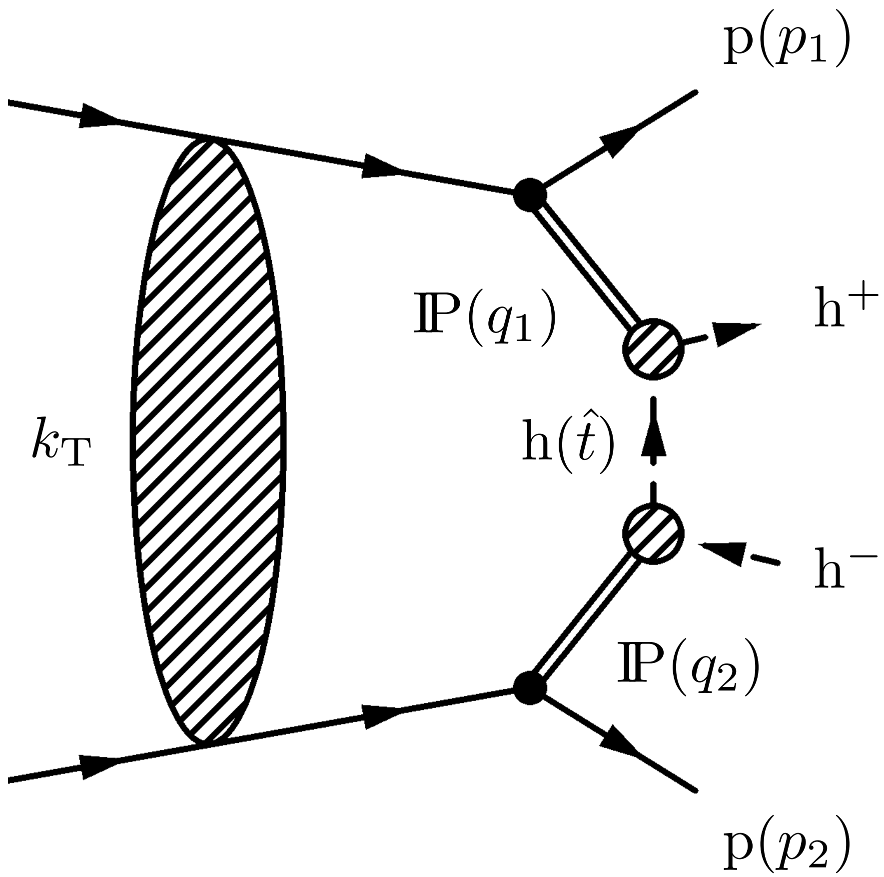
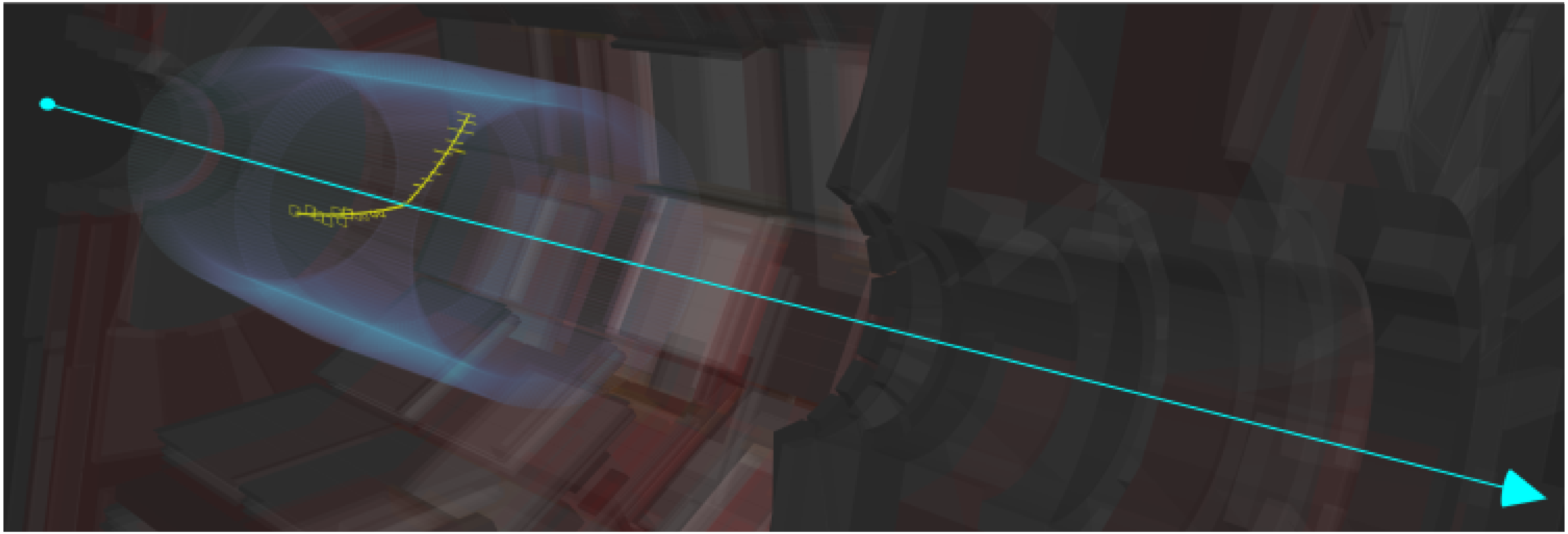


Forward physics at LHC energies

Ferenc Siklér
Wigner Research Centre for Physics, Budapest

ELFT Particle Physics Summer School 2024
Mátrafüred
May 29, 2024

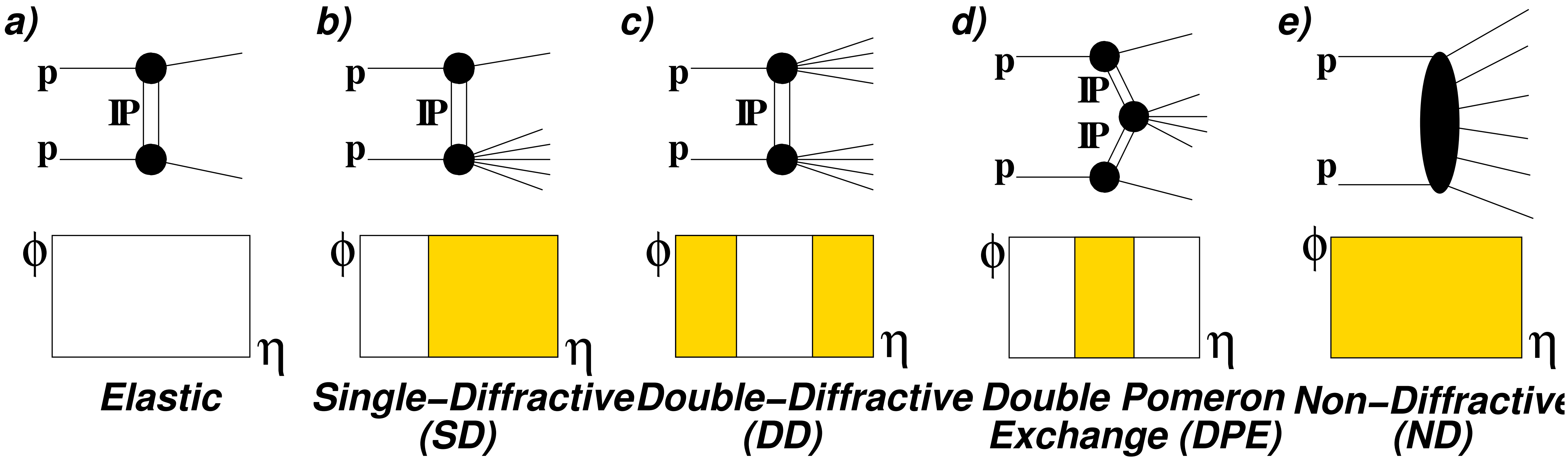
Forward physics at LHC energies



CMS Collaboration, “In search of the strong interaction: the pomeron”
Phys Rev D, in press

- High energy protons
  - Elastic scattering (single and multiple exchanges)
  - Central exclusive production of hadron pairs (double exchange)
  - Mentions: odderon, glueballs

Proton-proton collisions



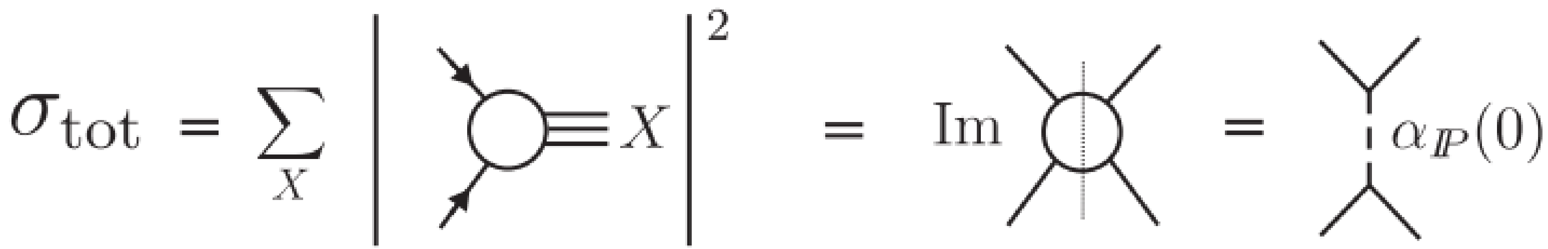
Diffraction – what is the exchanged particle?

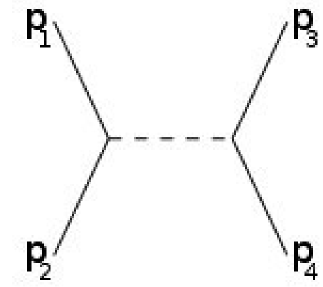
Actually, is it a particle?

Theory

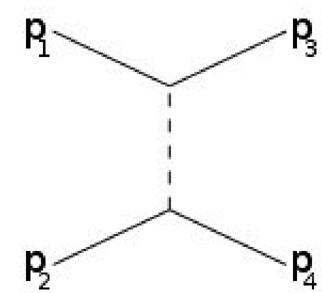
- Landscape
  - Mandelstam variables (s, t, u)
  - "s-channel eikonal" vs "t-channel Regge" approaches
  - **unitarity** of the scattering matrix (conservation of probability)
  - **crossing** symmetry (pp and $\mathrm{p\overline{p}}$ are related)
  - at high $\sqrt{s}$: many open channels, incoming wave absorbed
    scattering amplitude is imaginary; "shadow", **diffraction**
  - optical theorem

$$\sigma_{\text{tot}}(s) = \frac{4\pi}{k} \mathrm{Im}\, f(0)$$

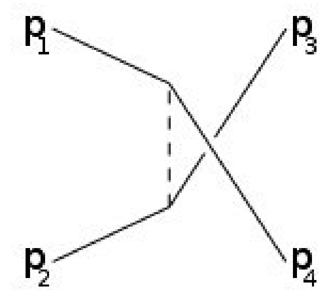




s-channel

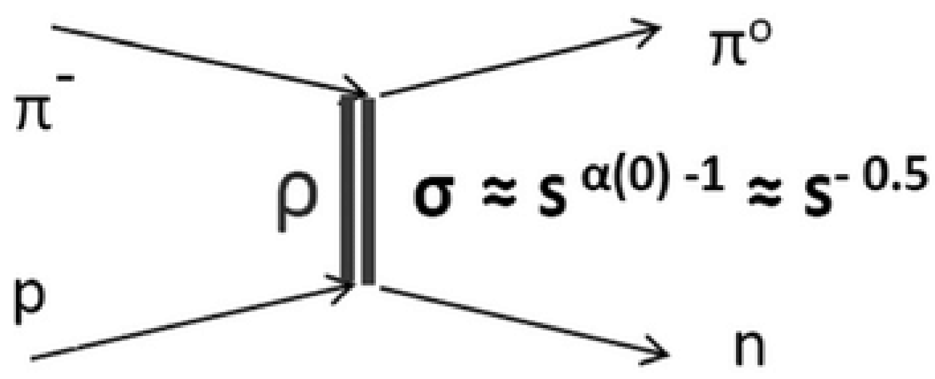


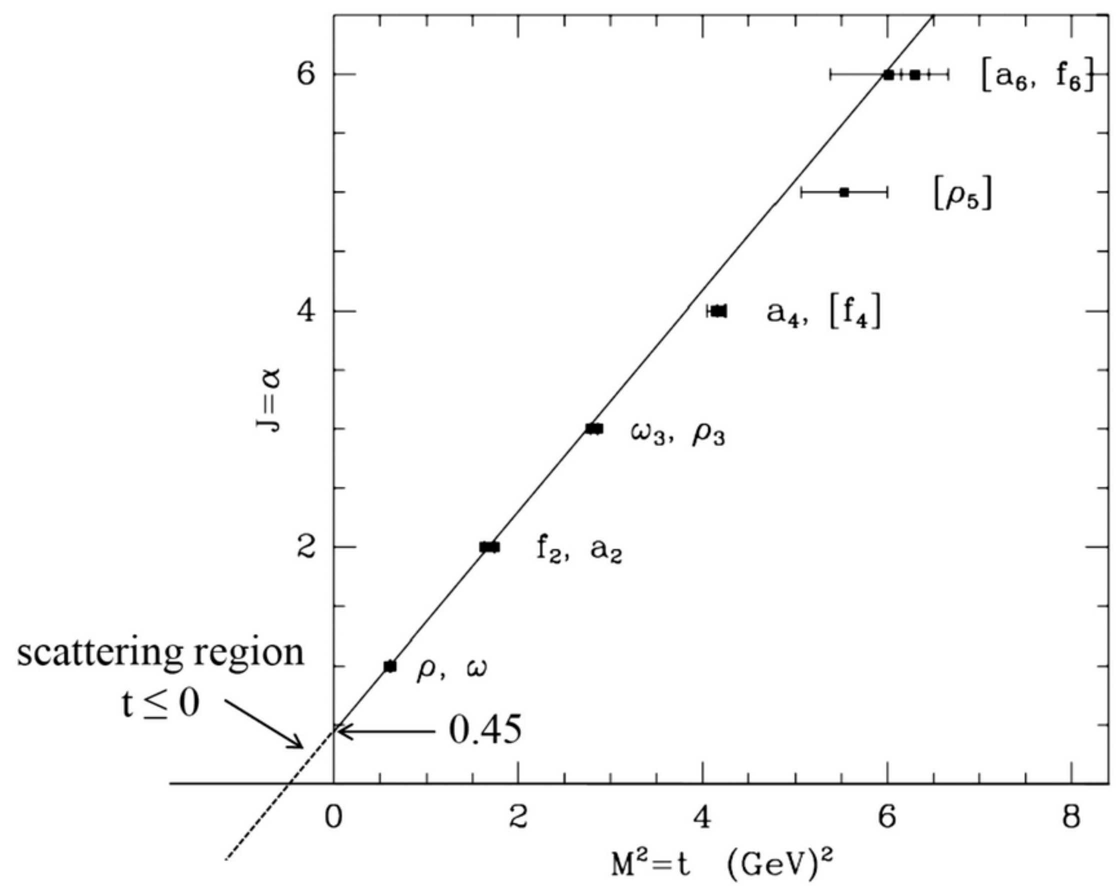
t-channel



u-channel

Small angle scattering



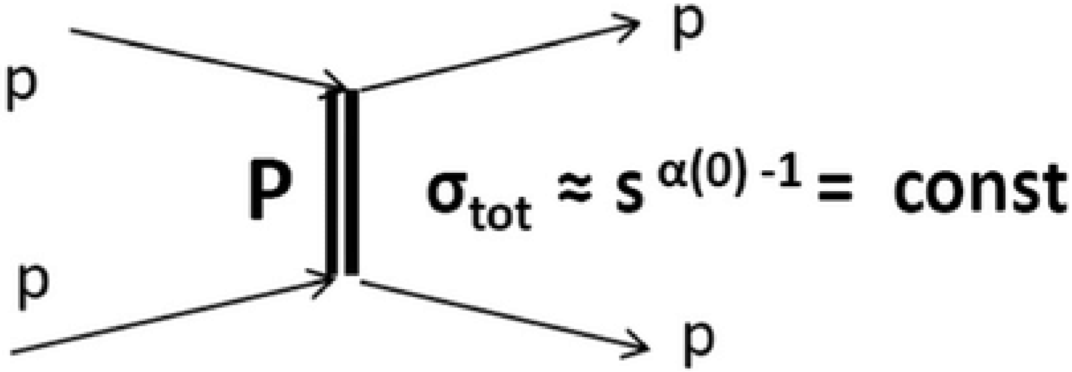


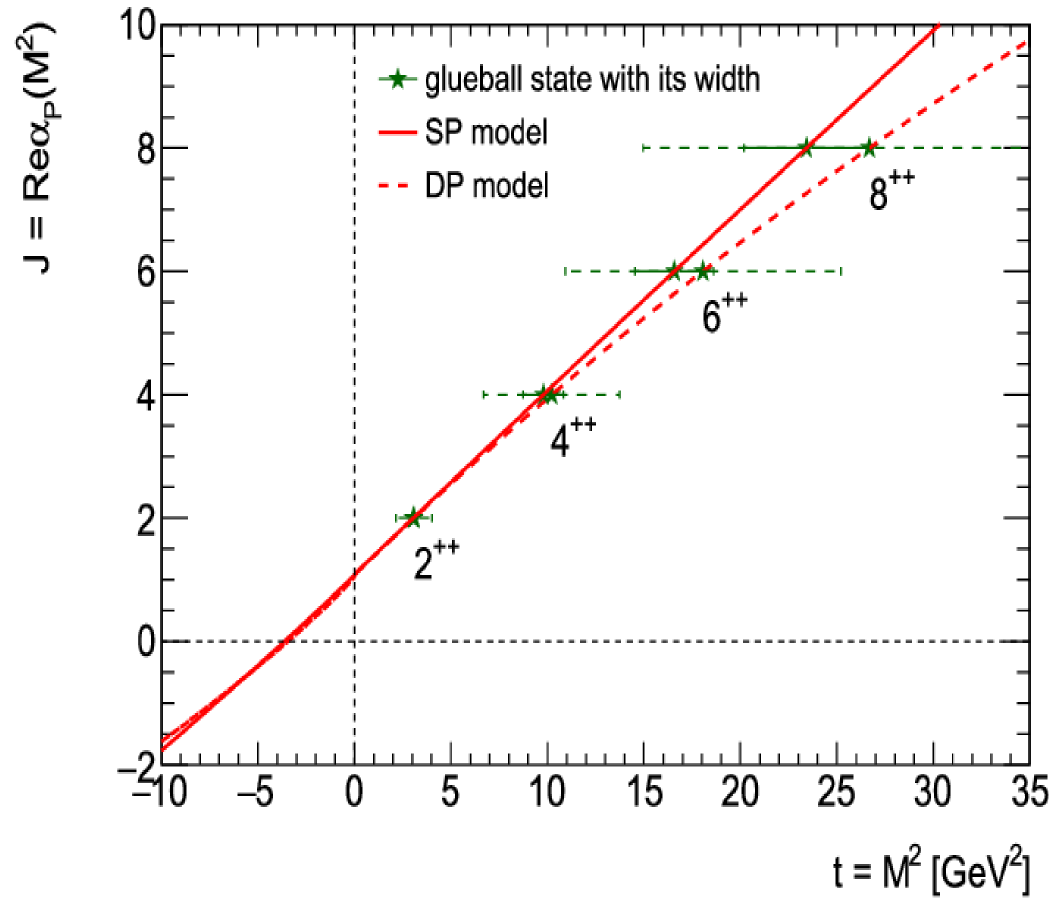
U Amaldi, "60 years of CERN experiments . . . "

Collective effect of exchanges of all the particles on a "Regge trajectory"

Chew-Frautschi plot – the ρ trajectory – practically linear

Small angle scattering – elastic



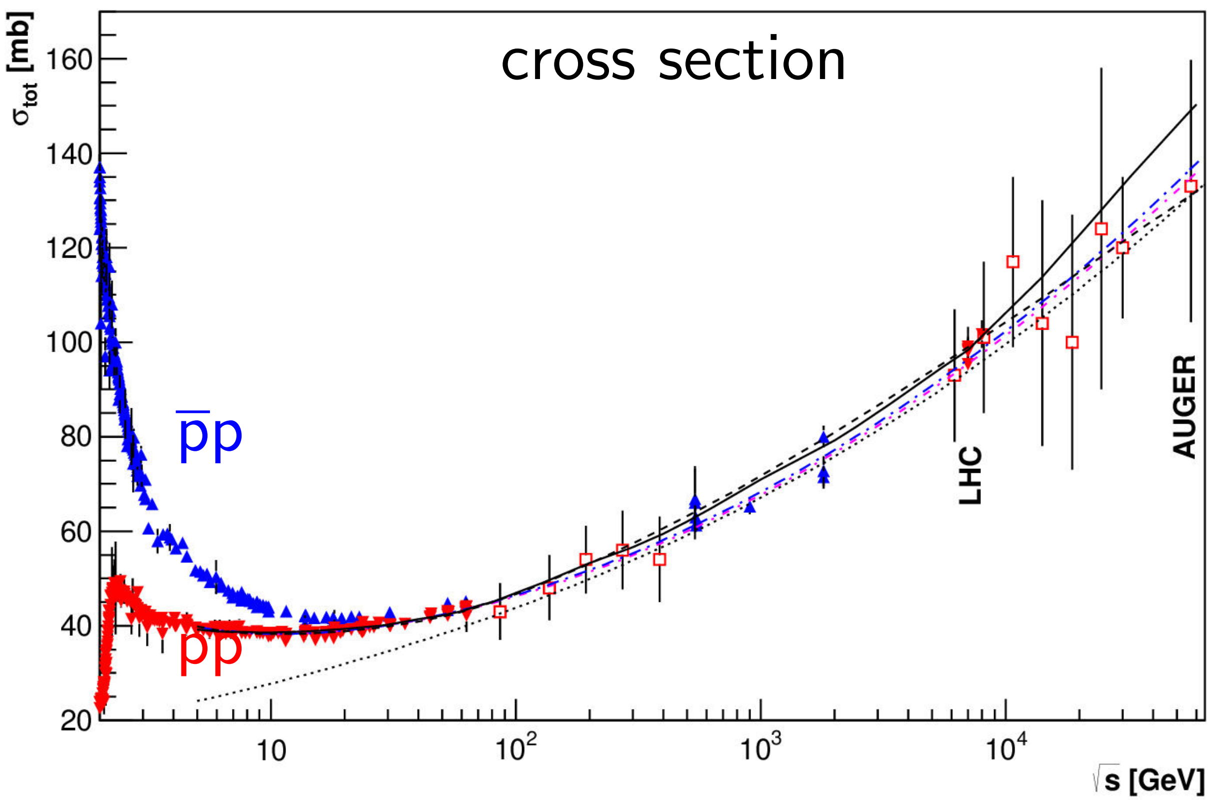


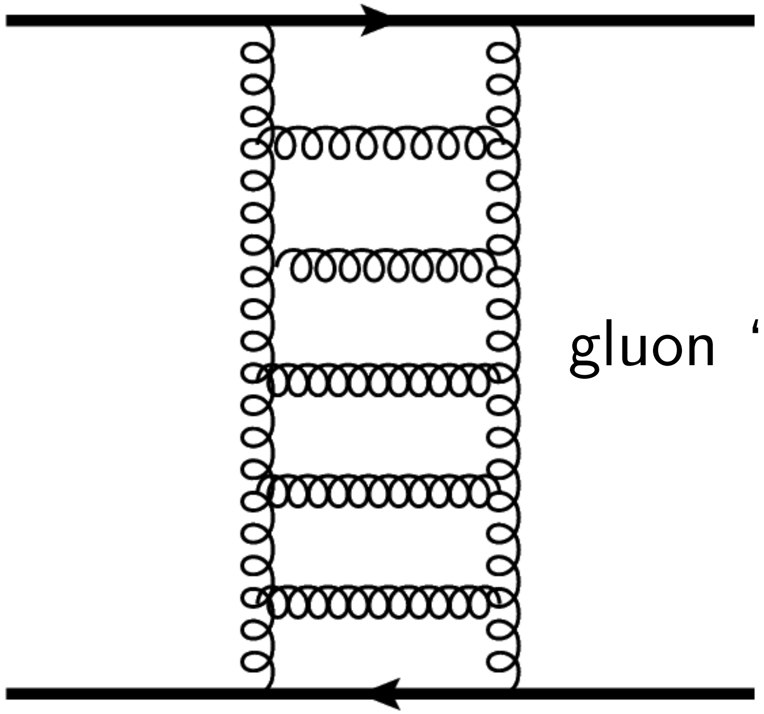
I Szanyi et al, Nucl Phys A 998 (2020) 121728

