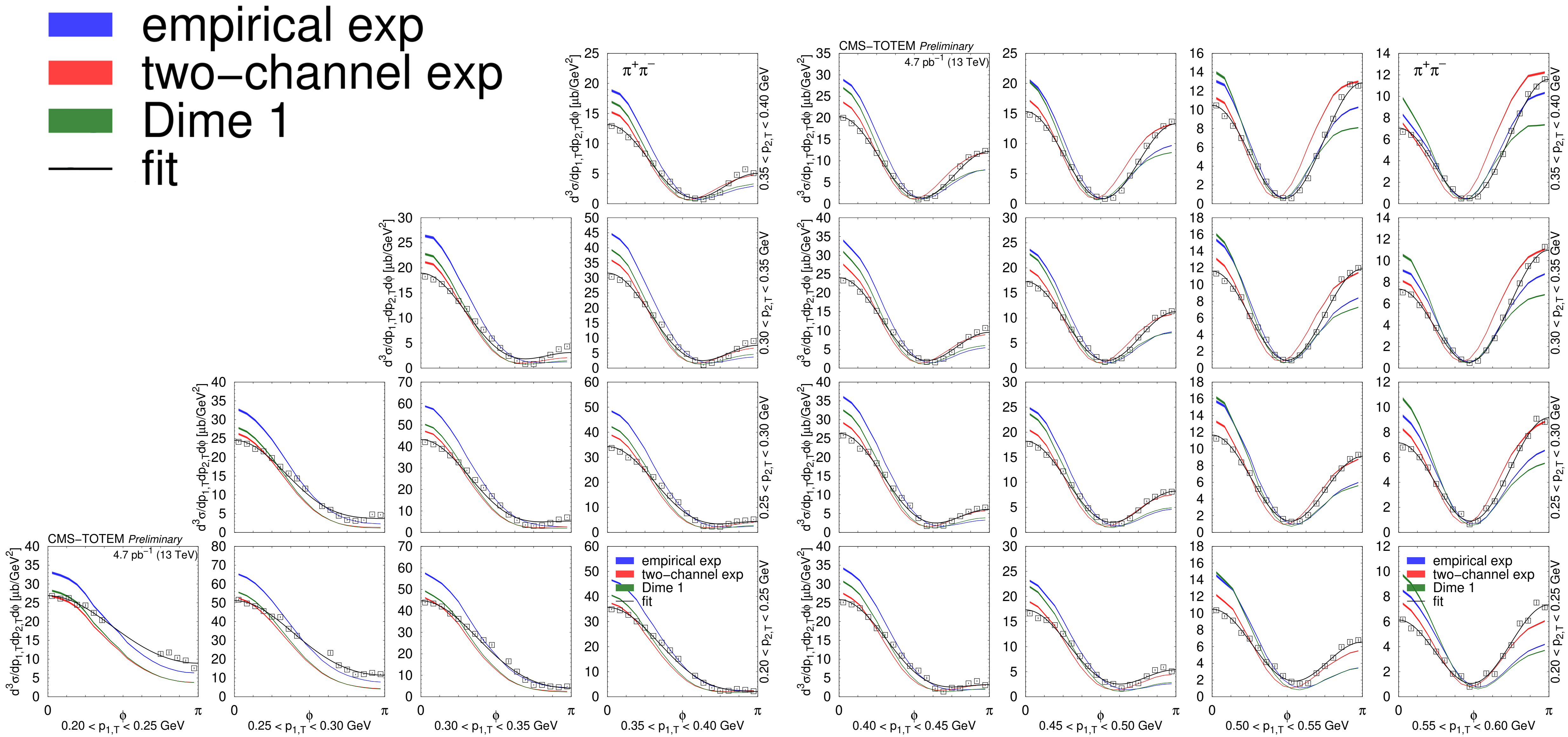
Model tuning – result

two-channel



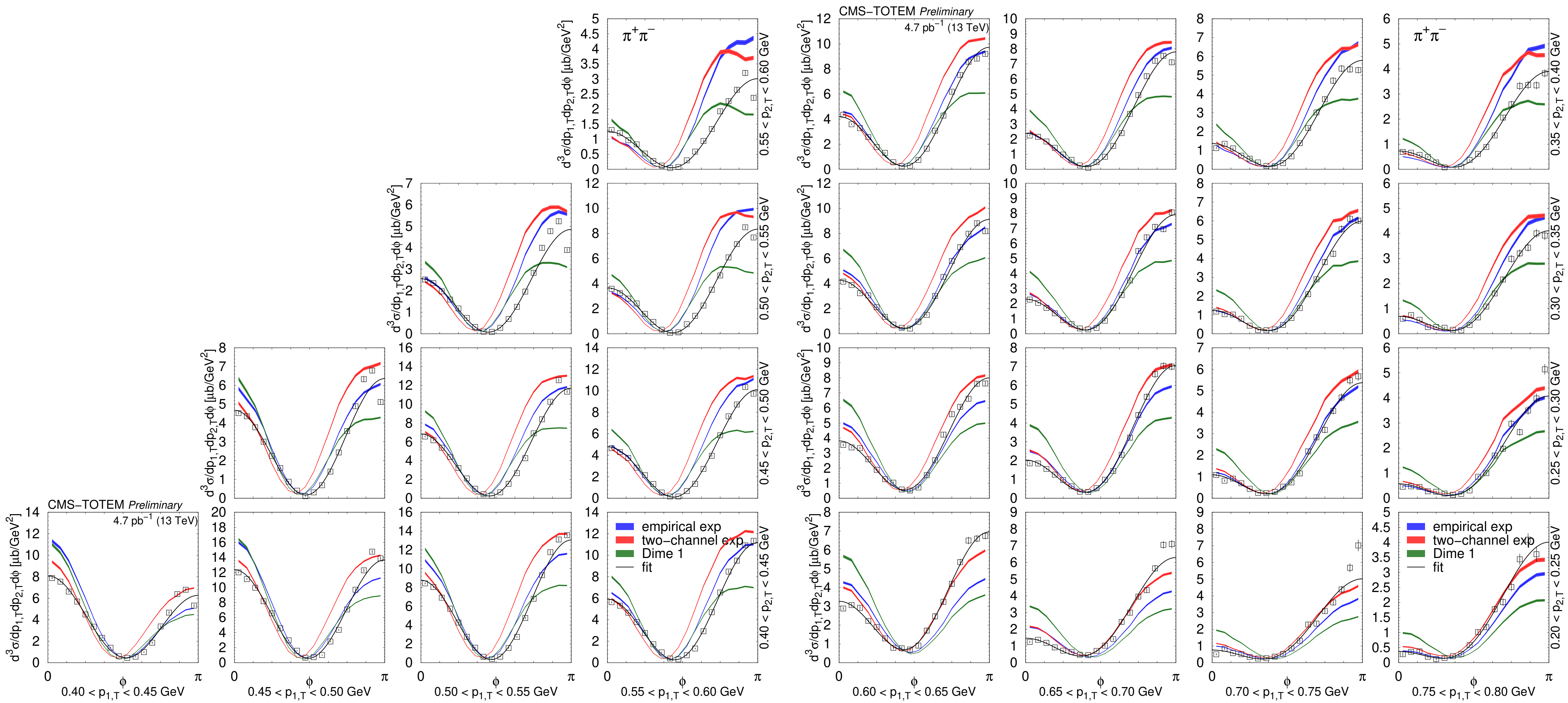
Remarkable agreement with DIME ("soft model 1"), although with unexpected eigenstate weights ($a_1 \approx a_2$) and eigenstate-pomeron coupling ($\gamma_1 \approx \gamma_2$)!