Collective effect of exchanges of a trajectory, the "pomeron", with intercept $\alpha_{\mathbb{P}}(0) \approx 1$

No particles (yet) on the trajectory – t-slope from forward scattering cross section

Pomeron ($\mathbb{P}$)





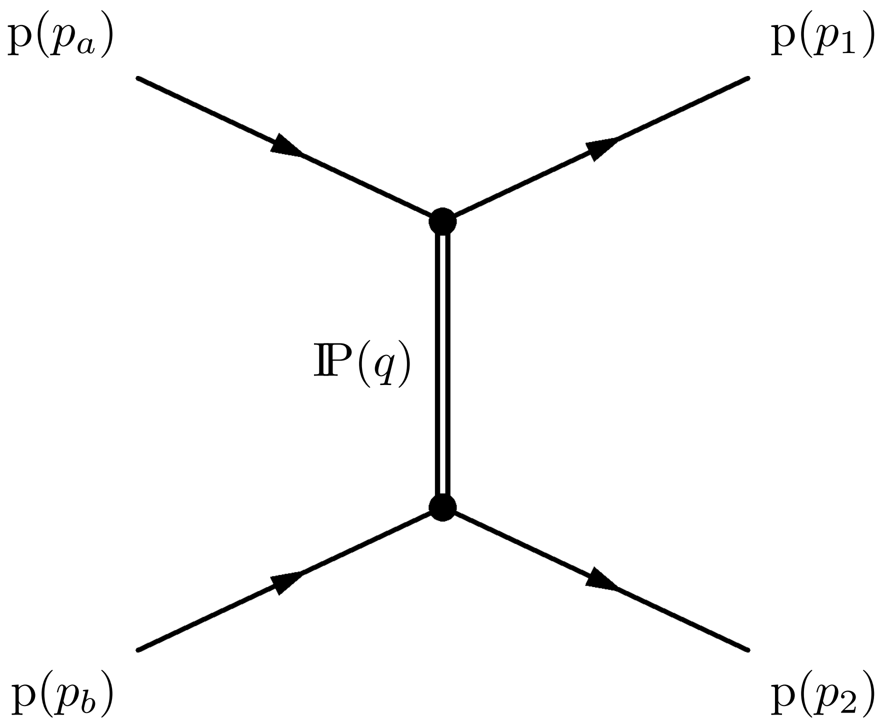
- Problems
  - the pp and $\bar{p}p$ cross sections are similar, and keep rising
  - why do they increase? exchange?
  - force carrier must have zero charges

Isaak Pomeranchuk

Vladimir Gribov

QCD language – exchange of gluon pair(?) $\sim$ gluon ladder

Elastic differential and total



- Cross sections

  the elastic amplitude scales as

  $$T_{\text{el}}(s,t) \propto (s/s_0)^{\alpha_{\mathbb{P}}(t)}$$

  the elastic differential cross section

  $$\frac{\mathrm{d}\sigma_{\text{el}}(t)}{\mathrm{d}t} = \frac{1}{4\pi}|T_{\text{el}}(t)|^2$$

  the total cross section

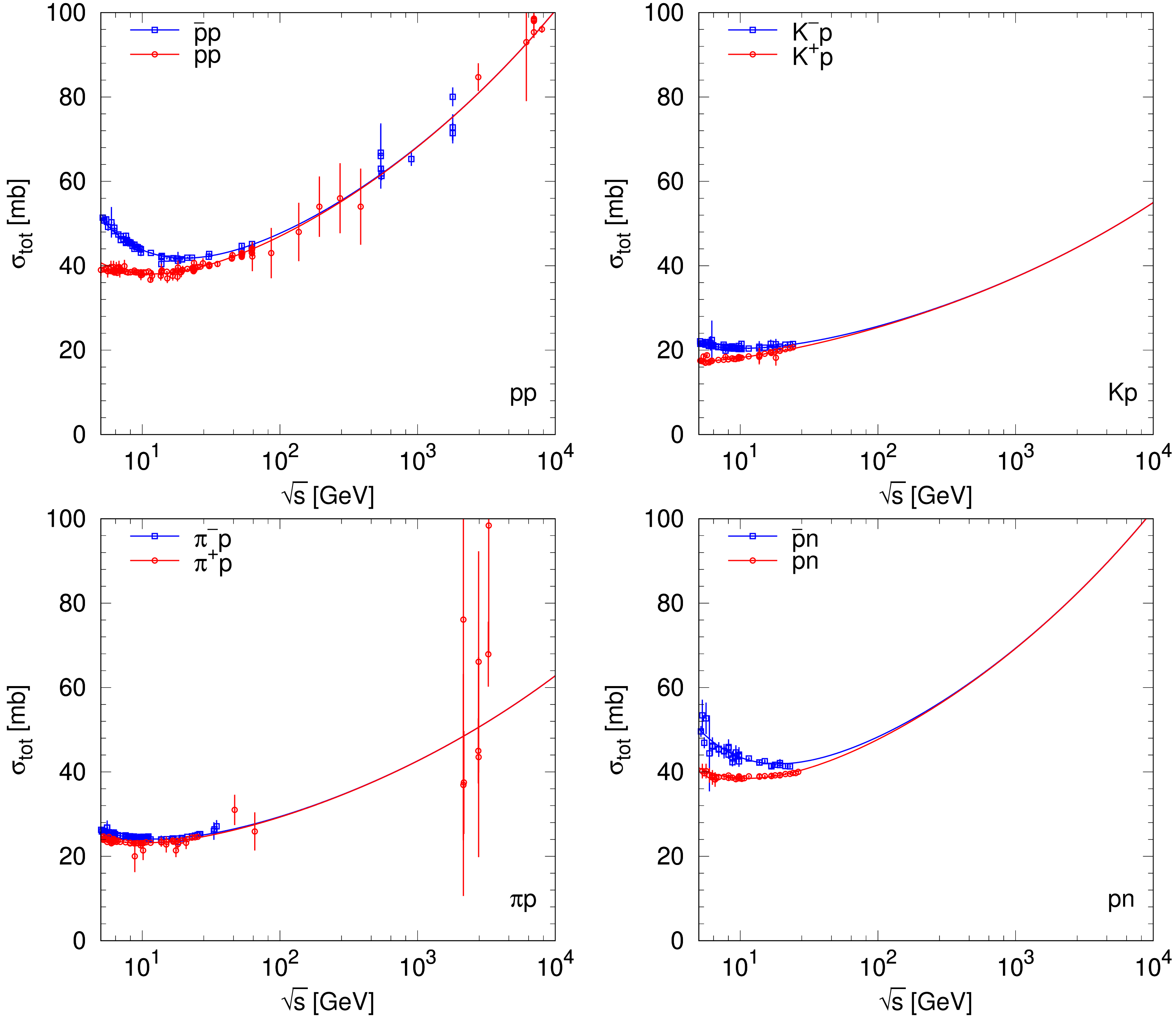
  $$\sigma_{\text{tot}} \propto (s/s_0)^{\alpha_{\mathbb{P}}(0)-1}$$

  the bare pomeron trajectory is

  $$\alpha_{\mathbb{P}}(t) = \alpha_0 + \alpha' t$$

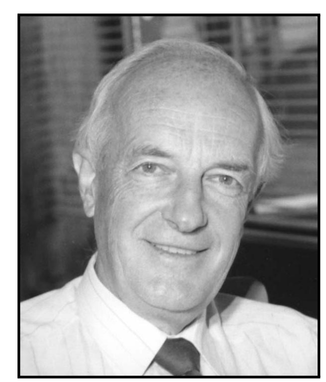
Can be more complicated

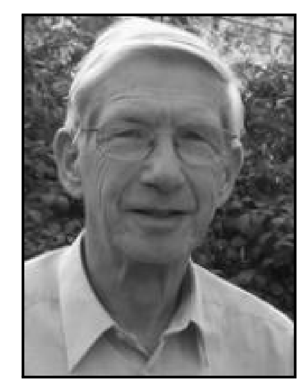
Total cross section



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

S Donnachie and P Landshoff, Nucl Phys B 231 (1983) 189
Phys Lett B 296 (1992) 227


Sandy Donnachie


Peter Landshoff

Total cross section

Pomeron- and reggeon-related parameters from the Donnachie-Landshoff fit, and from a refit for $\sqrt{s} > 5\,\text{GeV}$ using latest data. The numbers correspond to the $\pi^+\pi^-$ case, while those in brackets are for $\mathrm{K}^+\mathrm{K}^-$.

Parameter	Original	Refit	Remark
$C_{\mathbb{P}}$ [mb]	$13.63\ (11.82)$	$13.25 \pm 0.09\ (11.60 \pm 0.07)$	pomeron strength
$\alpha_{\mathbb{P}}(0)$	1.0808	1.0845 ± 0.0008	pomeron trajectory intercept
$\alpha'_{\mathbb{P}}(0)$ [GeV^{-2}]	0.25		pomeron trajectory slope
C_f [mb]	$31.79\ (17.255)$	$33.75 \pm 0.67\ (17.97 \pm 0.45)$	isoscalar strength
C_ρ [mb]	$4.23\ (9.105)$	$4.12 \pm 0.17\ (9.10 \pm 0.33)$	isovector strength
$\alpha_{\mathbb{R}}(0)$	0.5475	0.545 ± 0.008	reggeon trajectory intercept
$\alpha'_{\mathbb{R}}(0)$ [GeV^{-2}]	0.93		reggeon trajectory slope
$B_{\mathbb{P}}$ [GeV^{-2}]	$5.5 - 6.0$		pomeron slope, $\exp(B_{\mathbb{P}}/2 \cdot t)$
$B_{\mathbb{R}}$ [GeV^{-2}]	$4.0(?)$		reggeon slope, $\exp(B_{\mathbb{R}}/2 \cdot t)$

Donnachie-Landshoff fit on total cross sections

Pomeron and reggeon contributions

k_{T} and b spaces

The differential cross section is related to the scattering amplitude as

$$\frac{\mathrm{d}\sigma_{\mathsf{el}}(t)}{\mathrm{d}t} = \frac{1}{4\pi}|T_{\mathsf{el}}(k_{\mathrm{T}})|^2,$$

where $t \approx -k_{\mathrm{T}}^2 < 0$.

For small $|t|$, T_{el} is **mostly imaginary**: $\rho(t) \equiv \mathrm{Re}\, T_{\mathsf{el}}(t)/\,\mathrm{Im}\, T_{\mathsf{el}}(t)$ is small.

In impact parameter (b) space, the unitarity equation is

$$2\,\mathrm{Im}\, T_{\mathsf{el}}(b) = |T_{\mathsf{el}}(b)|^2 + G_{\mathsf{in}}(b),$$

The elastic **profile function** $T_{\mathsf{el}}(b)$, the overlap $G_{\mathsf{in}}(b)$, from the **opacity** $\Omega(b)$.

$$T_{\mathsf{el}}(b) = i\left(1 - e^{-\Omega(b)/2}\right),$$

$$G_{\mathsf{in}}(b) = 1 - e^{-\Omega(b)}$$

$\mathrm{d}\sigma_{\mathsf{el}}/\mathrm{d}t \propto \exp(Bt)$ (exponential) $\Leftrightarrow$ $t_{\mathsf{el}}(b) \propto \exp[-b^2/(2B)]$ (Gaussian)

Proton opacity, screening

The **amplitude of the single pomeron exchange** is

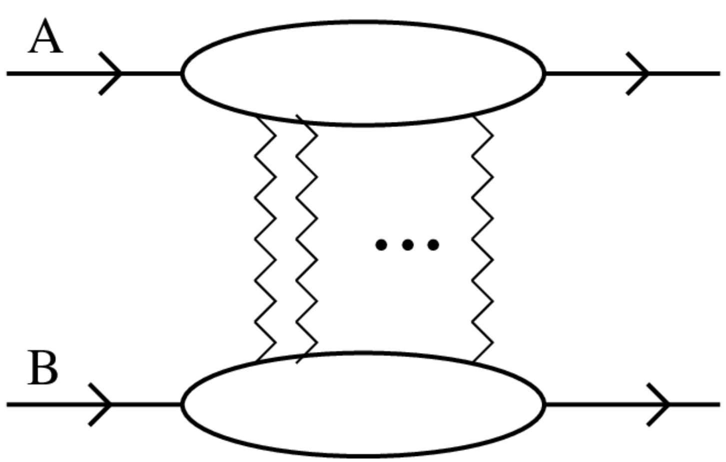
$$\Omega(k_\mathrm{T}) = \eta\sigma_0 F_p^2(t)(s/s_0)^{\alpha_{\mathbb{P}}(t)-1},$$

where $F_p(t)$ is the proton-pomeron form factor, and the (even) signature factor is

$$\eta = i + \tan[\pi/2 \cdot (\alpha_{\mathbb{P}}(t)-1)] \qquad [\approx i e^{-i\frac{\pi}{2}(\alpha_{\mathbb{P}}(t)-1)}].$$

The **opacity** $\Omega(b)$ is obtained through a Fourier transform

$$\Omega(b) = -i \cdot \frac{1}{2\pi}\int \Omega(k_\mathrm{T}) J_0(k_\mathrm{T} b)\, k_\mathrm{T}\, \mathrm{d}k_\mathrm{T}.$$



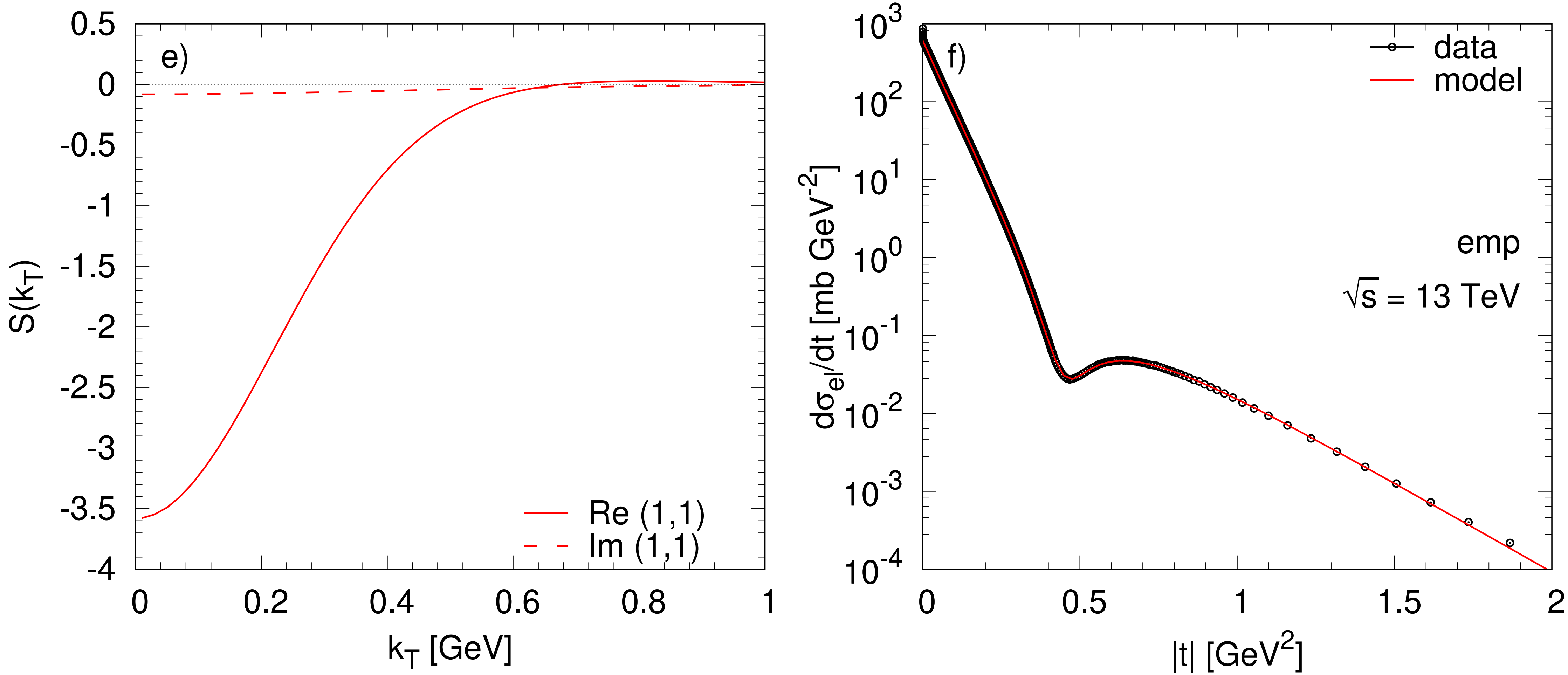
Multiple exchanges (eikonalised opacity),
its Fourier transform gives the screening amplitude S,

$$t_{\mathsf{el}}(b) = i\left(1 - e^{-\Omega(b)/2}\right),$$

$$S(k_\mathrm{T}) = \frac{i}{2\pi}\int t_{\mathsf{el}}(b) J_0(k_\mathrm{T} b)\, b\, \mathrm{d}b,$$

and the elastic amplitude $T_{\mathsf{el}}(k_\mathrm{T}) = (2\pi)^2 \cdot S(k_\mathrm{T})$.

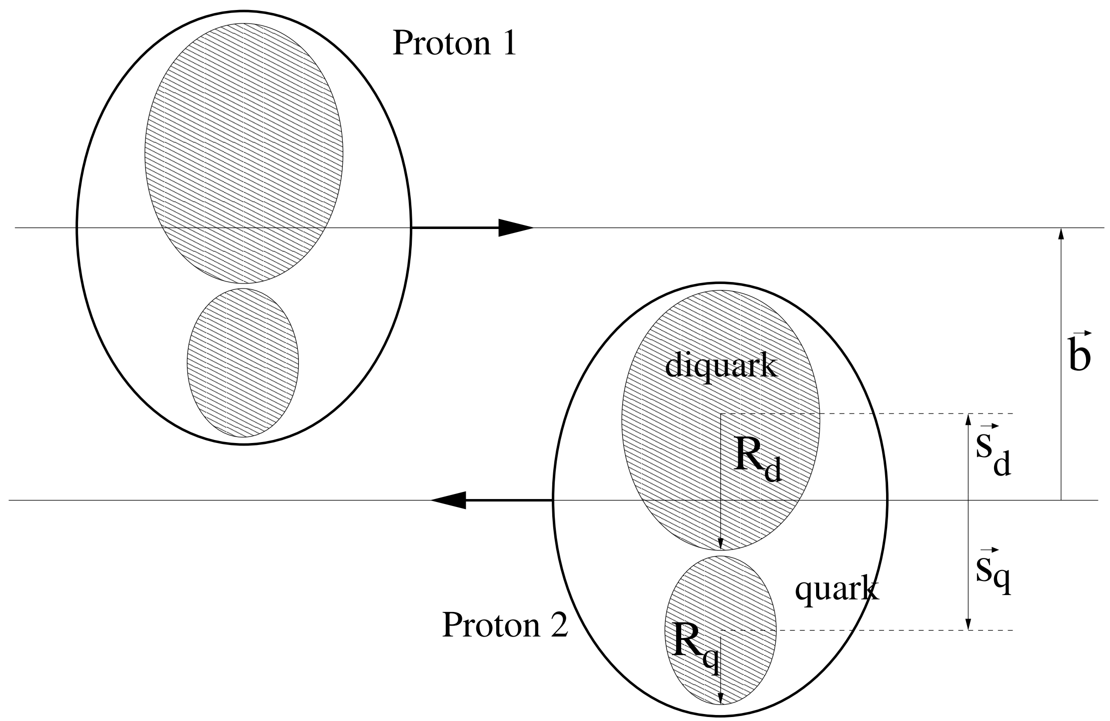
Theory – S from empirical parametrisation

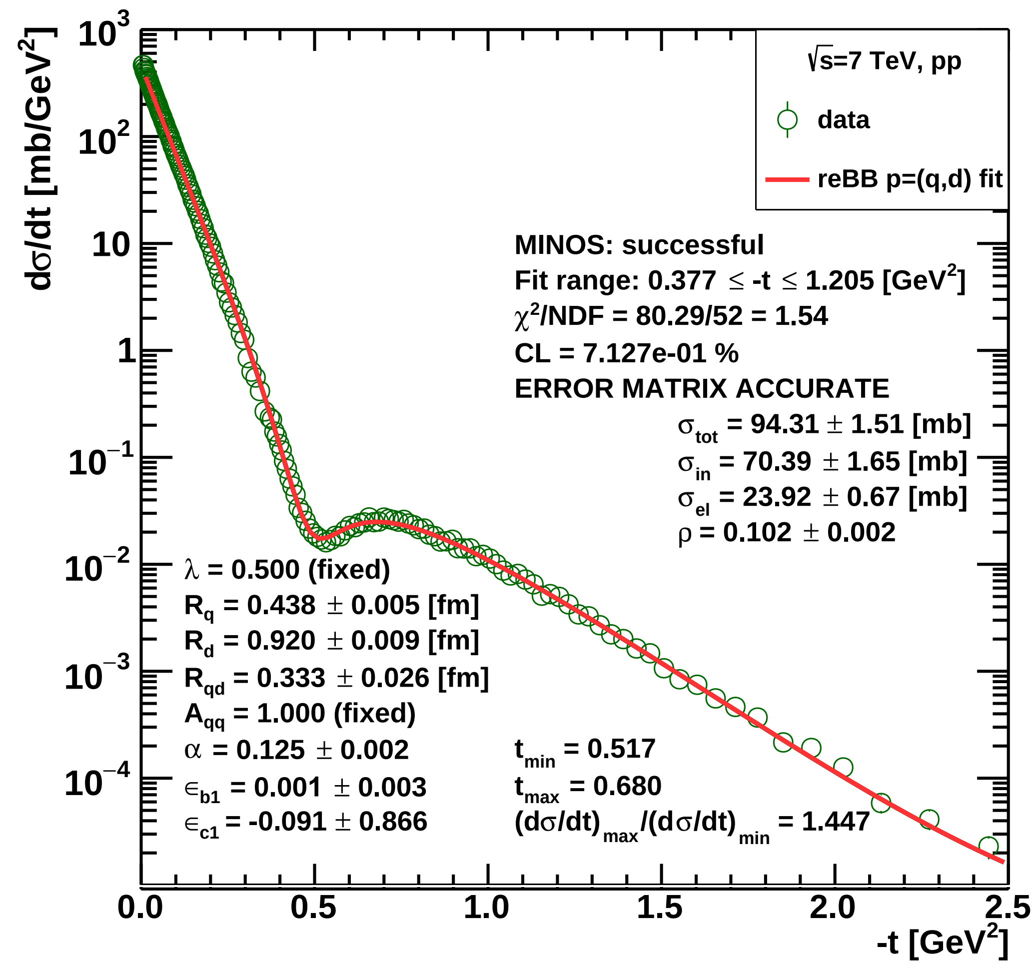


Get it from $S(k_\mathrm{T}) = T_\mathrm{el}(k_\mathrm{T})/(2\pi)^2$ where $T_\mathrm{el}(t) = i\left[G(t)\sqrt{A}e^{Bt/2} + e^{i\phi}\sqrt{C}e^{Dt/2}\right]$