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



Good quality

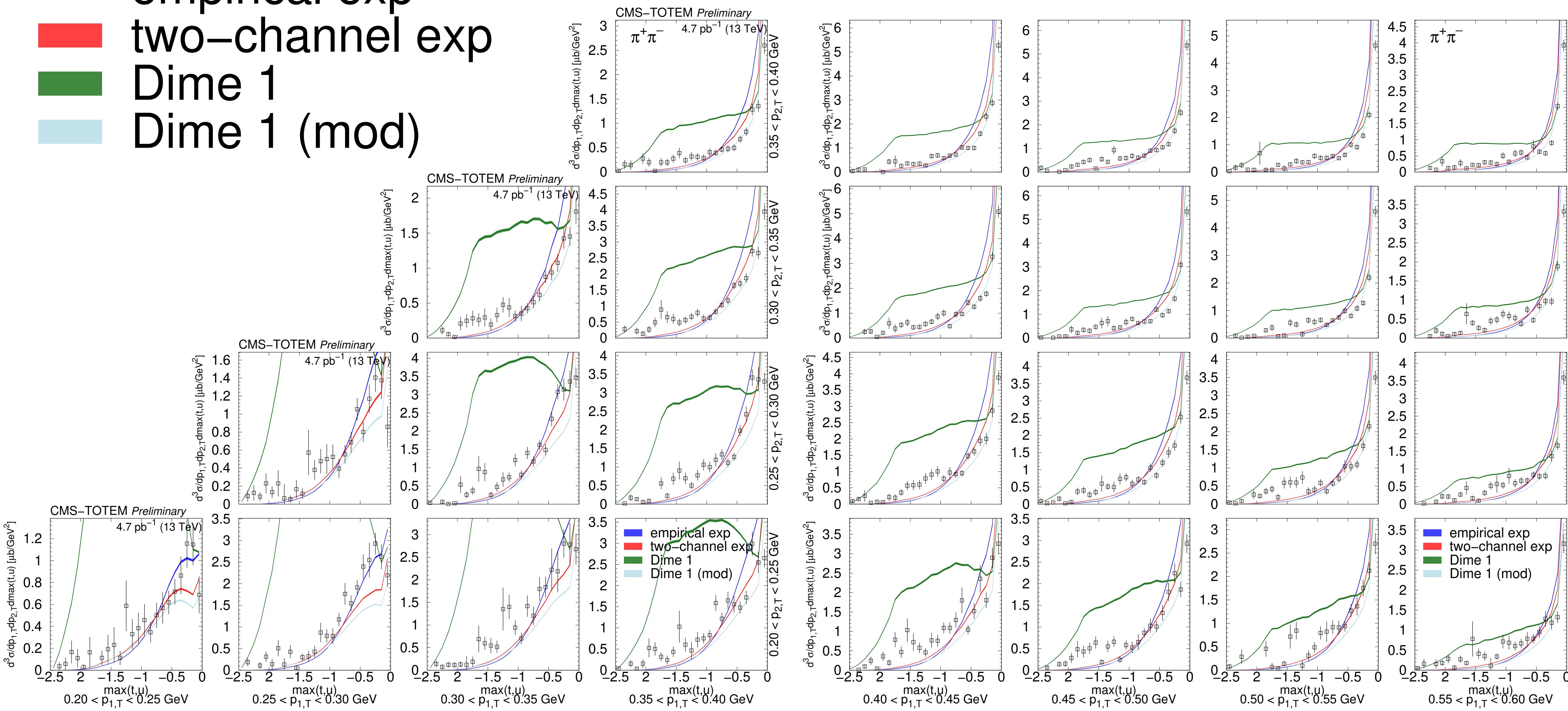
$\mathrm{d}\sigma/\mathrm{d}\phi - \pi^+\pi^-$