Empirical parametrisation to TOTEM data (Phillips-Barger model)

Theory – S from real extended Bialas-Bzdak model



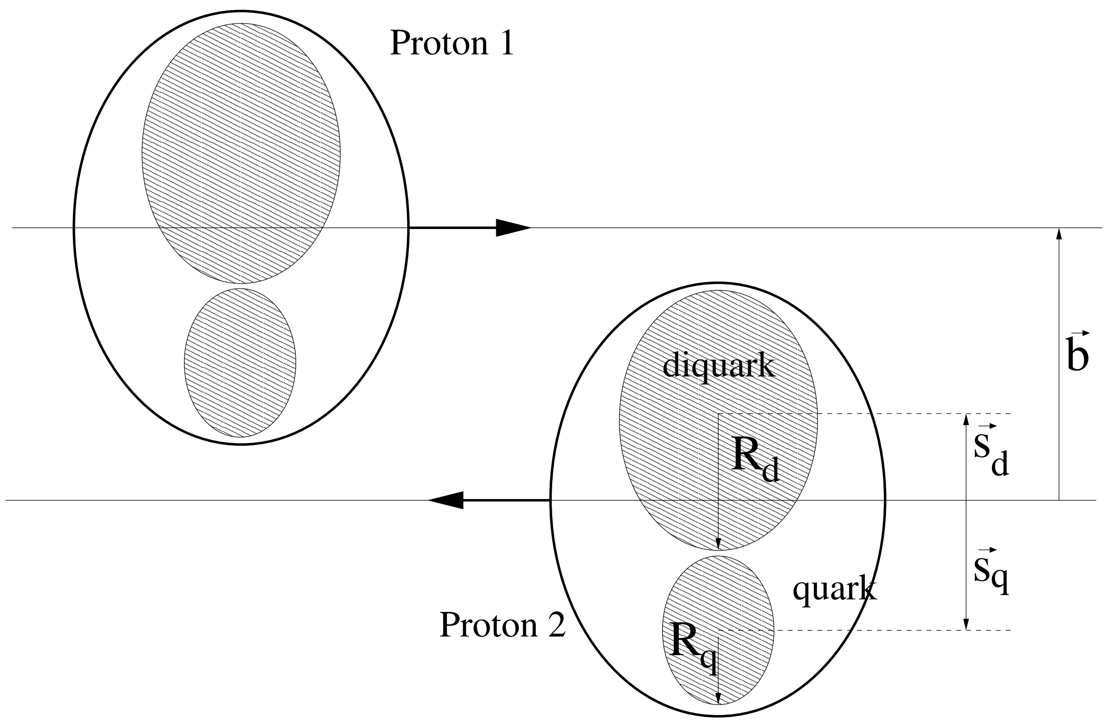


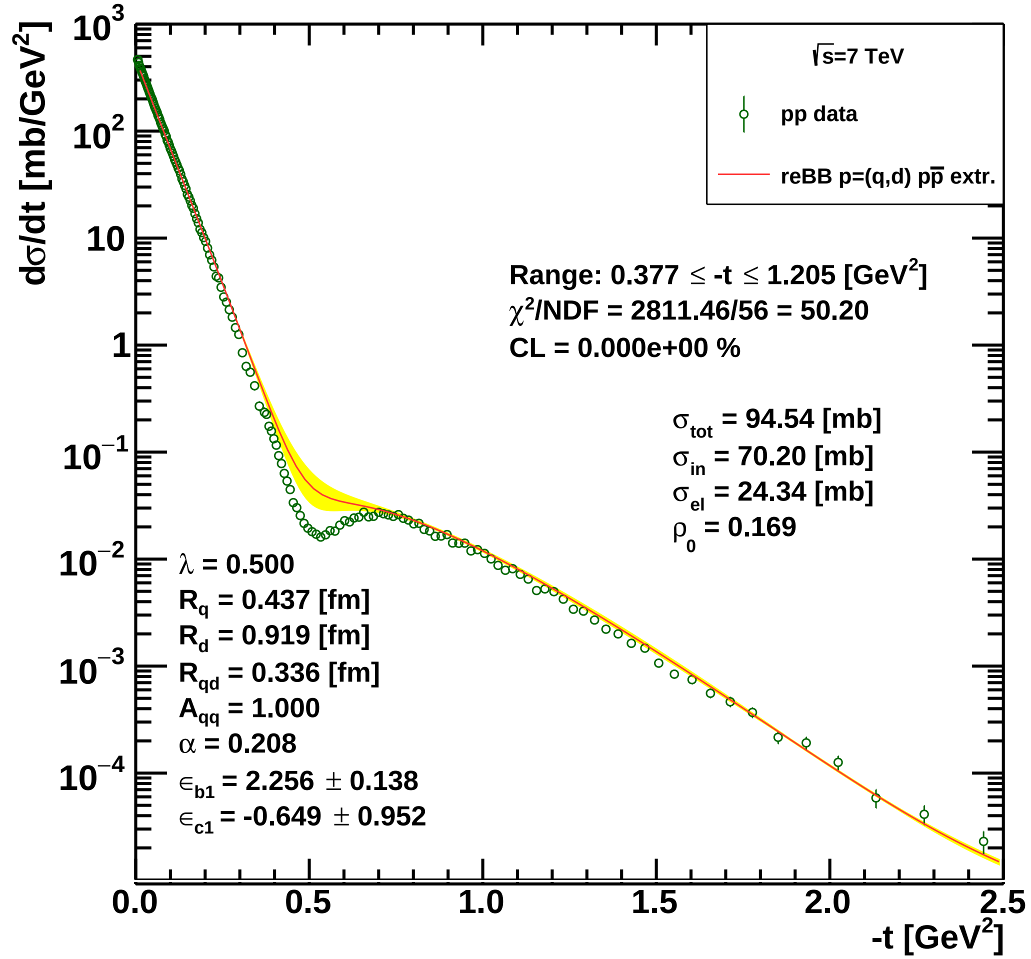
I Szanyi, T Csörgő, Eur Phys J C 81 (2021) 611

Proton as weakly bound state of a constituent quark and a diquark: $p = (q, d)$

Nice description – used also for the odderon study

Theory – S from real extended Bialas-Bzdak model



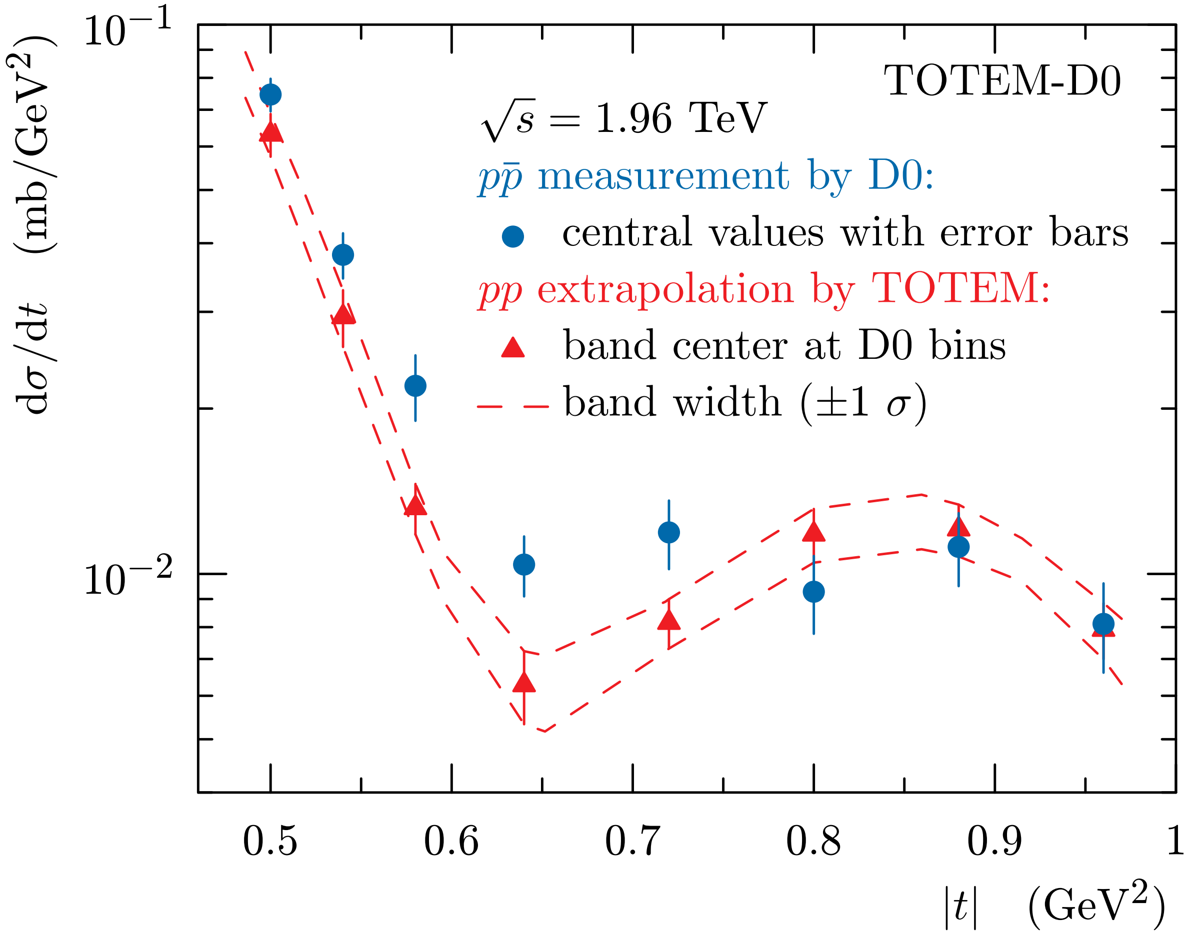


I Szanyi, T Csörgő, Eur Phys J C 81 (2021) 611

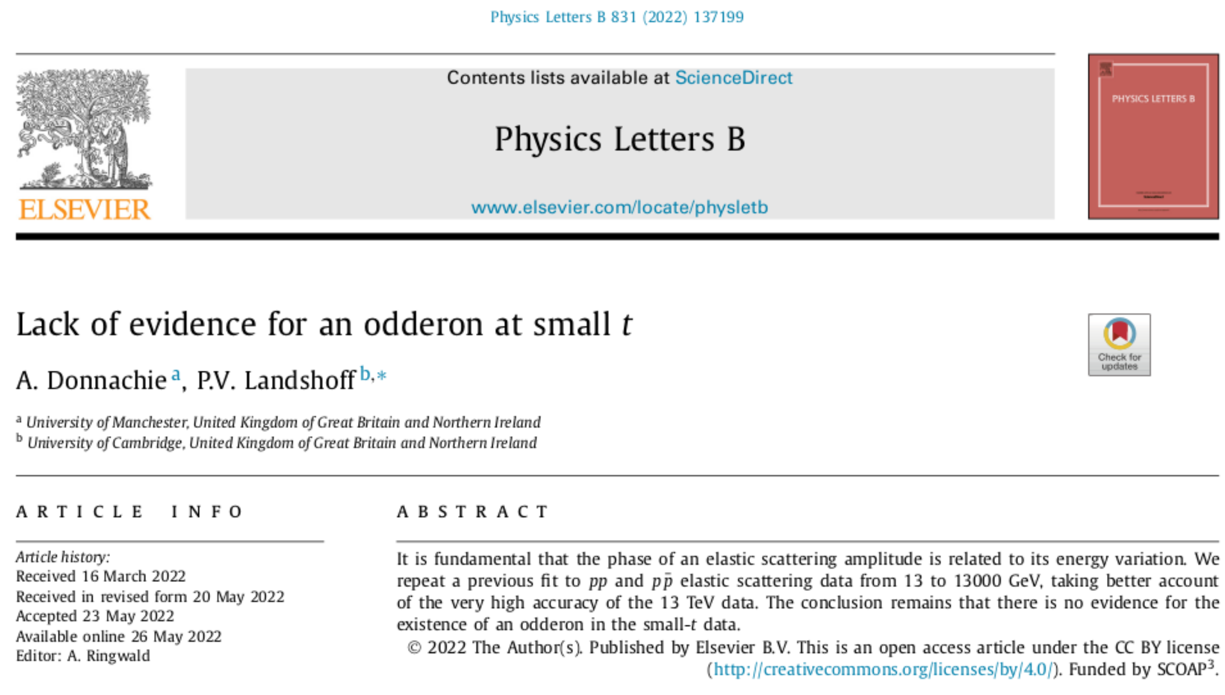
Proton as weakly bound state of a constituent quark and a diquark: $p = (q, d)$

On the right: pp (data) vs $\mathrm{p\overline{p}}$ (extrapolated)

Pomeron → Odderon



D0 and TOTEM Collaborations, Phys Rev Lett 127 (2021) 062003



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Lack of evidence for an odderon at small t

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ABSTRACT

It is fundamental that the phase of an elastic scattering amplitude is related to its energy variation. We repeat a previous fit to pp and $p\bar{p}$ elastic scattering data from 13 to 13000 GeV, taking better account of the very high accuracy of the 13 TeV data. The conclusion remains that there is no evidence for the existence of an odderon in the small-t data.

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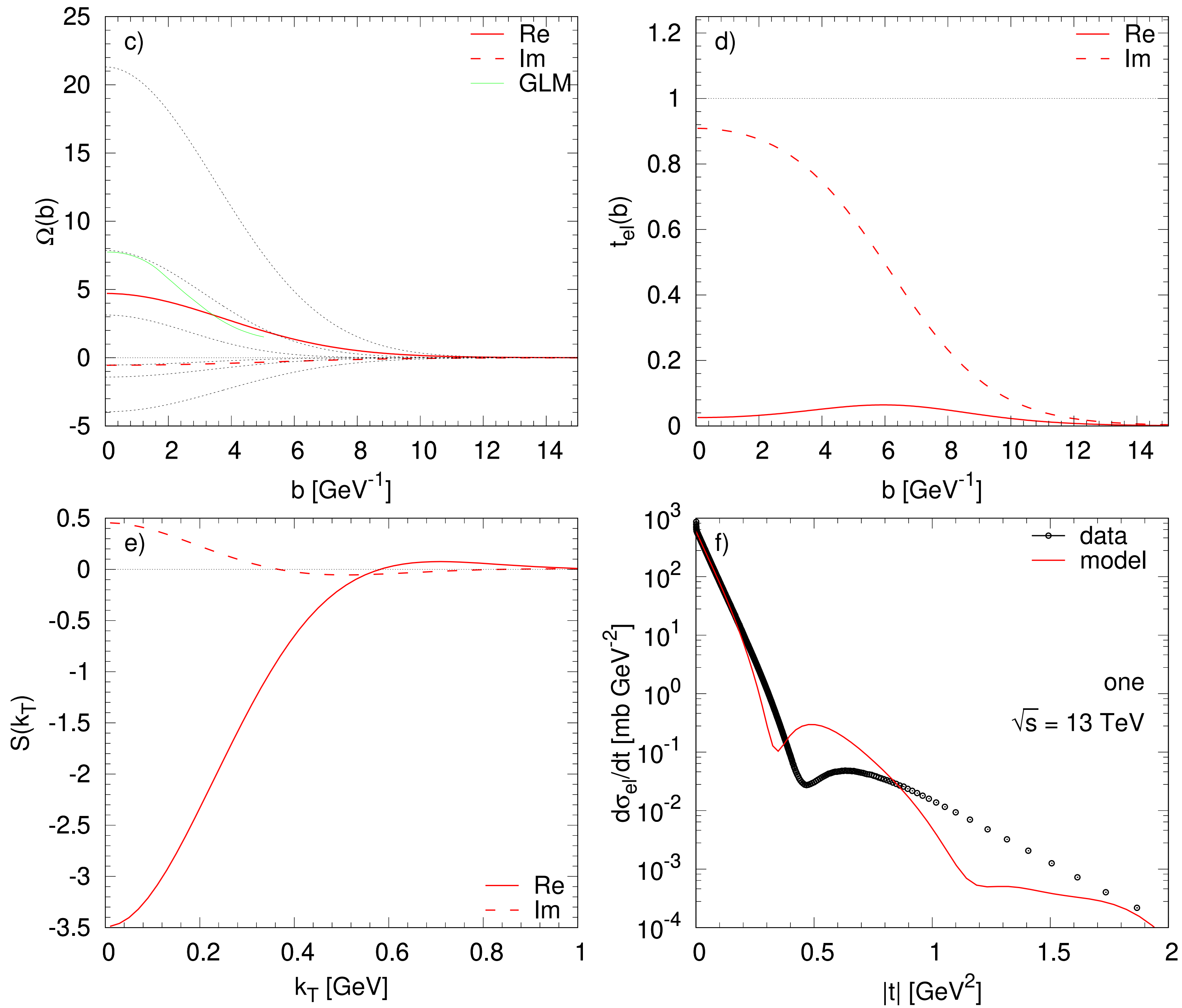
Discovery – extrapolations and scaling – evidence for odd component

Theory – S from pomeron exchanges – one channel



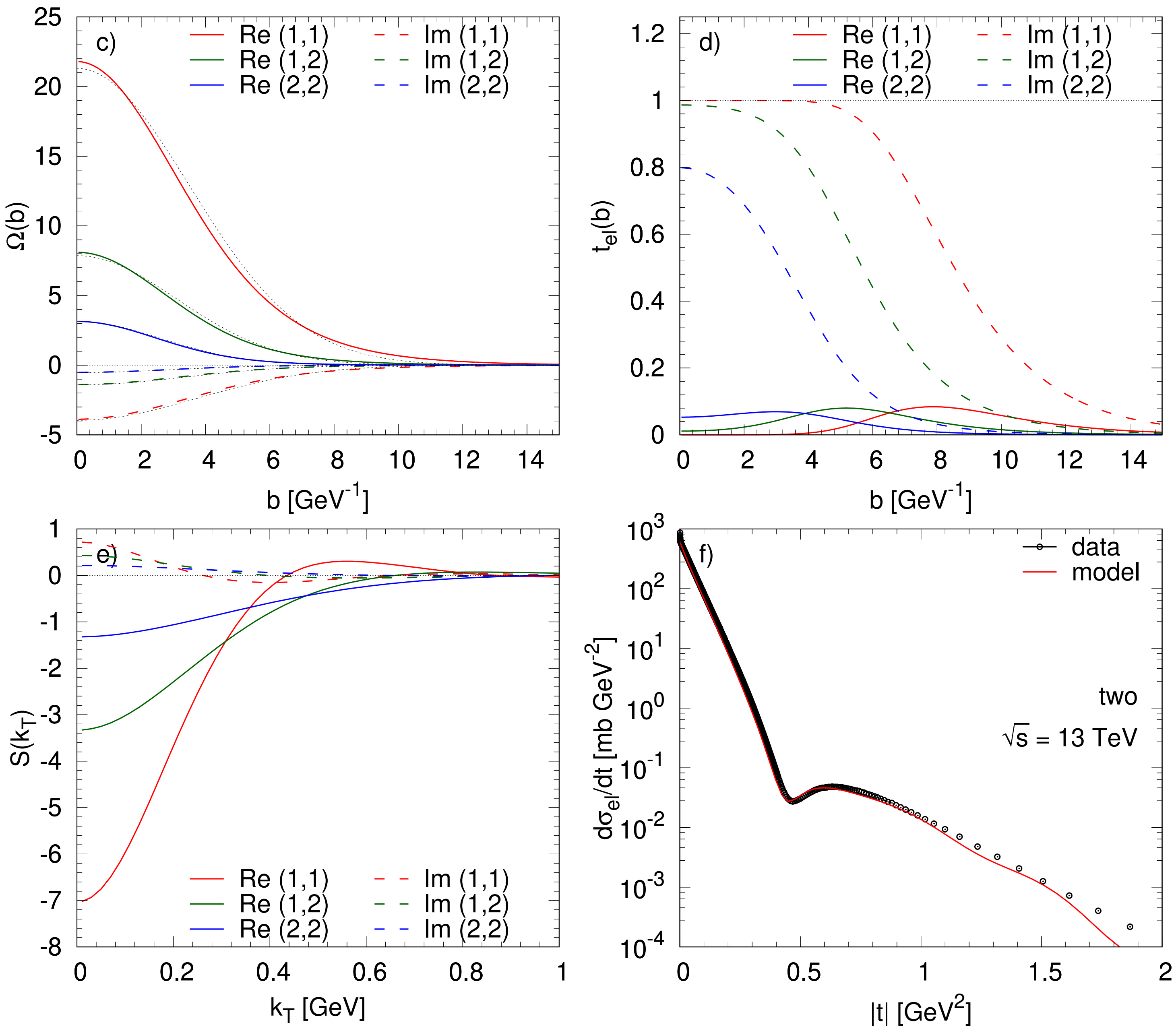
– amplitude of $\mathbb{P}$ exchange
$$\Omega(k_\mathrm{T}) = \eta\sigma_0 F_p^2(t)(s/s_0)^{\alpha_\mathbb{P}(t)-1}$$
proton-$\mathbb{P}$ form factor $F_p(t)$, signature factor η

– opacity $\Omega(b)$ from Fourier
$$\Omega(b) = -i \cdot \frac{1}{2\pi}\int \Omega(k_\mathrm{T}) J_0(k_\mathrm{T} b)\, k_\mathrm{T}\, \mathrm{d}k_\mathrm{T}$$