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

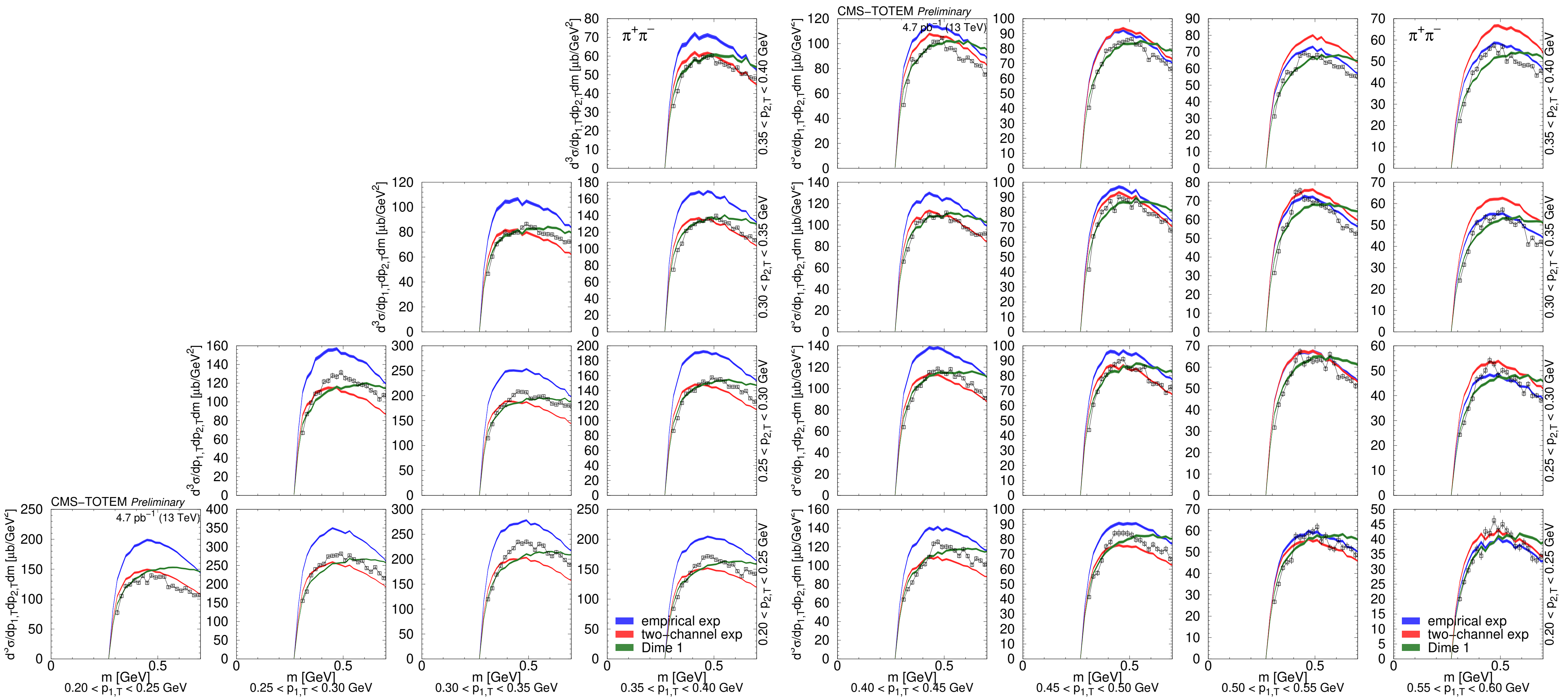
$\mathrm{d}\sigma/\mathrm{d}\max(\hat{t},\hat{u})$ – $\pi^+\pi^-$

- empirical exp