– multiple exchanges
$$t_\mathrm{el}(b) = i\left(1 - e^{-\Omega(b)/2}\right)$$

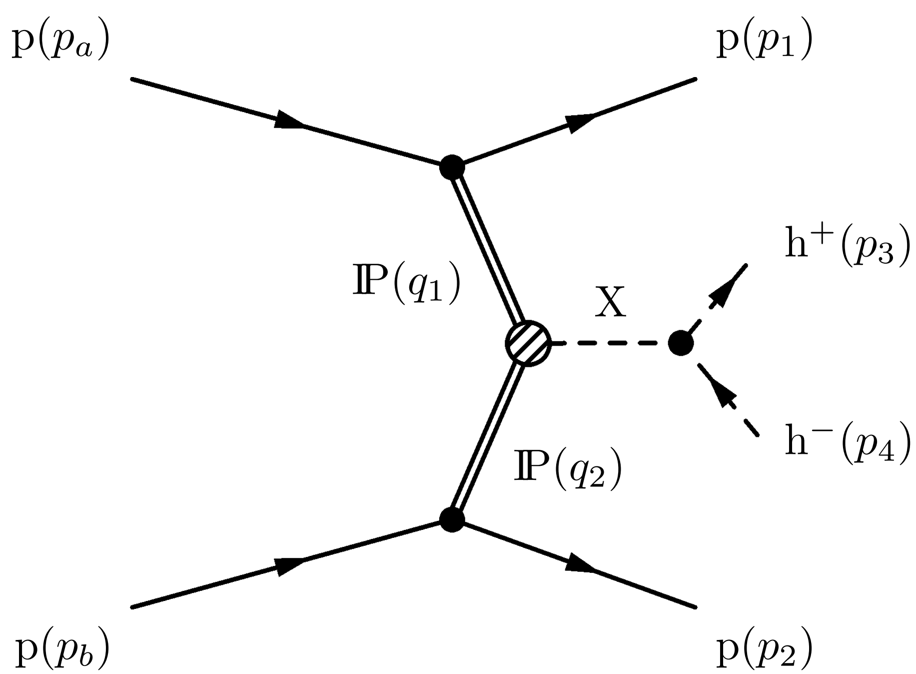
– elastic amplitude
$$T_\mathrm{el}(k_\mathrm{T}) = -\, i \cdot 2\pi \int t_\mathrm{el}(b) J_0(k_\mathrm{T} b)\, b\, \mathrm{d}b$$

Theory – S from pomeron exchanges – two channels



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

Central exclusive production – data



- CMS+TOTEM dataset
  - **two scattered protons** and **two central hadrons**
  - a central system (X) was created
  - the invariants are

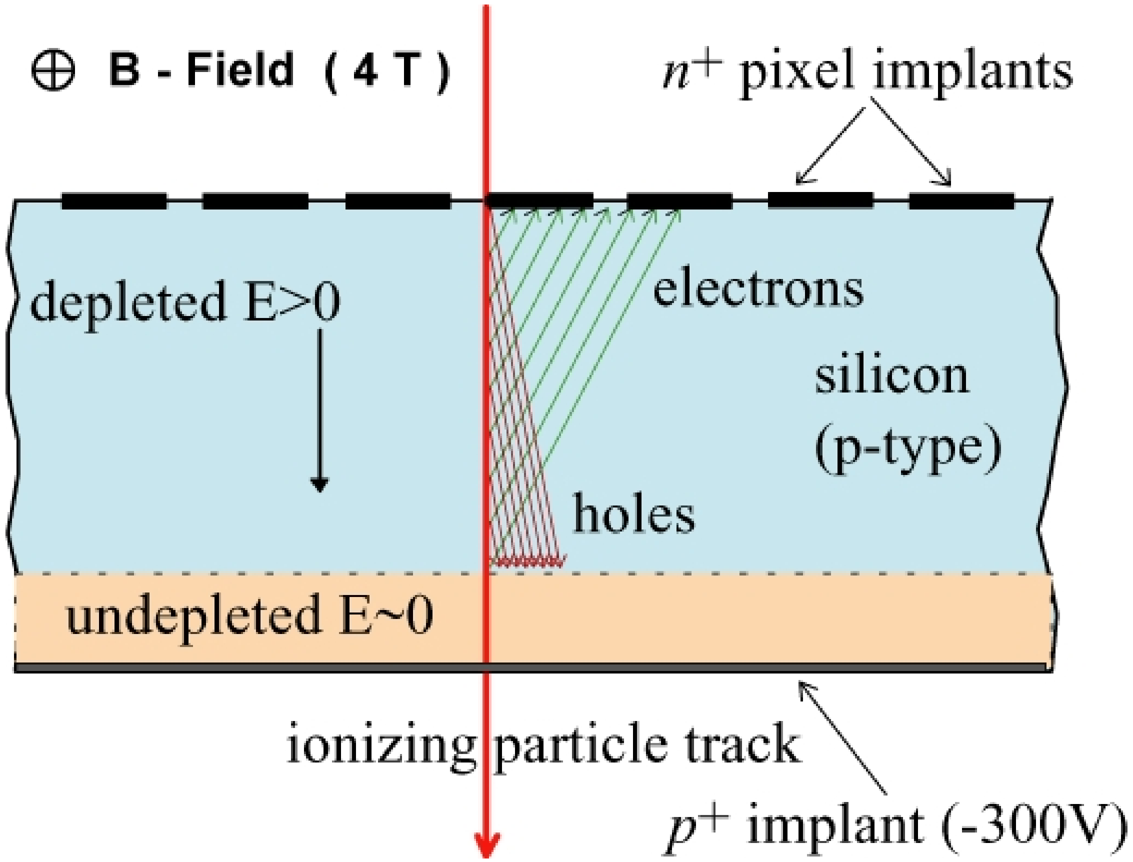
    $q_1^2 = t_1 \approx \underline{\underline{-p_{1\mathrm{T}}^2}} < 0,$

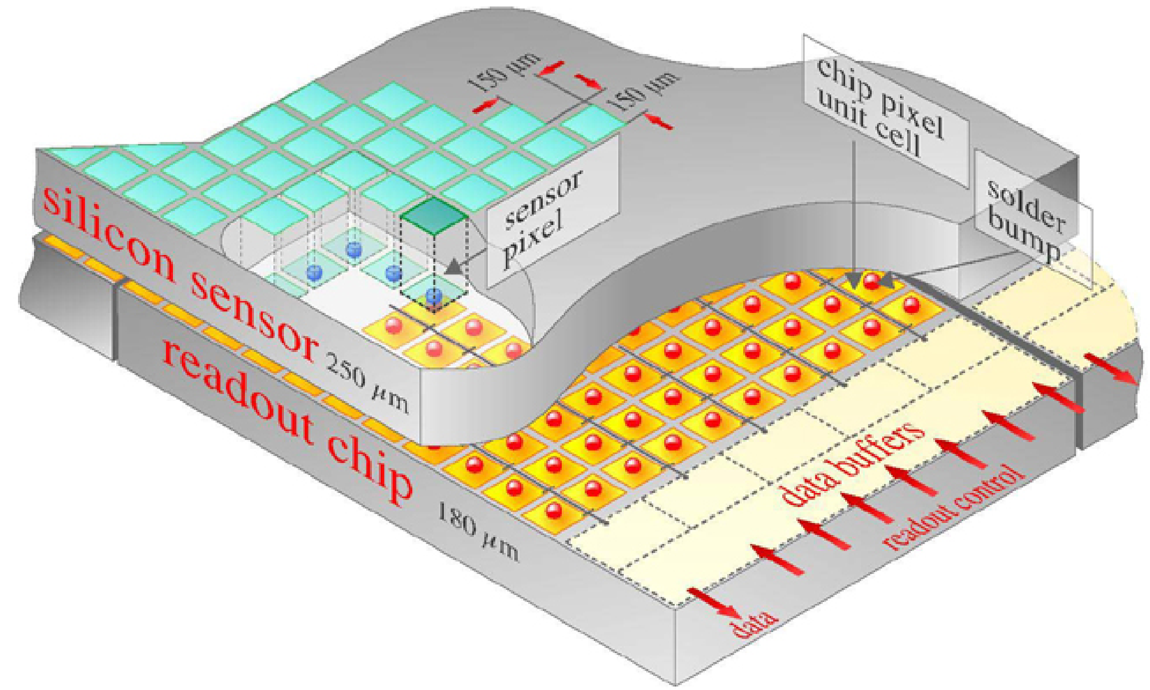
    $q_2^2 = t_2 \approx \underline{\underline{-p_{2\mathrm{T}}^2}} < 0,$

    and $p_X^2 = \underline{\underline{m^2}}$

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

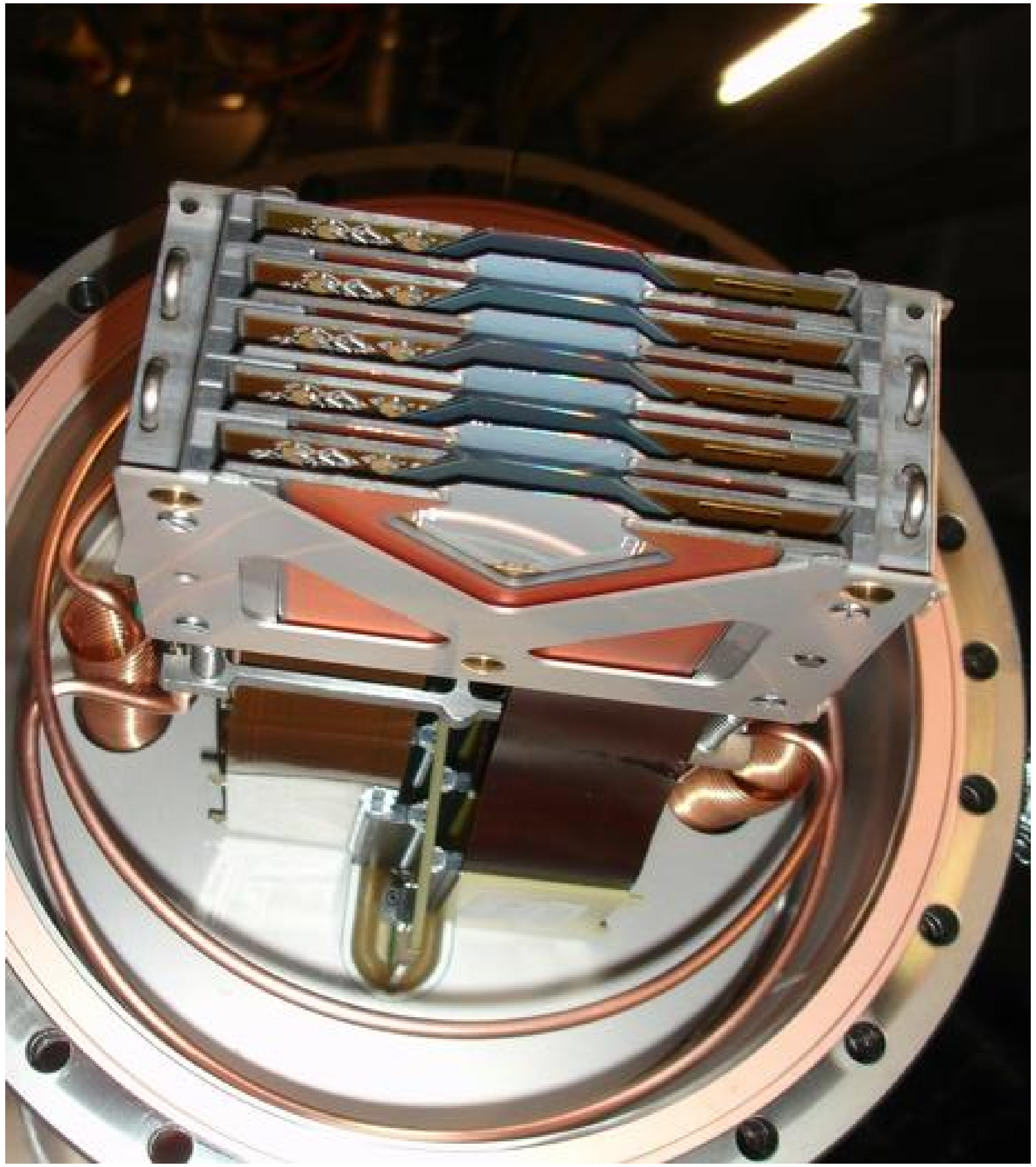
Silicon trackers





Charged particle → electron-hole pairs → drift and diffusion → readout

Scattered protons – roman pots

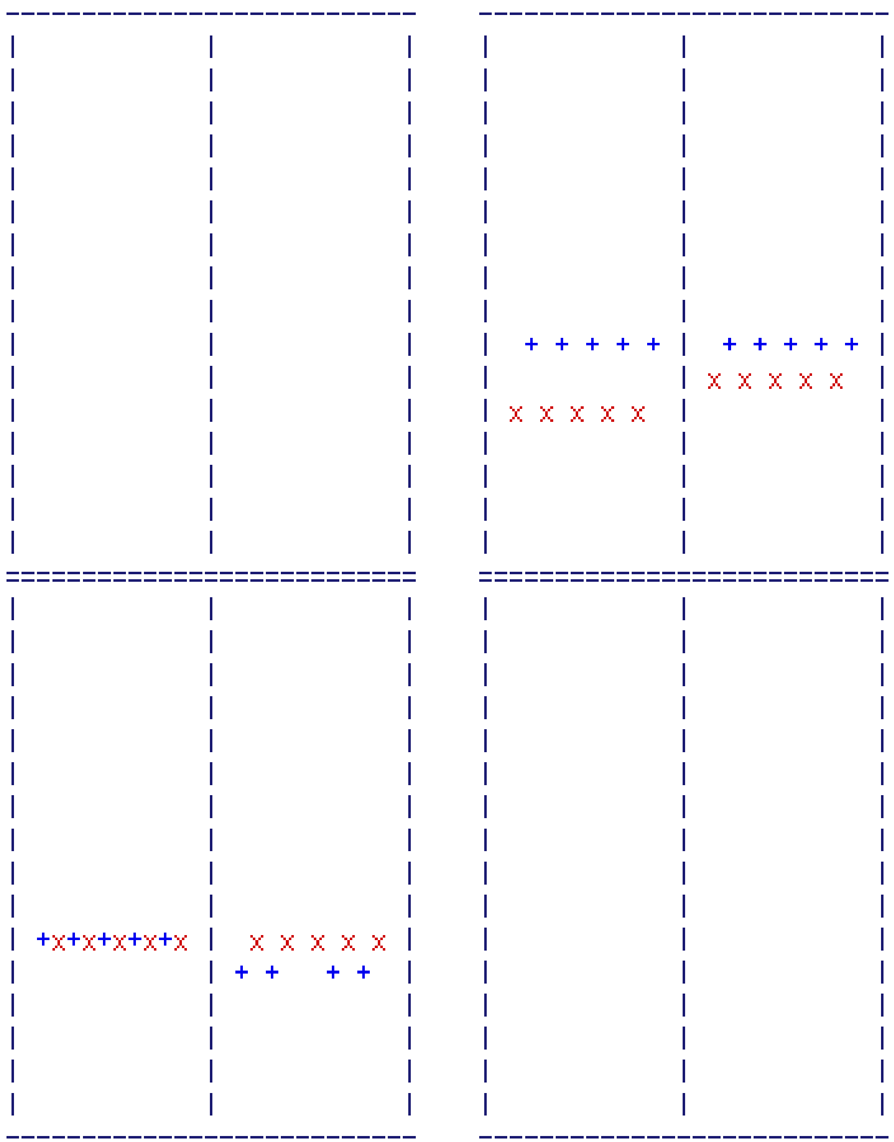


- Details
  - two arms (in sectors 45 and 56)
  - near and far stations (at $\approx$213 and 220 m)
  - top and bottom pots
  - within a pot: 5 planes in 'u' and 5 planes in 'v' directions
  - each plane has: 4×128 strips
- Two pots per arm

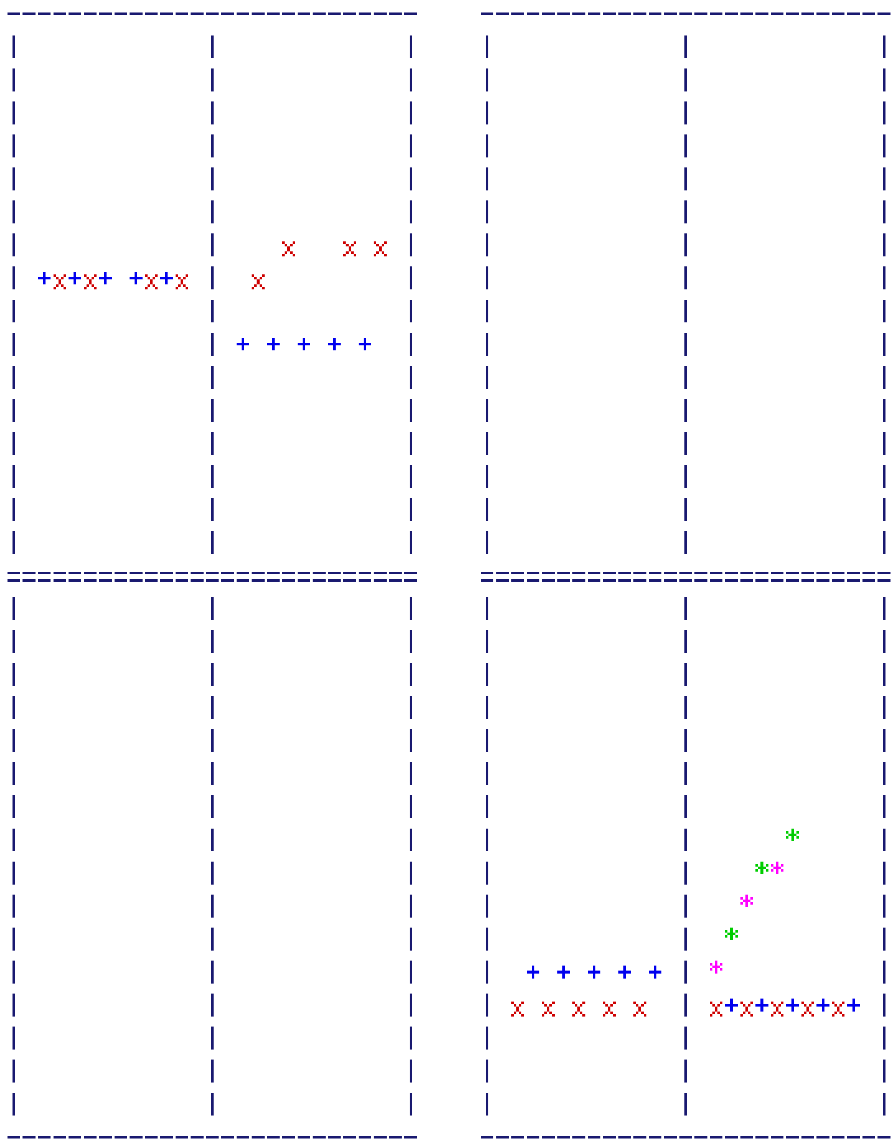
$\rightarrow$ two measurements

$\rightarrow$ location and momentum at IP

Roman pots – close look at events (not to scale!)

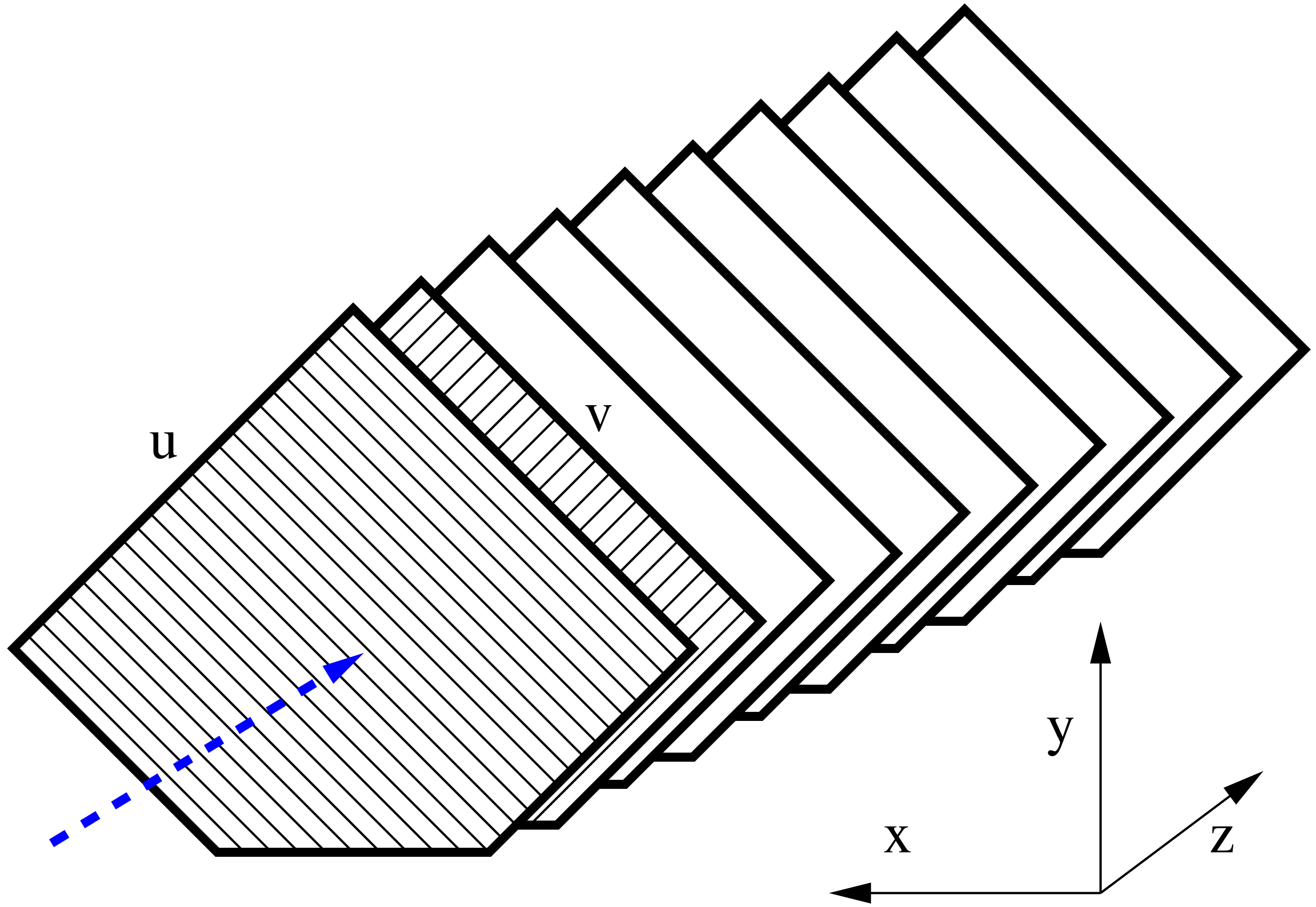


Normal



Normal with secondary (1% within a station)