- two–channel exp
- Dime 1
- Dime 1 (mod)



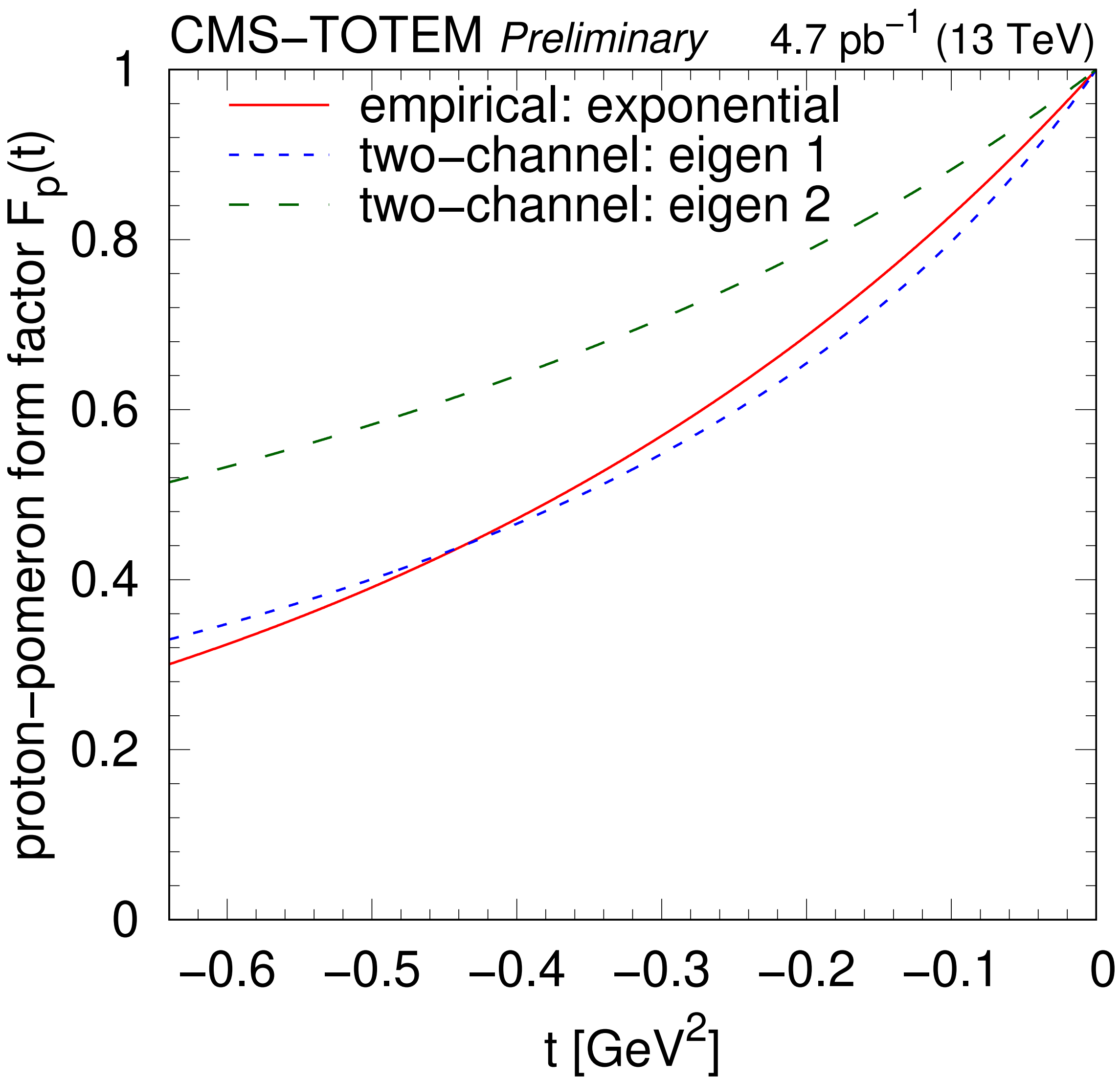
Virtual hadrons – important to fix the value of b_{exp} ($0.45 \to 0.9\,\text{GeV}^{-2}$)