Roman pots – protons

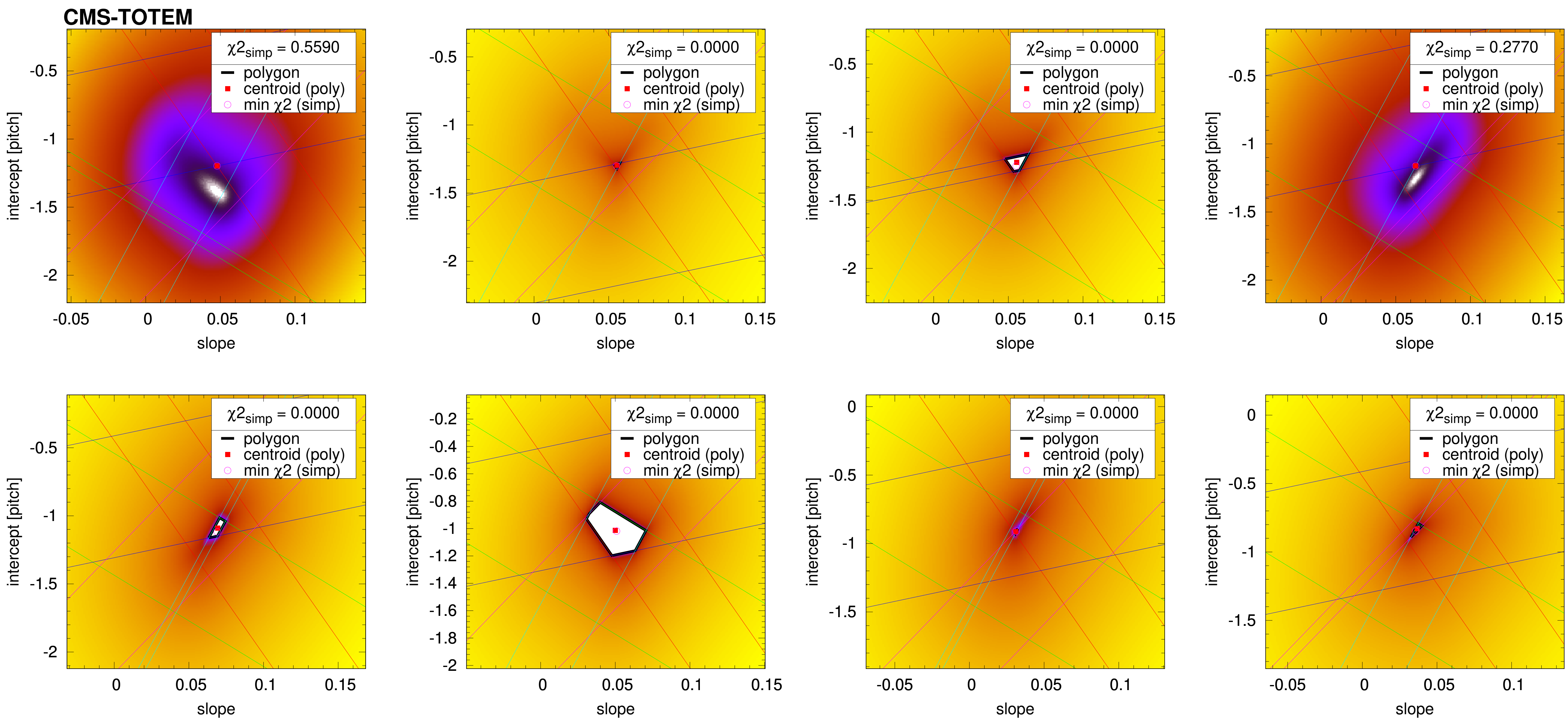


Track model: $u_i = az_i + b + \delta_i$

Digital hit information (strip number) vs usual normally-distributed uncertainties

Expected location on the ith plane: measured u_i, slope a, intercept b, shift δ_i

Roman pots – fitting tracklets (5 planes)

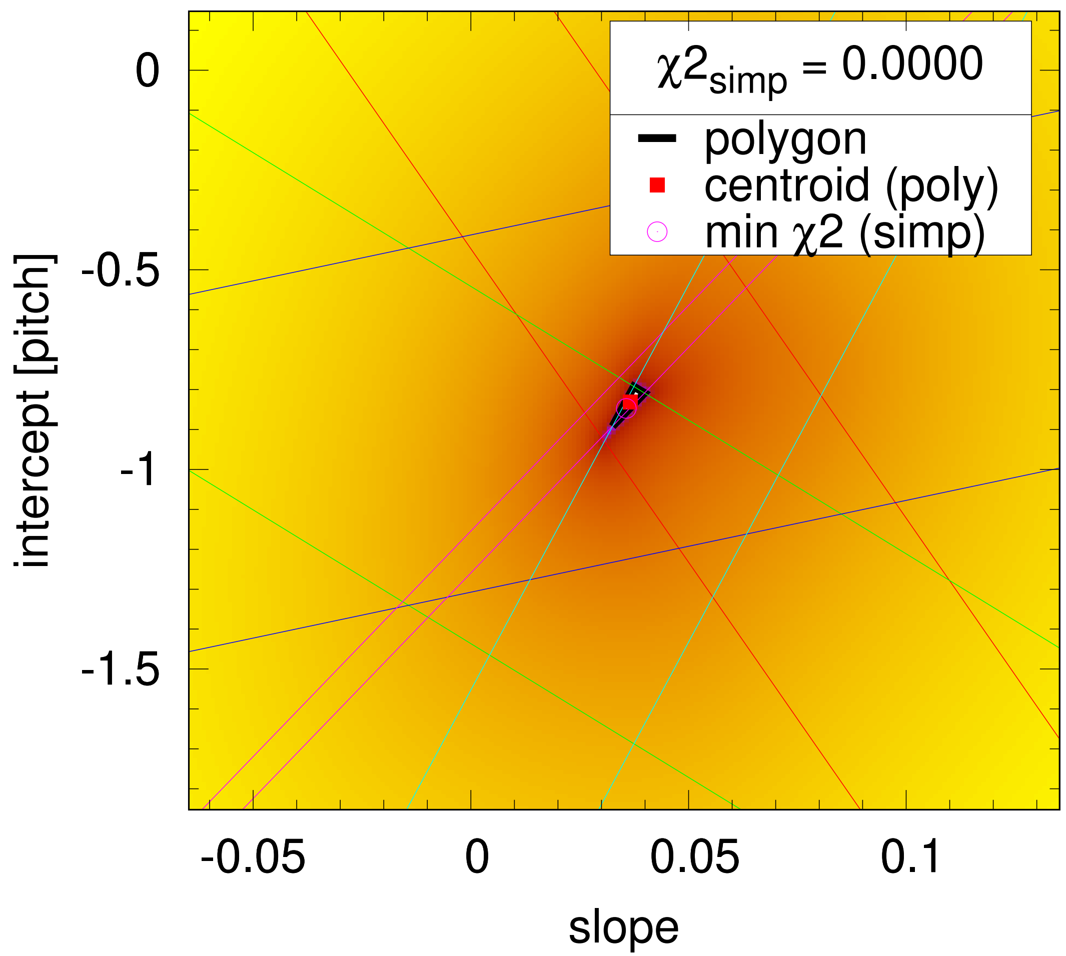


Track intercept vs slope (at local $z = 0$)

Find intersection of bands: polygon

Use that for relative alignment of ‘u’ and ‘v’ planes

Roman pots – fitting tracklets (5 planes)



Bands

$$y_i^{\text{clus}} - az_i - \delta_i - w < b < y_i^{\text{clus}} - az_i - \delta_i + w,$$

Centroid

$$C_x = \frac{1}{6A}\sum_{j=0}^{n-1}(x_j + x_{i+j})(x_j\ y_{j+1} - x_{j+1}\ y_j),$$

$$C_y = \frac{1}{6A}\sum_{j=0}^{n-1}(y_j + y_{i+j})(x_j\ y_{j+1} - x_{j+1}\ y_j),$$

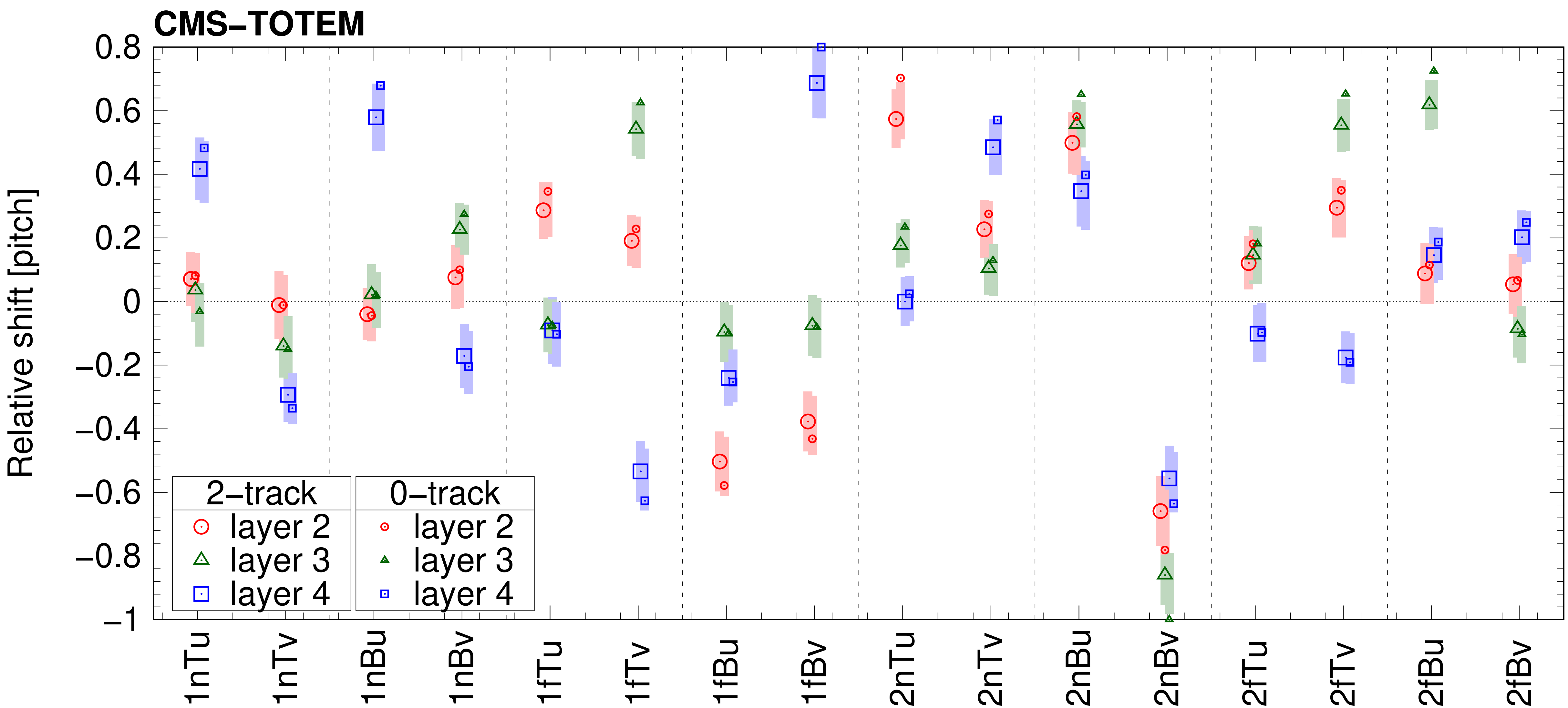
Area of the polygon is $A = \frac{1}{2}\sum_{j=0}^{n-1}(x_j\ y_{j+1} - x_{j+1}\ y_j)$

Variance through the moment of inertia

$$\sigma_y^2 = \frac{1}{12A}\sum_{j=0}(x_j y_{j+1} - x_{j+1} y_j)(y_j^2 + y_j y_{j_1}^2 + y_{j+1}^2)$$

Use global χ^2 of all tracklets to optimize relative shifts

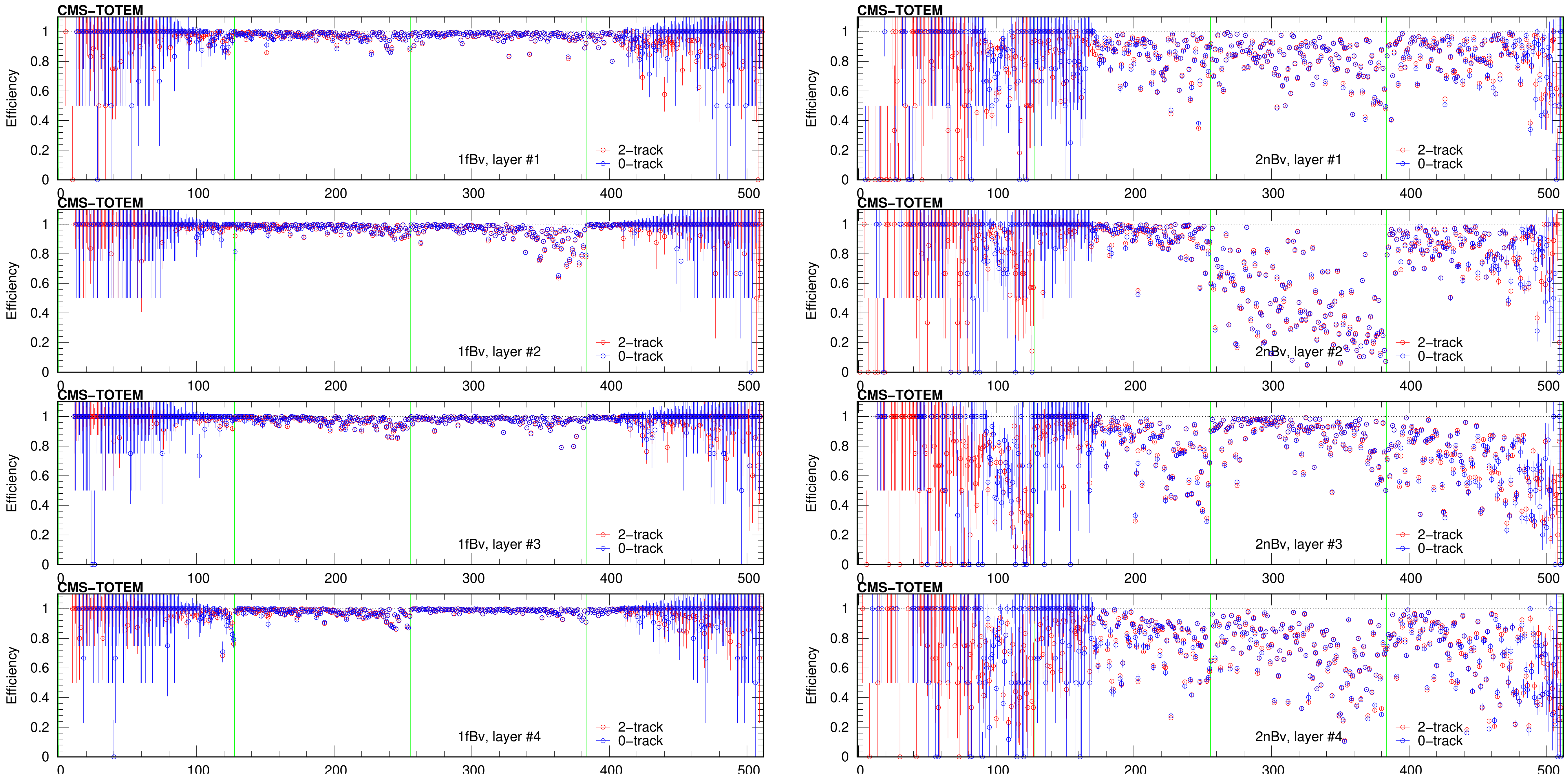
Roman pots – relative alignment of planes



Relative shifts in pitch (66 μm) units, for central exclusive elastic events

Translation and shear (weak modes)! Planes 1 and 5 are fixed

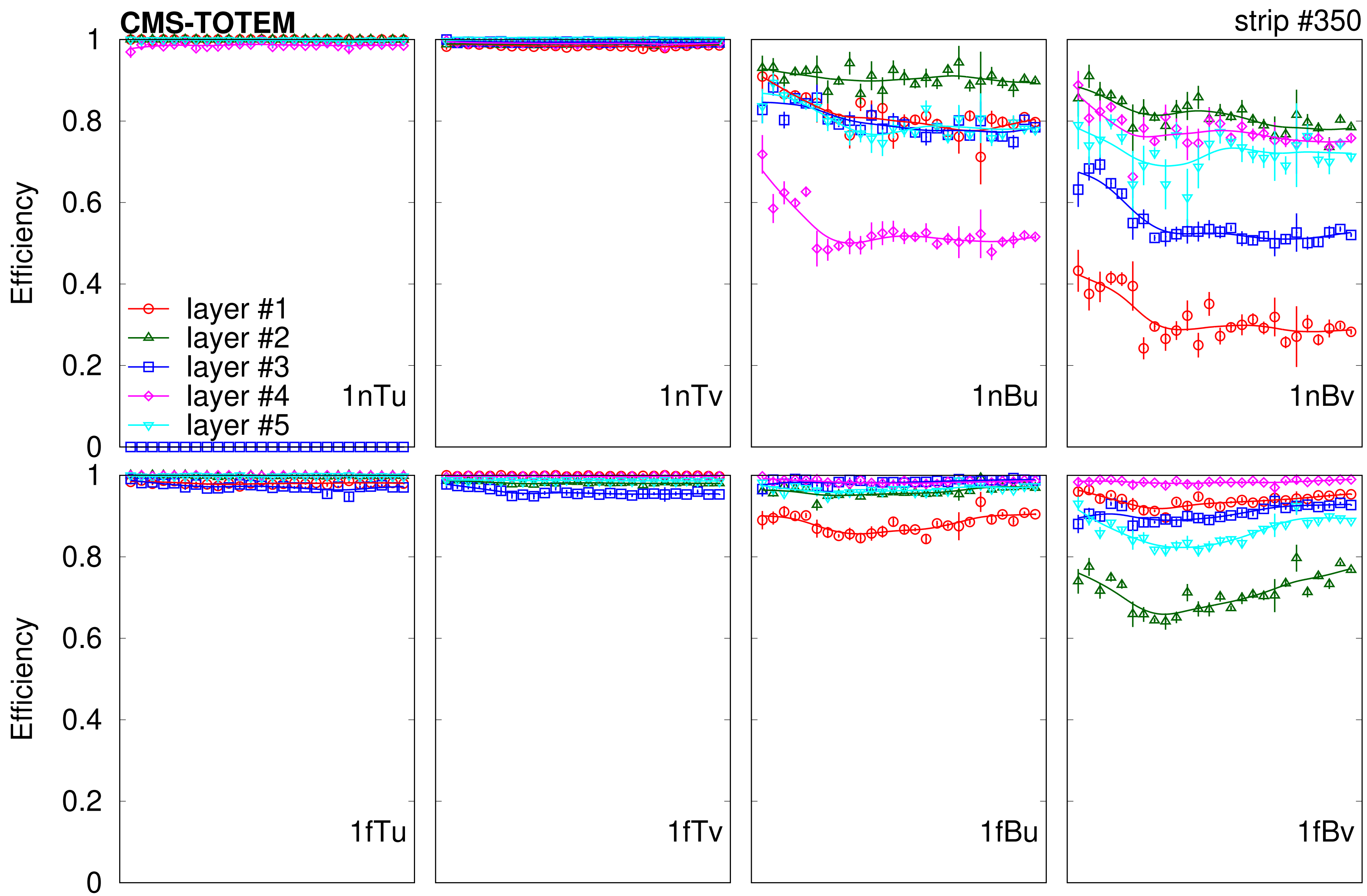
Roman pots – strip-level inefficiencies



Extract efficiencies through “tag and probe”

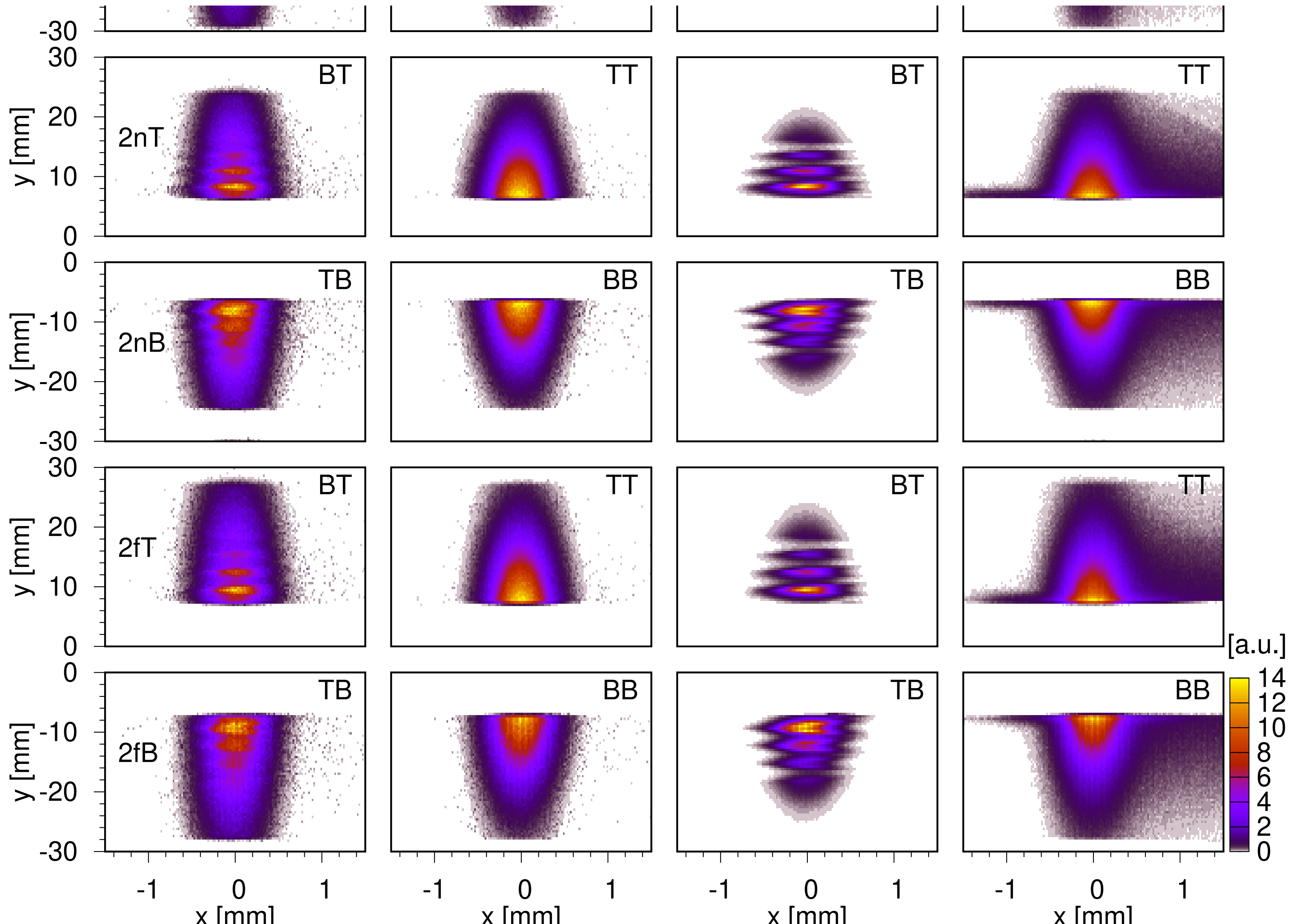
Likely connected to suboptimal settings (VFAT chips à 128 channels)

Roman pots – strip-level efficiencies vs run



Changes wrt run number (here, for a given strip #350)

Roman pots – proton hit locations



Efficiency corrected

Beam optics studies – local vs global

The transverse coordinates of a particle (proton) at a path length s

$$x(s) = \sqrt{\beta_x(s)\varepsilon}\,\cos\left[\phi_0 + \Delta\mu(s)\right] + D_x(s)\Delta p/p,$$

with betatron amplitude β, emittance ε, phase offset ϕ_0, phase advance $\Delta\mu$, dispersion function D, relative momentum loss $\Delta p/p$.

The dependencies around a given location can be **linearised**,

$$x_1 = v_{x,1}x^* + L_{x,1}\theta_x^* + D_{x,1}\Delta p/p, \qquad x_2 = v_{x,2}x^* + L_{x,2}\theta_x^* + D_{x,2}\Delta p/p,$$

magnification $v(s) = \sqrt{\beta(s)/\beta^*}\cos\Delta\mu$ and **effective length** $L(s) = \sqrt{\beta(s)\beta^*}\sin\Delta\mu$.

For elastic and central exclusive collisions $|\Delta p/p| \ll 1$, the above equations solved as

$$x^* = (L_{x,2}x_1 - L_{x,1}x_2)/|d|, \qquad \theta_x^* = (v_{x,1}x_2 - v_{x,2}x_1)/|d|,$$

where $|d| = v_{x,1}L_{x,2} - v_{x,2}L_{x,1}$ is the distance between the near and far pots.

Beam optics studies – near vs far

The variance $\mathrm{var}(x^*)$ is obtained as

$$\mathrm{var}(x^*) = \frac{\mathrm{var}(x_n)\mathrm{var}(x_f) - \mathrm{cov}(x_n, x_f)^2}{\mathrm{var}(x_f)v_n^2 - 2\mathrm{cov}(x_n, x_f)v_n v_f + \mathrm{var}(x_n)v_f^2}.$$

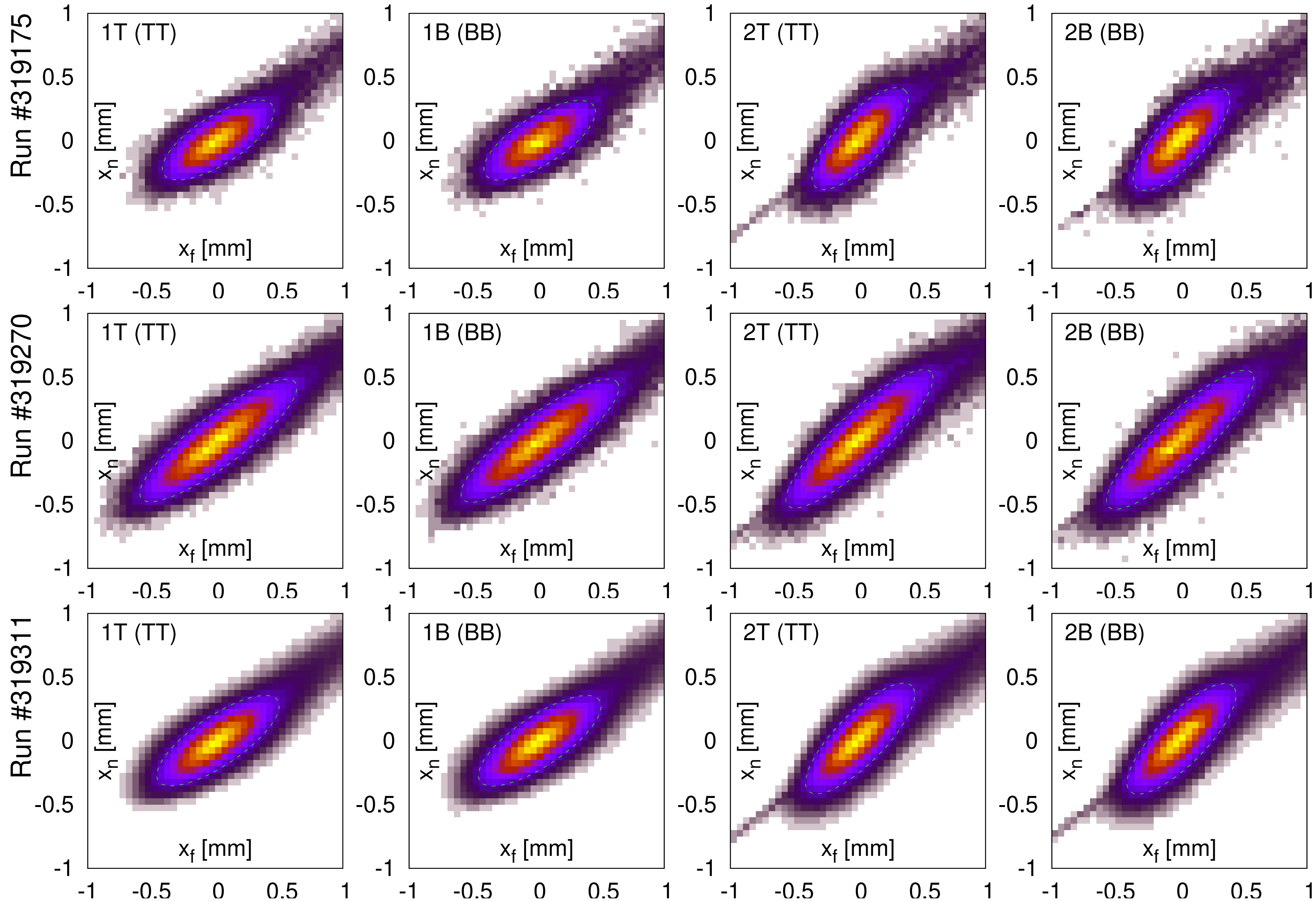
The ratio of far and near effective lengths is

$$\frac{L_{x,f}}{L_{x,n}} = \sqrt{\frac{\mathrm{var}(x_2) - \mathrm{var}(x^*)v_2^2}{\mathrm{var}(x_1) - \mathrm{var}(x^*)v_1^2}}.$$

The variance of the emission angle is

$$\mathrm{var}(\theta_x^*) = \frac{\mathrm{var}(v_f x_n - v_n x_f)}{d^2},$$

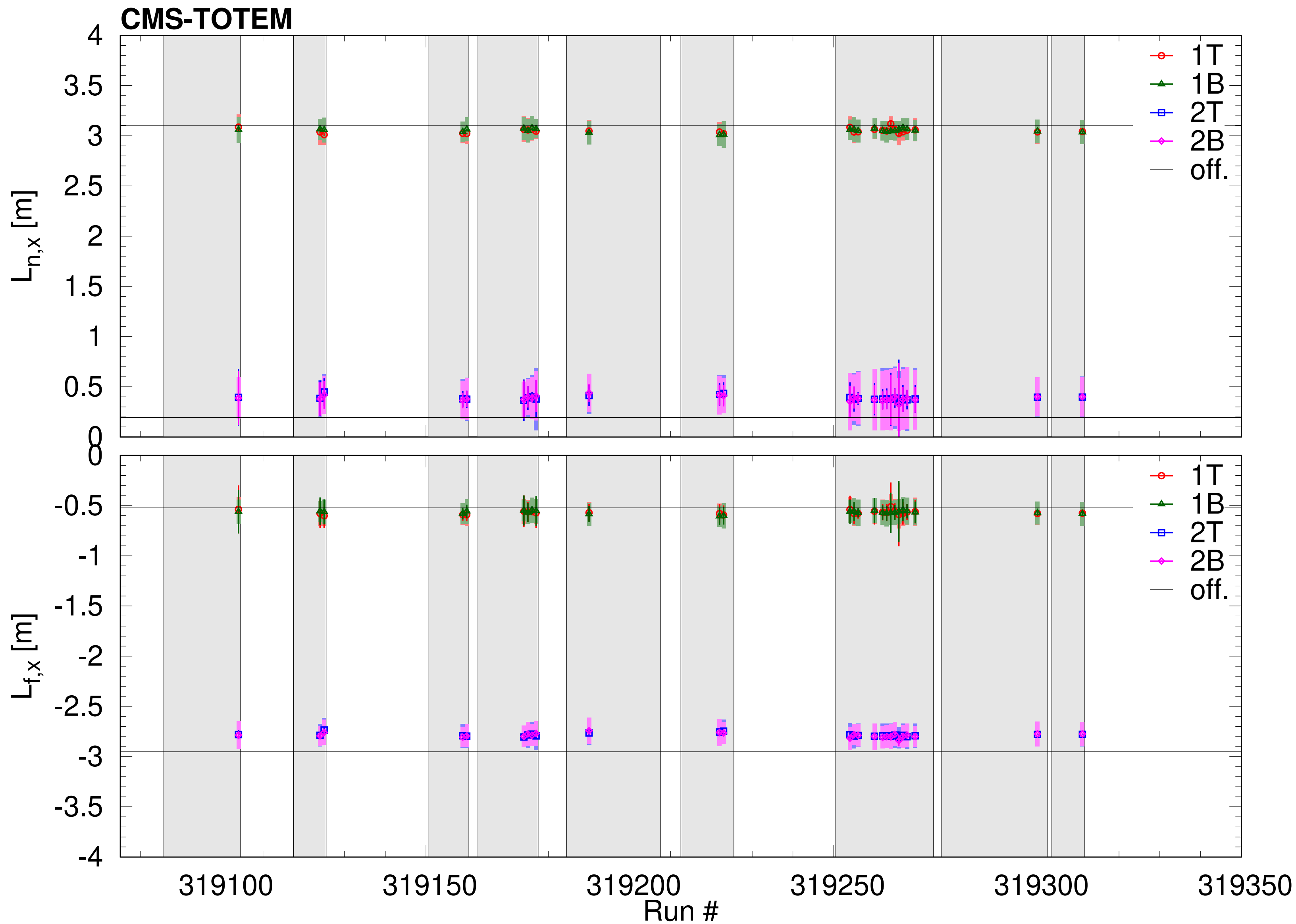
Beam optics studies – near vs far



Left arm vs right arm asymmetry

Extract effective lengths L_x from near-far hit covariances

Beam optics studies – effective lengths L_n (near) and L_f (far)



Arm	Station	L_x [m] nominal	L_x [m] estimated
1	near	3.10	3.05
1	far	-0.52	-0.58
2	near	0.19	0.39
2	far	-2.95	-2.79

Comparing to nominal numbers, nice match

Scattered protons – absolute alignment per run – x direction

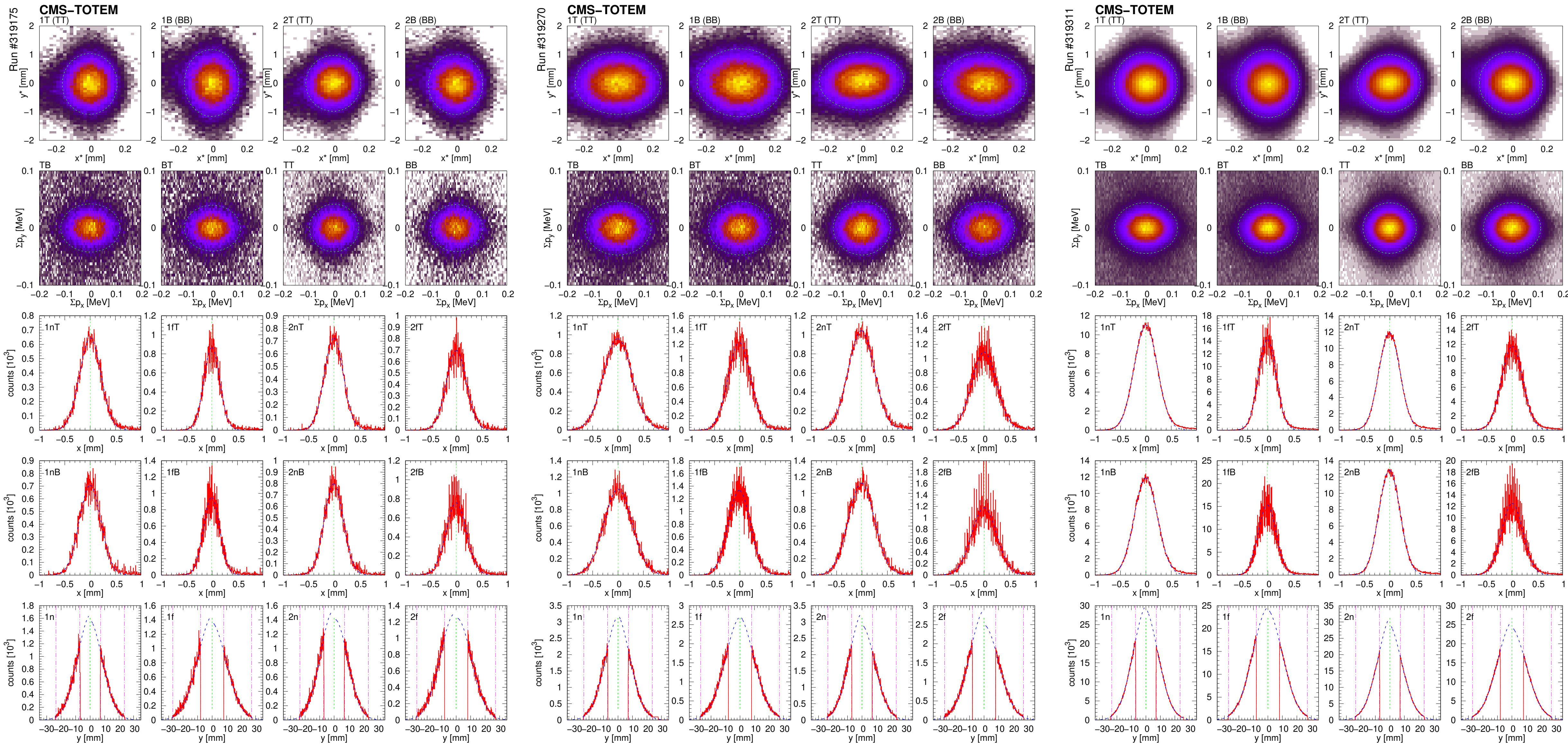
$$A_x = \begin{pmatrix} L_{1f}/d & -L_{1n}/d & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & L_{1f}/d & -L_{1n}/d & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & L_{2f}/d & -L_{2n}/d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & L_{2f}/d & -L_{2n}/d \\ -pv_{1f}/d & pv_{1n} & 0 & 0 & 0 & 0 & -pv_{2f}/d & pv_{2n}/d \\ 0 & 0 & -pv_{1f}/d & pv_{1n}/d & -pv_{2f}/d & pv_{2n}/d & 0 & 0 \\ -pv_{1f}/d & pv_{1n}/d & 0 & 0 & -pv_{2f}/d & pv_{2n}/d & 0 & 0 \\ 0 & 0 & -pv_{1f}/d & pv_{1n}/d & 0 & 0 & -pv_{2f}/d & pv_{2n}/d \end{pmatrix},$$

and the transformation itself is

$$A_x \begin{pmatrix} \delta x_{1nT} \\ \delta x_{1fT} \\ \delta x_{1nB} \\ \delta x_{1fB} \\ \delta x_{2nT} \\ \delta x_{2fT} \\ \delta x_{2nB} \\ \delta x_{2fB} \end{pmatrix} = \begin{pmatrix} -\overline{x^*}_{1T} \\ -\overline{x^*}_{1B} \\ -\overline{x^*}_{2T} \\ -\overline{x^*}_{2B} \\ -\overline{\sum p_x}_{TB} \\ -\overline{\sum p_x}_{BT} \\ -\overline{\sum p_x}_{TT} \\ -\overline{\sum p_x}_{BB} \end{pmatrix}.$$

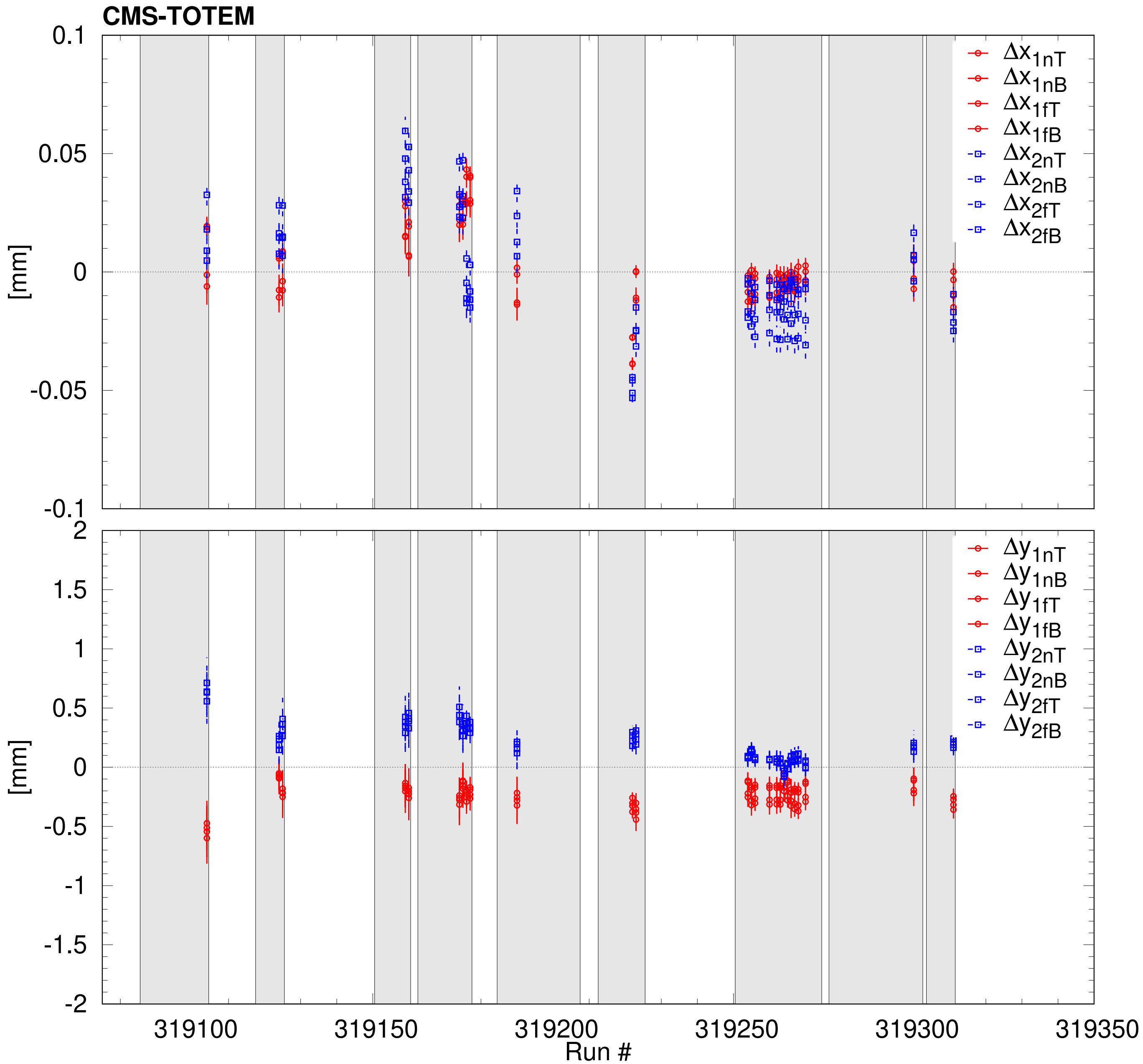
From measured quantities to alignment

Scattered protons – absolute alignment per run – aligned



Use symmetries for interaction point (x^*, y^*), momentum sums $(\sum p_x, \sum p_y)$, local hits (x, y)

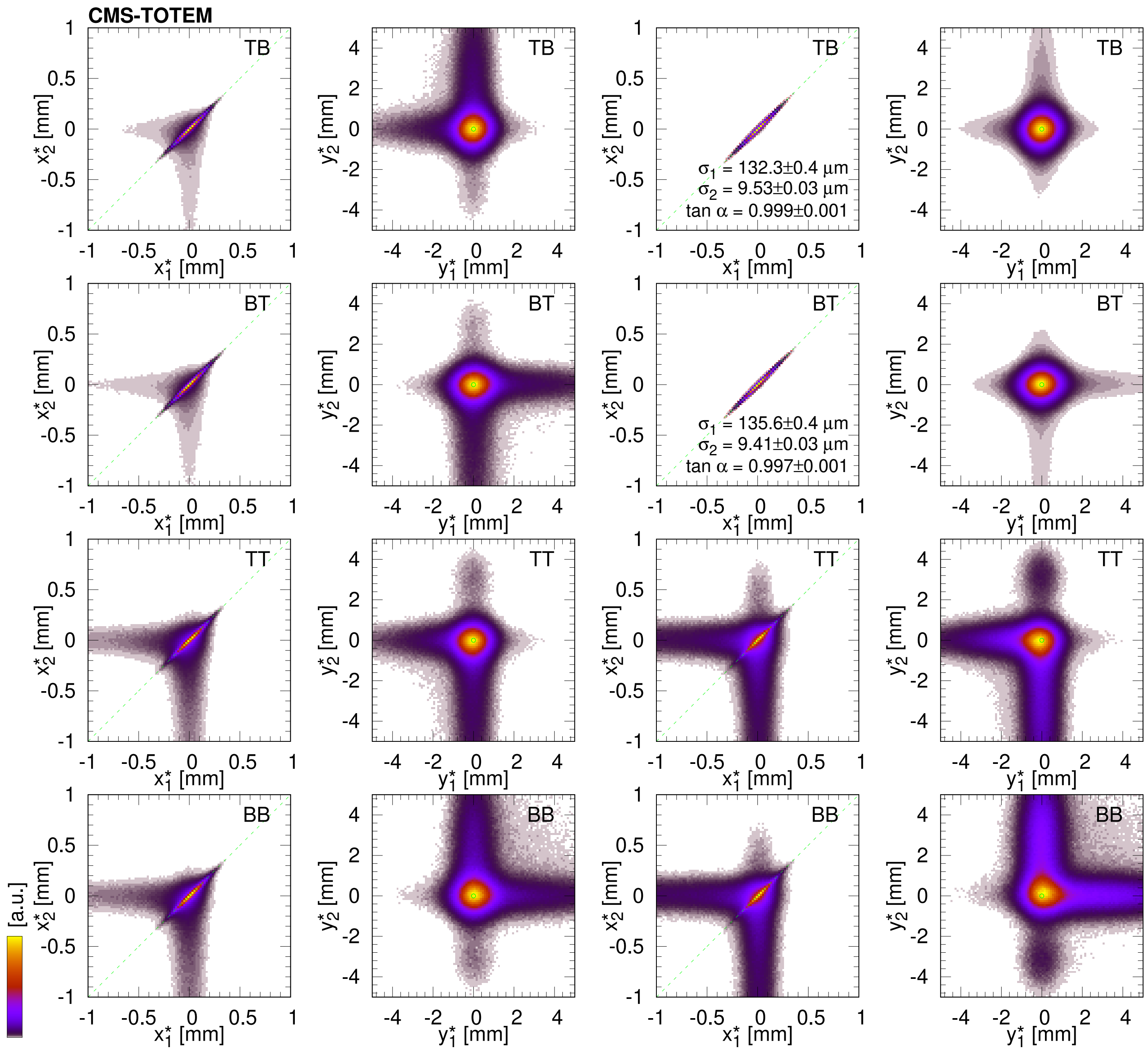
Scattered protons – deduced displacements vs run



- Deduced displacements
  - in x direction (lateral): similar changes in both arms
  - in y direction (up-down): changes are opposite in arm 1/2