$d\sigma/dm$ – $\pi^+\pi^-$

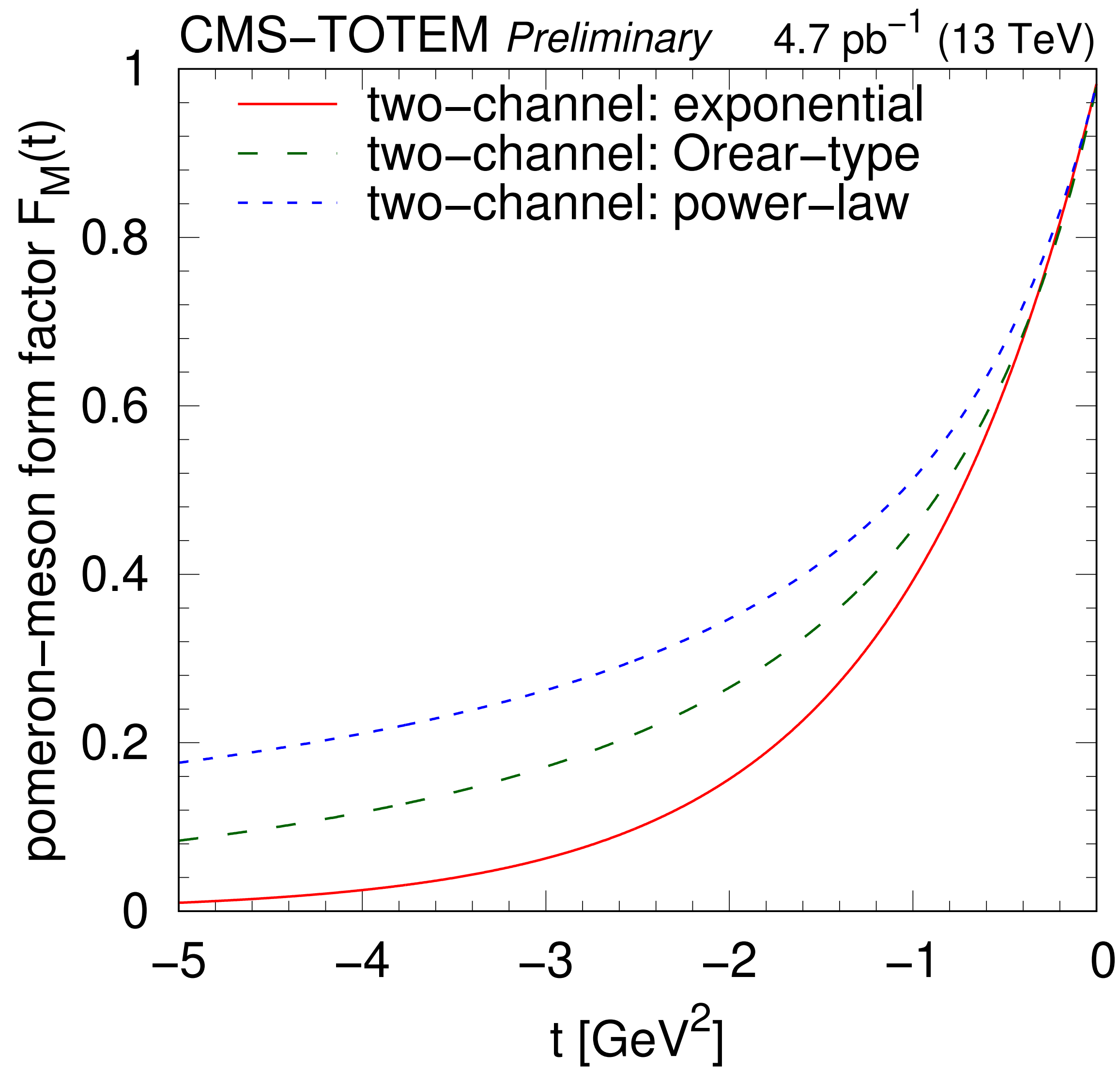


Invariant mass spectra of the central two-hadron system

Form factors – t-dependence

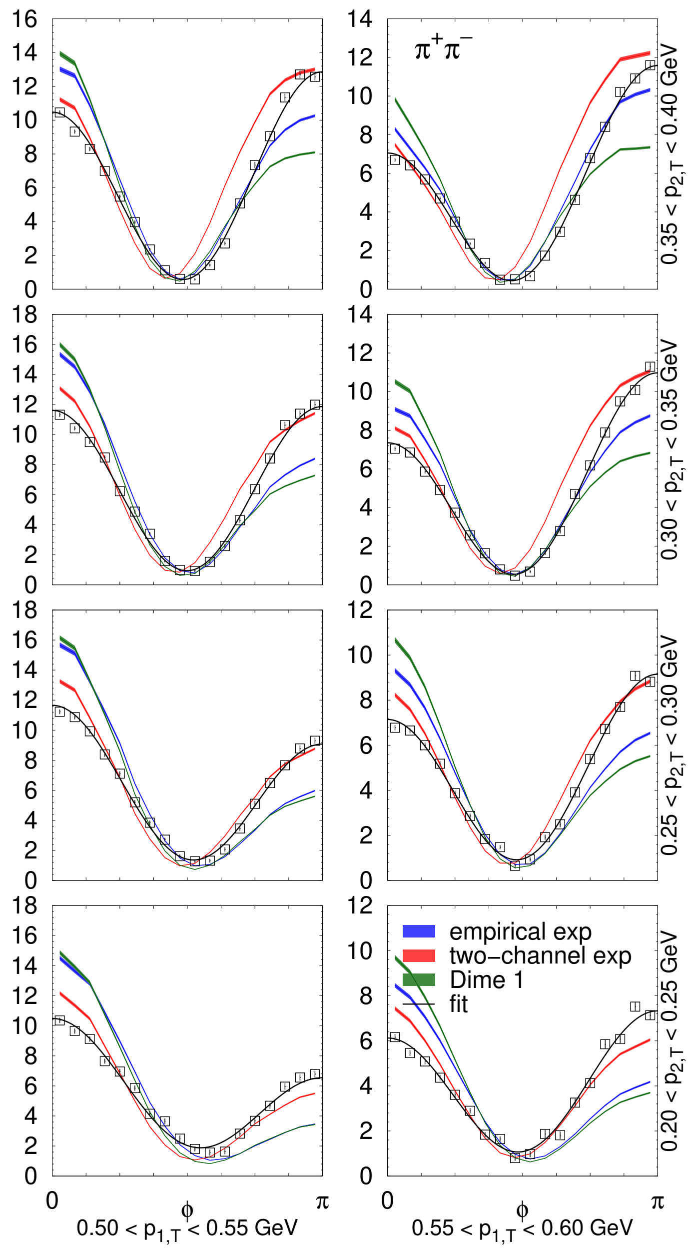


proton-pomeron



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 K^+K^- resonances!)