Points to common source
Drifting LHC proton orbits

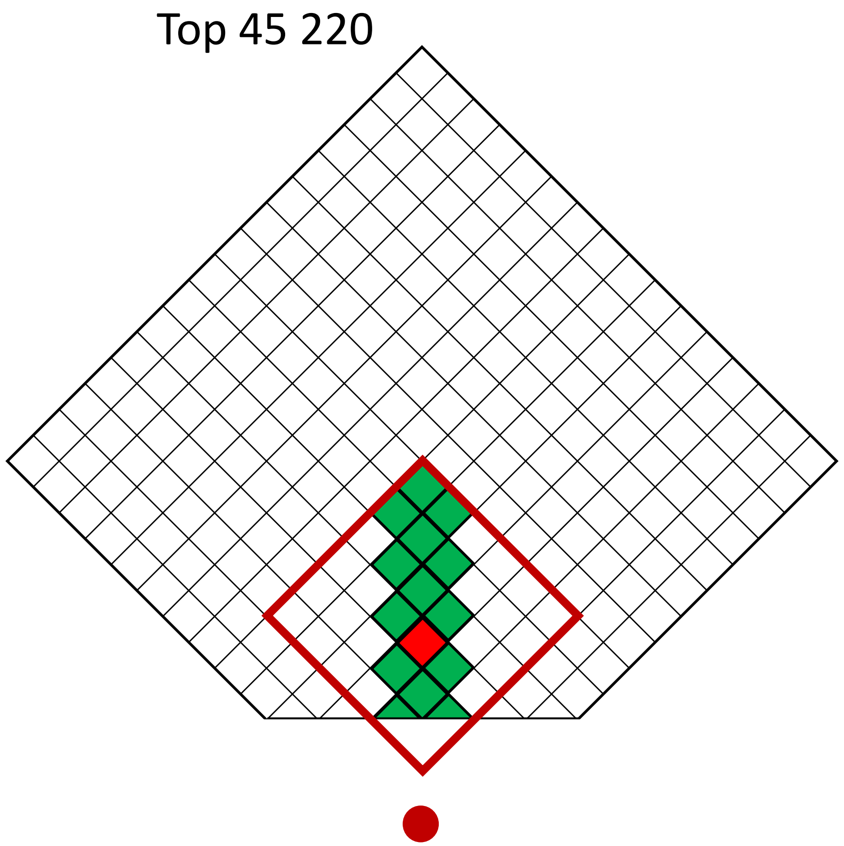
Results – collision vertex

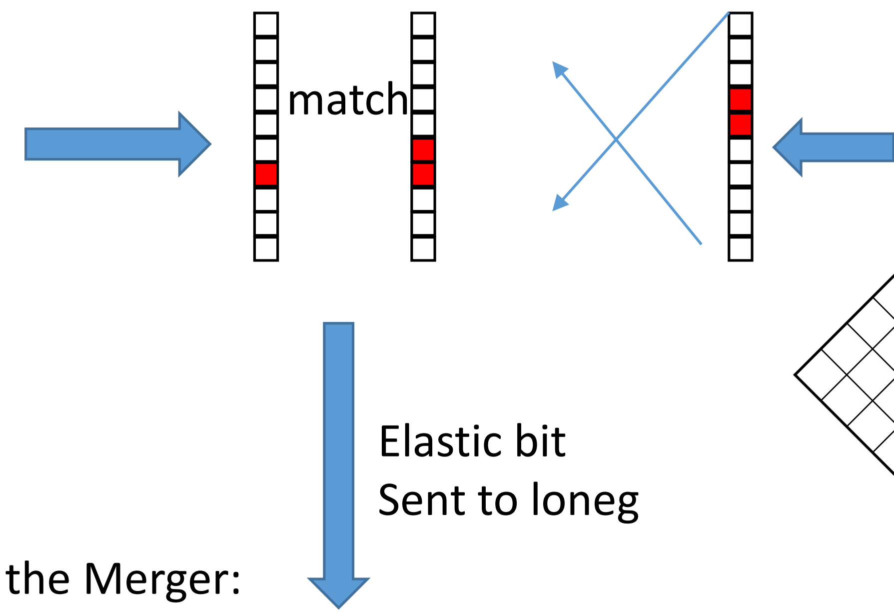


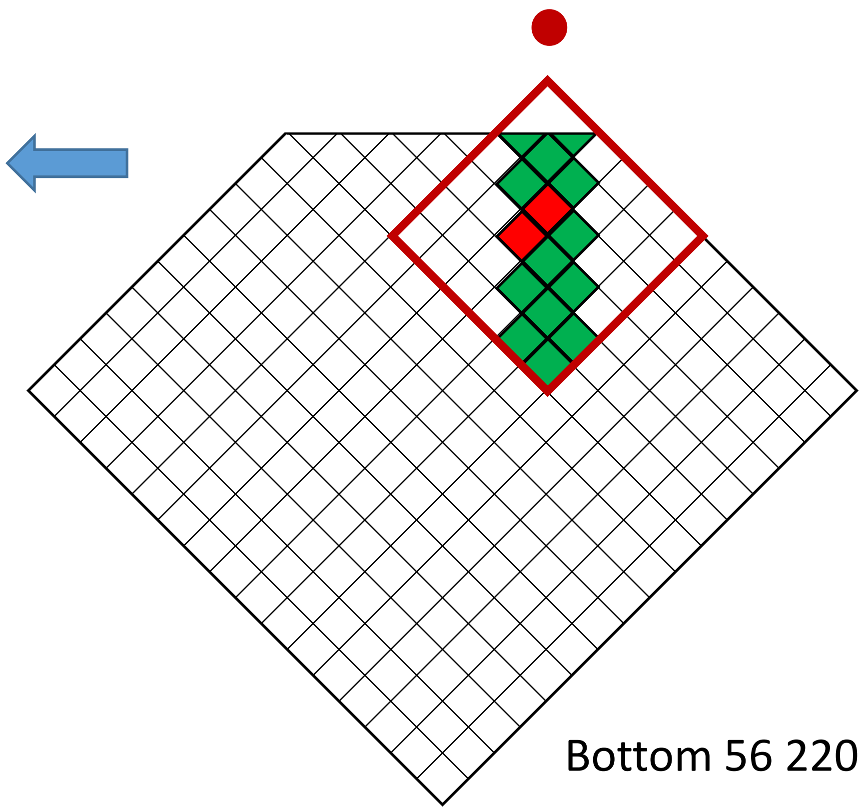
- Reconstructed vertices
  - from using both arms
  - joint distribution of x^* or y^* coordinates of the primary pp interaction
  - beam spot normally distributed with size $\sigma \approx 95\,\mu$m with precision $6 - 7\,\mu$m

Roman pots – elastic veto

Inside the Merger FPGA the t/map coming from paired RP are checked for eventual match (bottom t-map are inverted). If there is at least 1 common bit on both t-maps a veto is generated and sent to the LONEG



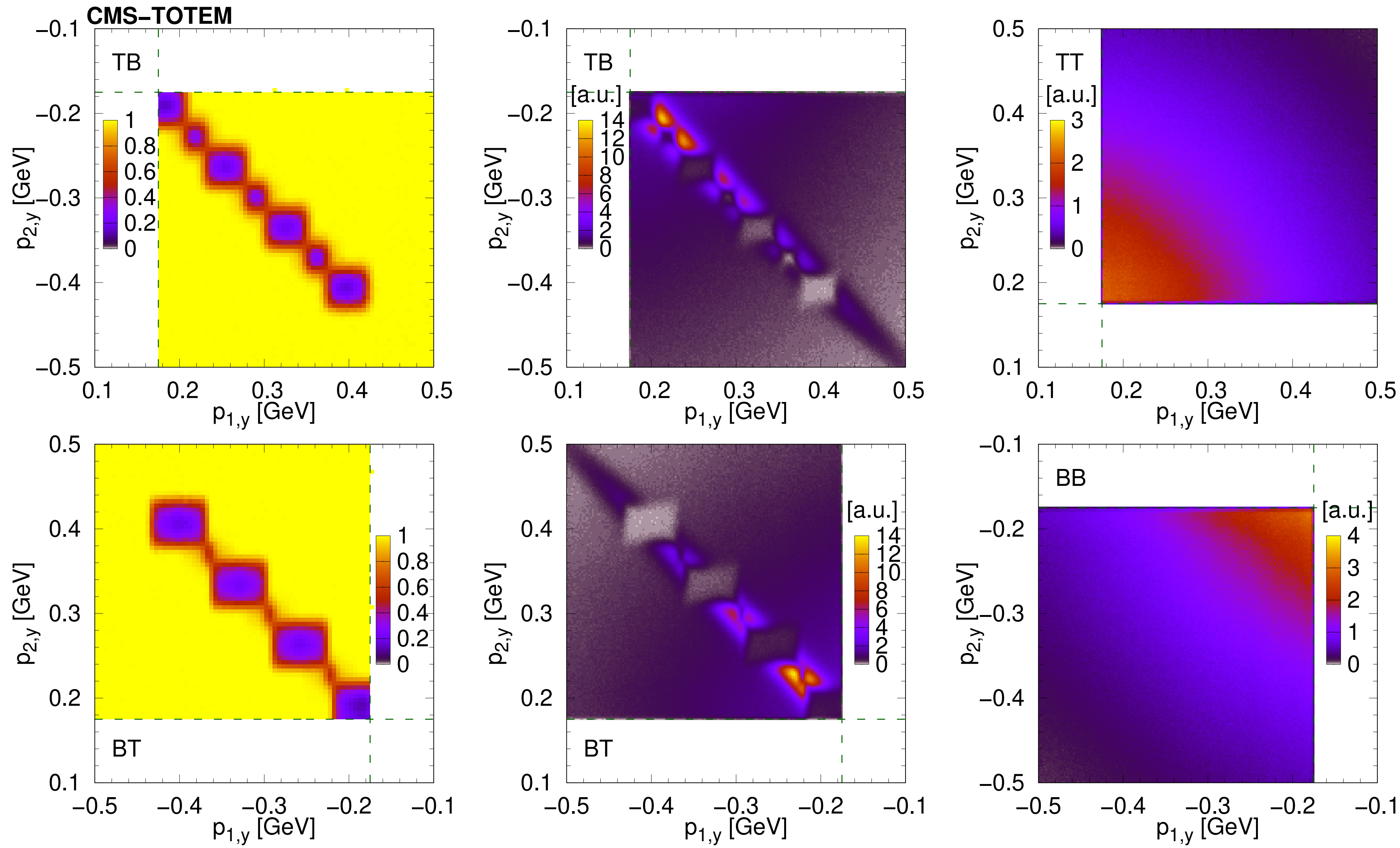




We have total of 4 diagonal veto bit from the Merger:

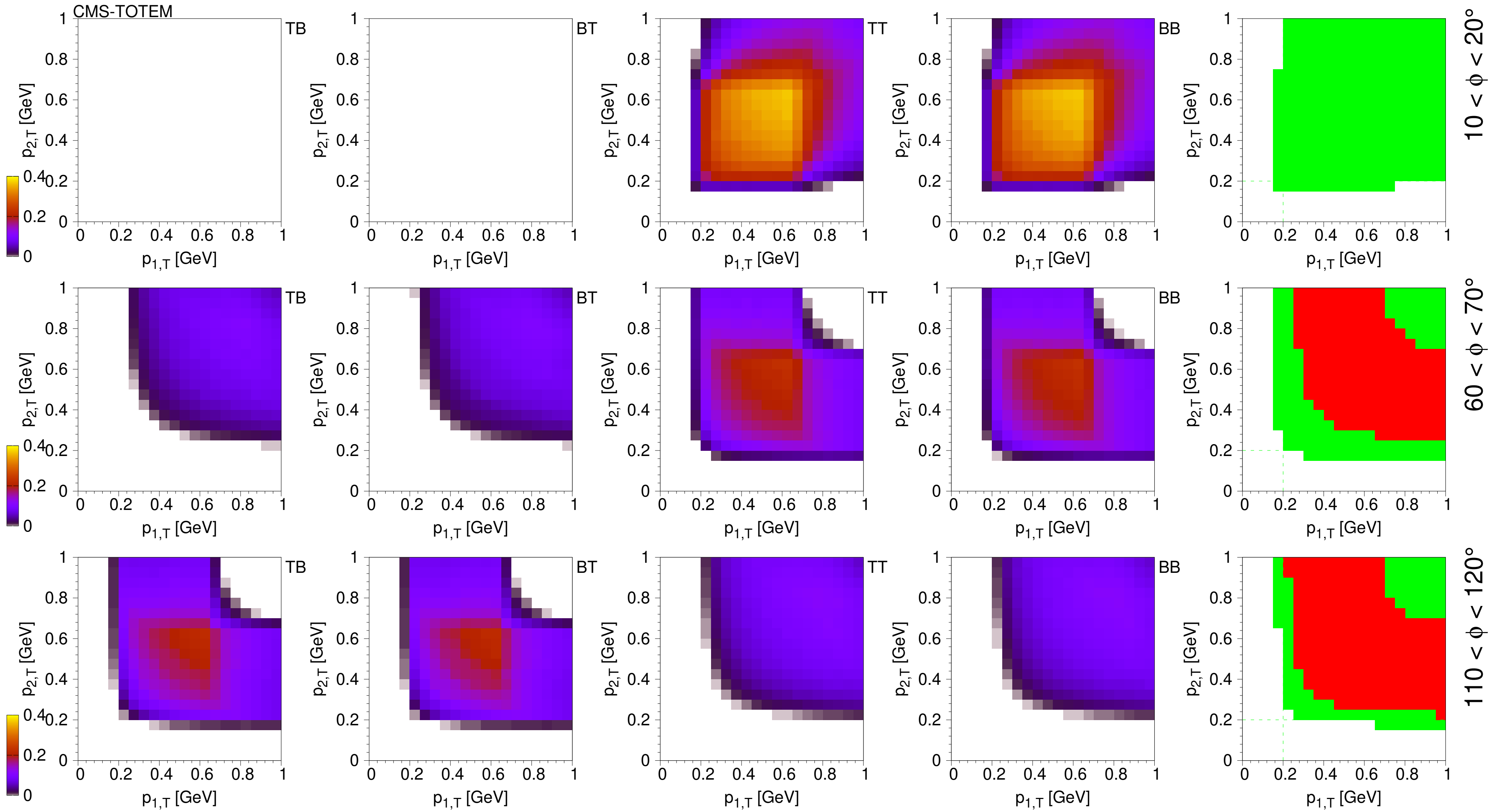
Elastic_220_45T_56B   Elastic_220_45B_56T
Elastic_210_45T_56B   Elastic_210_45B_56T

Roman pots – elastic veto



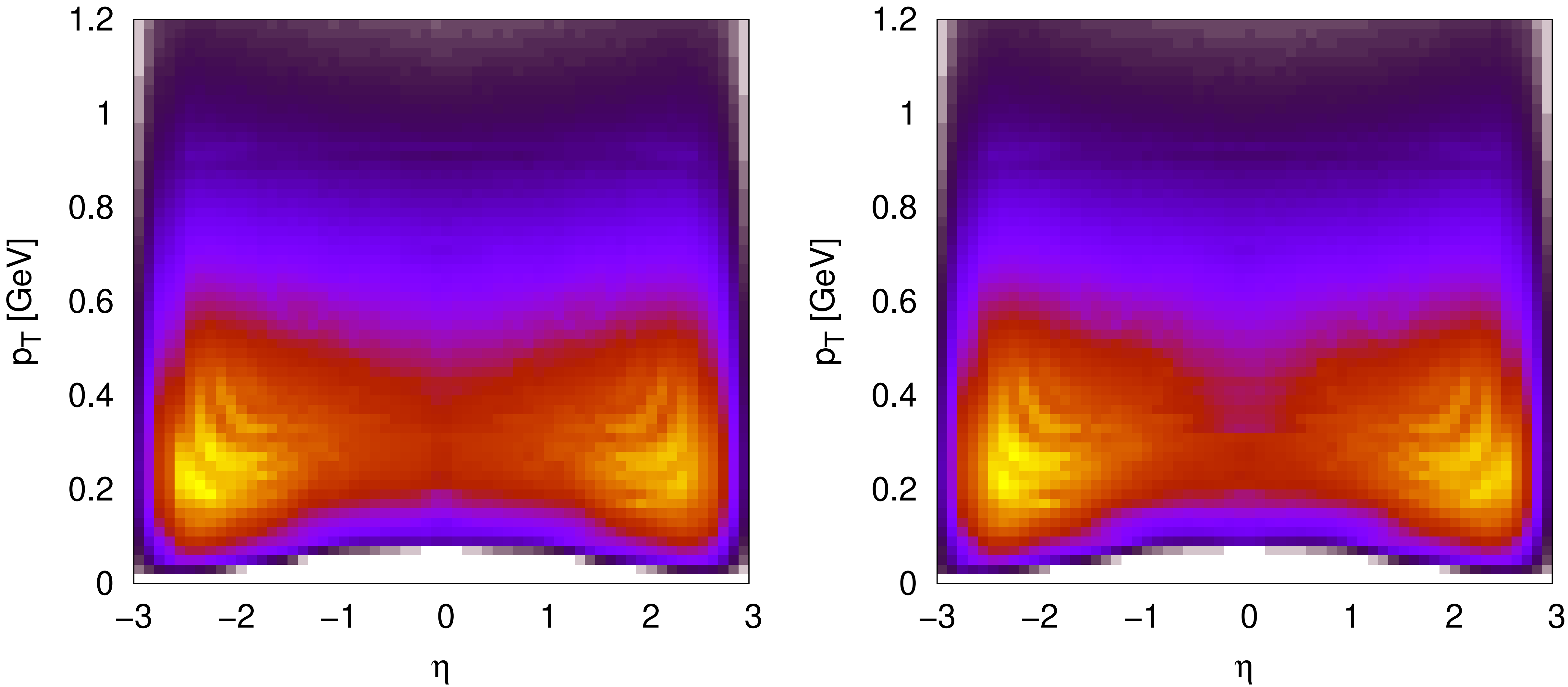
Calculated suppression efficiency of elastic-like events as functions of p_y in arms 1 and 2
Measured correlation of detected proton momenta $(p_{1,y}, p_{2,y})$ in arm 1 vs 2

Roman pots – proton-pair acceptance and coverage vs ϕ_{pp}



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

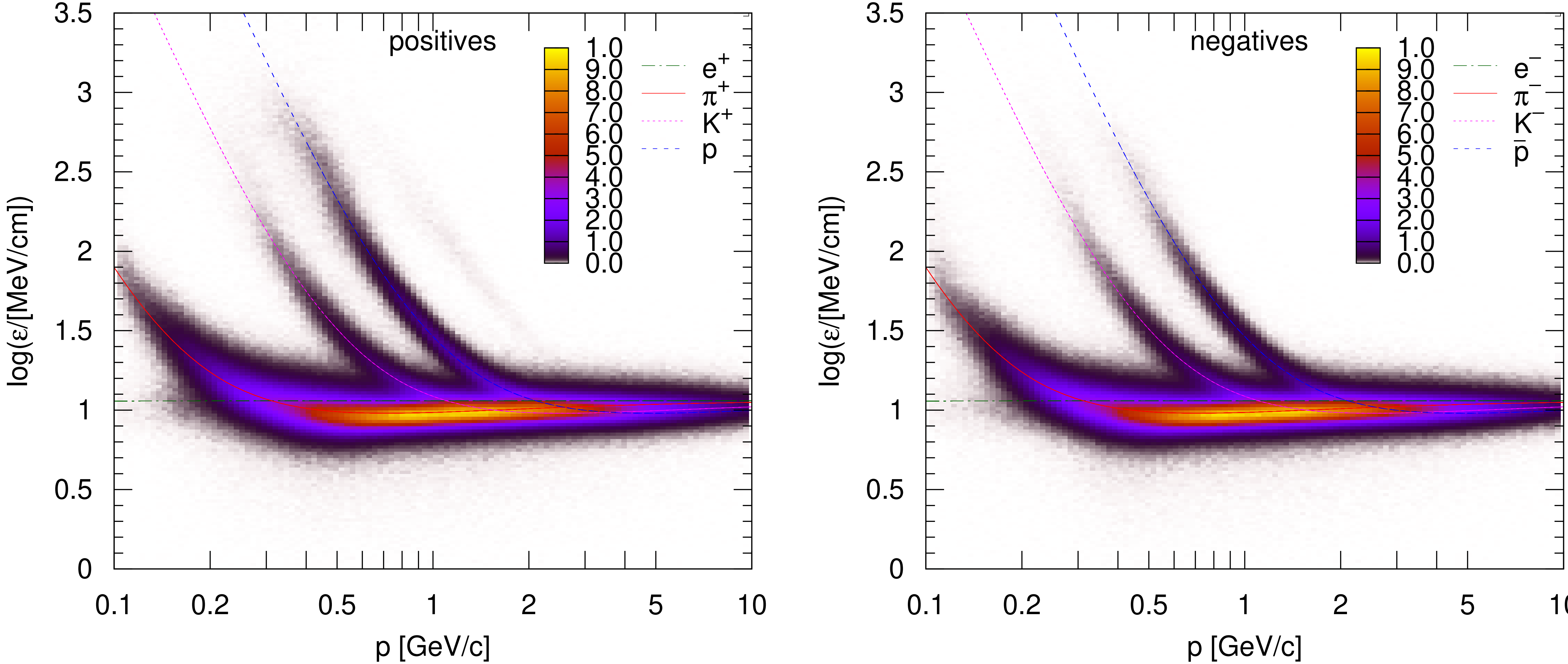
Central hadrons – high-level trigger



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

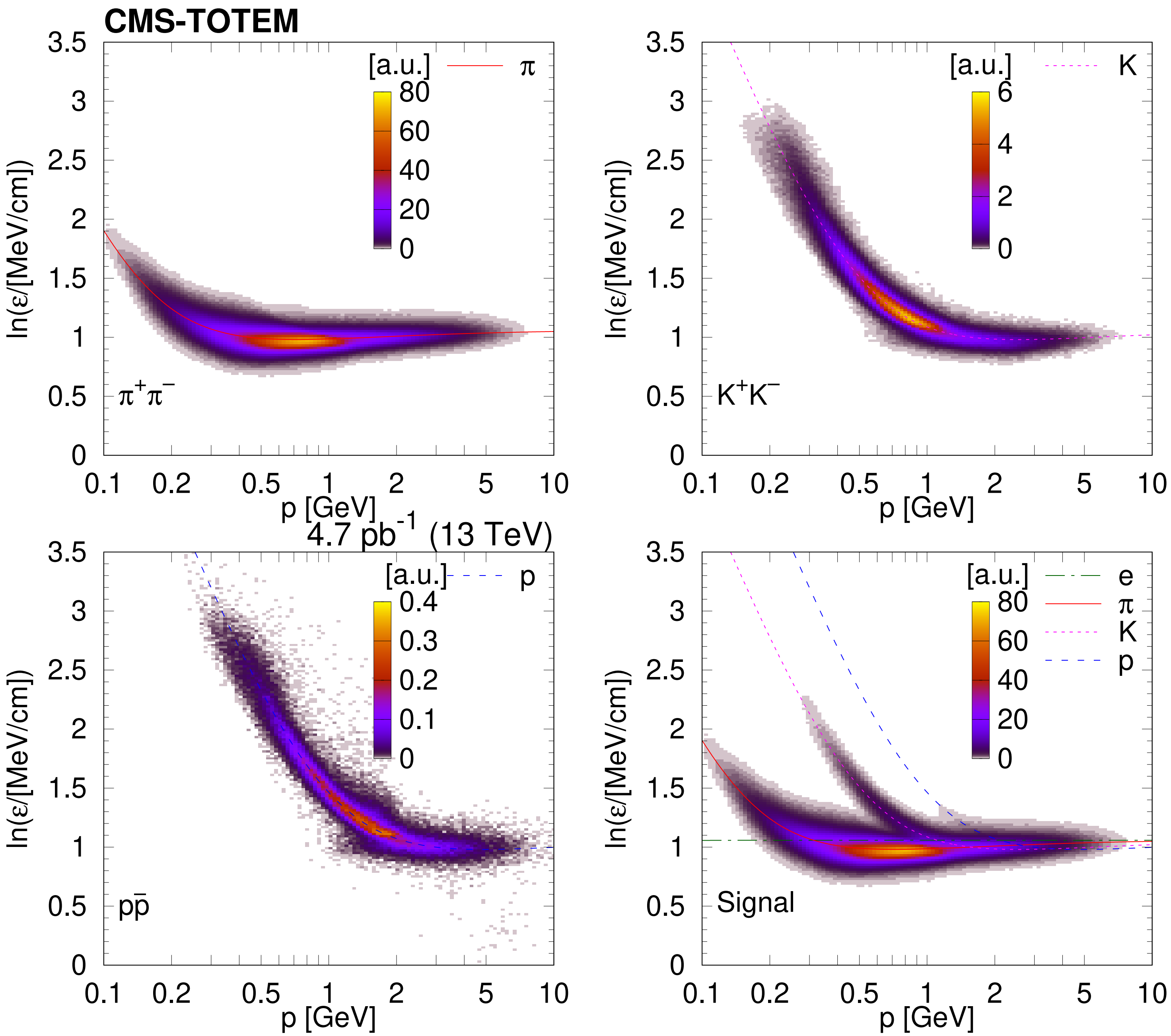
Inefficiencies, valleys to be corrected

Central tracks – estimate of most probable ε



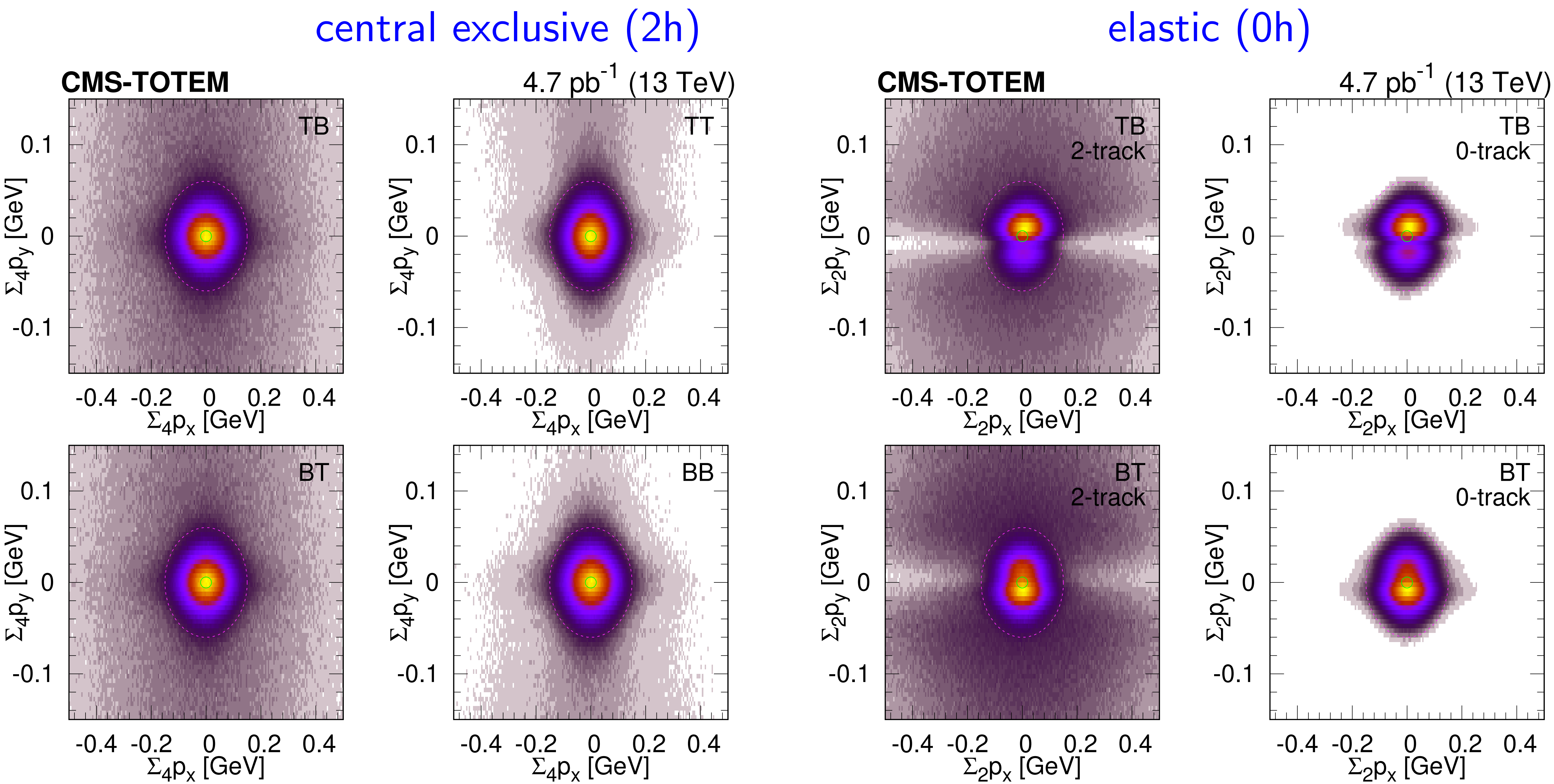
Through maximum likelihood method, using all pixel and strip hits per track

Central tracks – particle identification through dE/dx



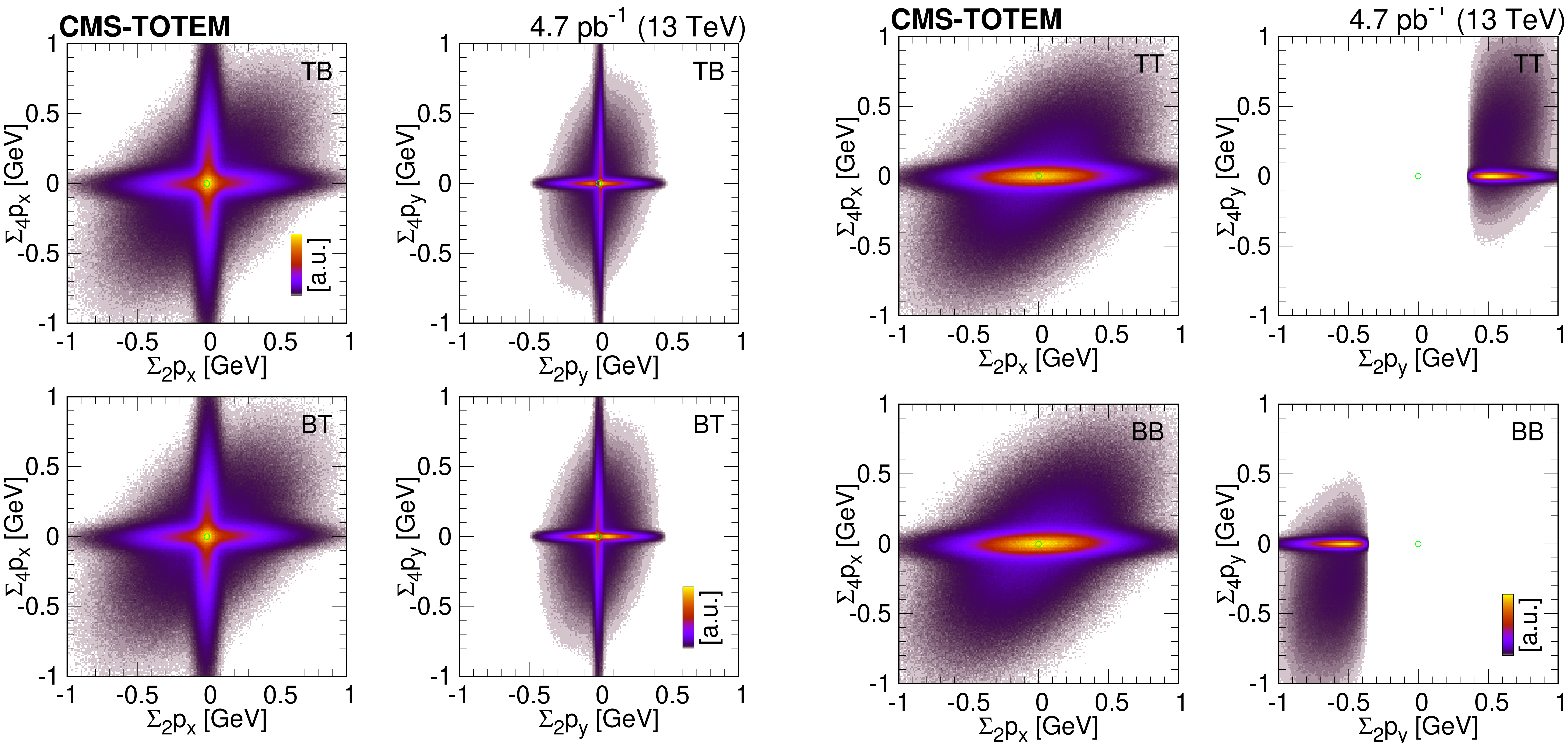
- Particle pair
  - identified as type $\mathrm{h}^+\mathrm{h}^-$ if $P_{1,\mathrm{h}}P_{2,\mathrm{h}} > 10 \cdot P_{1,i}P_{2,i}$ for all $i \neq h$
- Proof of exclusivity
  - $\pi^+\pi^-$, $\mathrm{K}^+\mathrm{K}^-$, and $\mathrm{p}\overline{\mathrm{p}}$ pairs
  - conservation laws at work: charge,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

Results – momentum sums



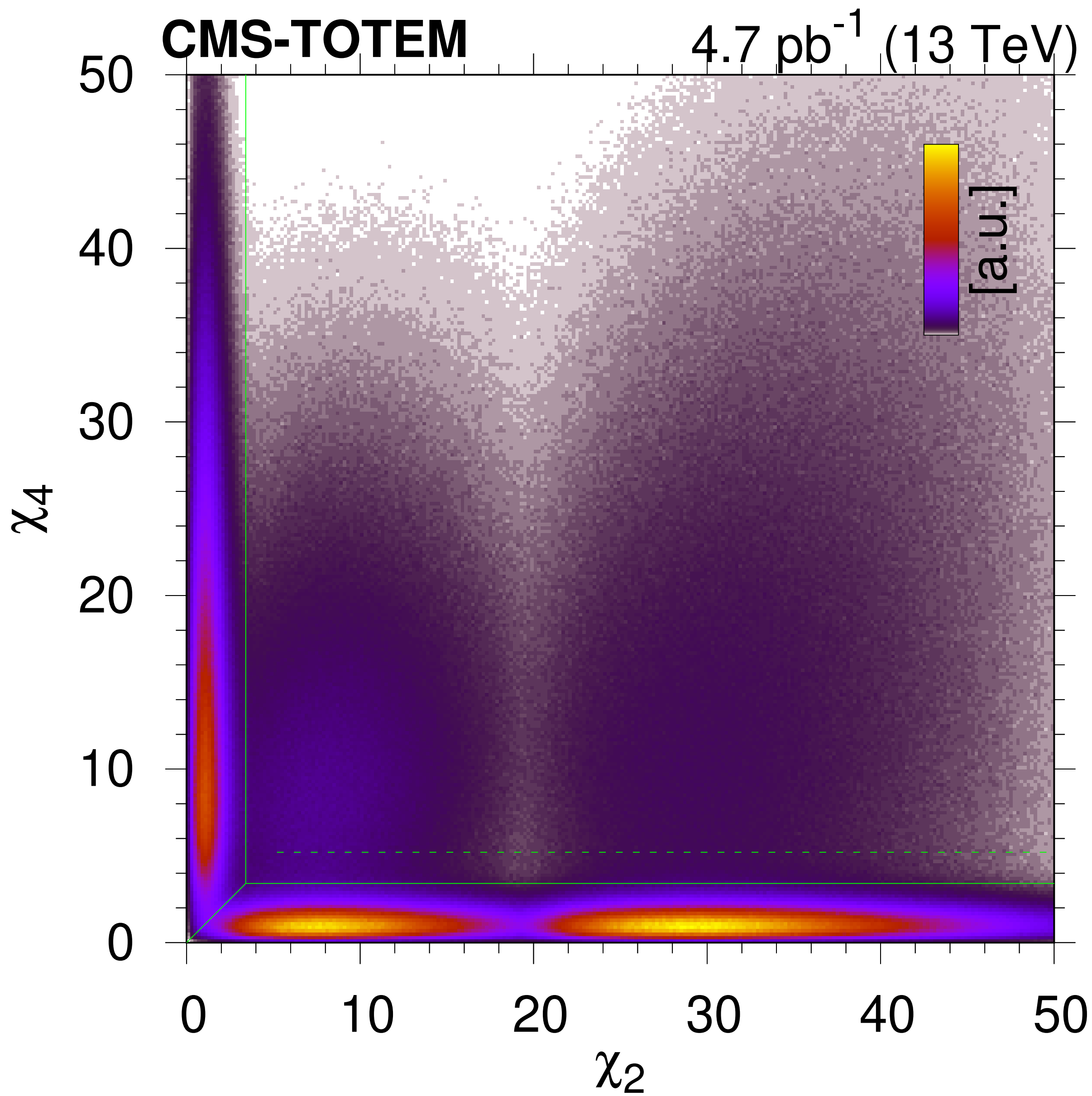
Ellipses with semi-minor axes of 150 MeV (x) and 60 MeV (y) are overlaid

Results – momentum sums – true exclusive vs pile-up



Based on $\left(\sum_4 p_x \text{ vs } \sum_2 p_x,\ \sum_4 p_y \text{ vs } \sum_2 p_y\right)$

Event classification – χ



Mahalanobis distance χ, based on the value and covariance of momentum sums, defined in the multivariate normal case as

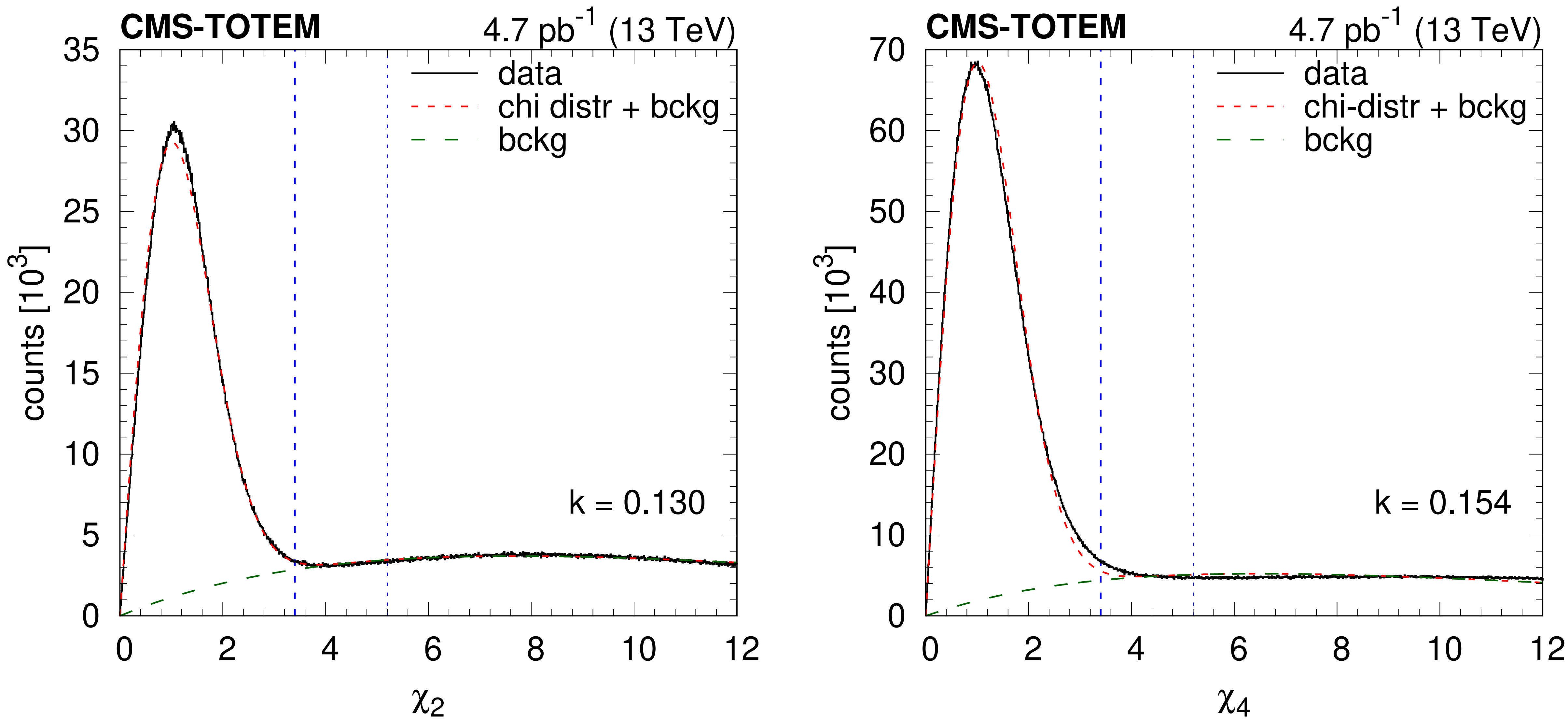
$$\chi(\mathbf{s}) = (\mathbf{s}^T V^{-1} \mathbf{s})^{1/2}$$

where $\mathbf{s} = \sum \mathbf{p}_\mathrm{T}$, V is the covariance matrix. For 2D vectors $\mathbf{s} = (s_x, s_y)$,

$$\chi(\mathbf{s}) = \left(\frac{V_{yy} s_x^2 - 2V_{xy} s_x s_y + V_{xx} s_y^2}{V_{xx} V_{yy} - V_{xy}^2} \right)^{1/2}$$

The χ_2 values are based on $\sum_2 \mathbf{p}_\mathrm{T}$, while χ_4 are computed from $\sum_4 \mathbf{p}_\mathrm{T}$.

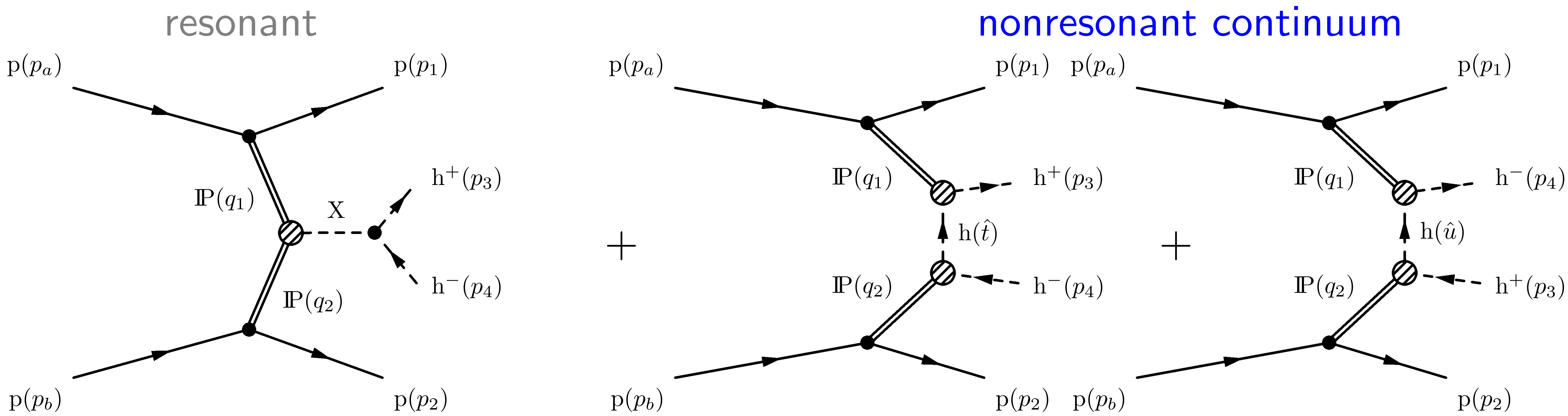
Event classification – signal and sideband



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

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

Theory – resonances vs background!



- Nonresonant continuum

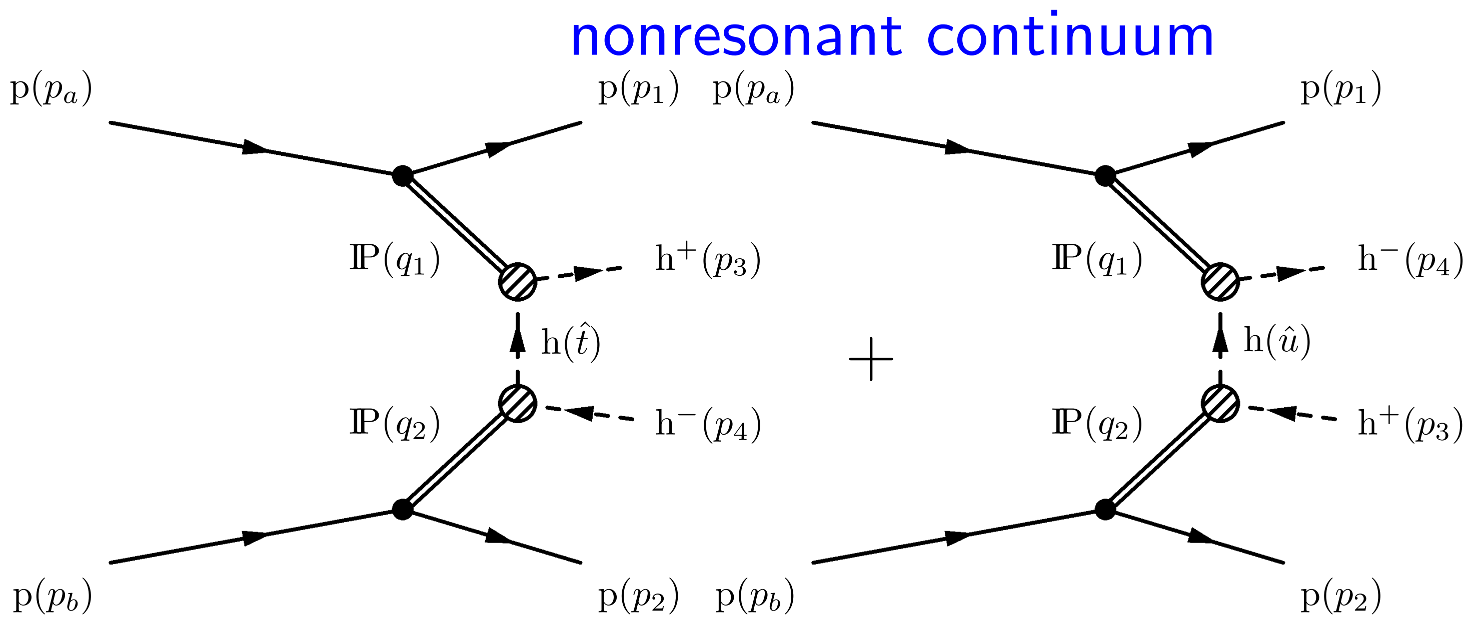
  The matrix element for the nonresonant continuum process is

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

  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 ($> 20\,$GeV) the pomeron exchange dominates

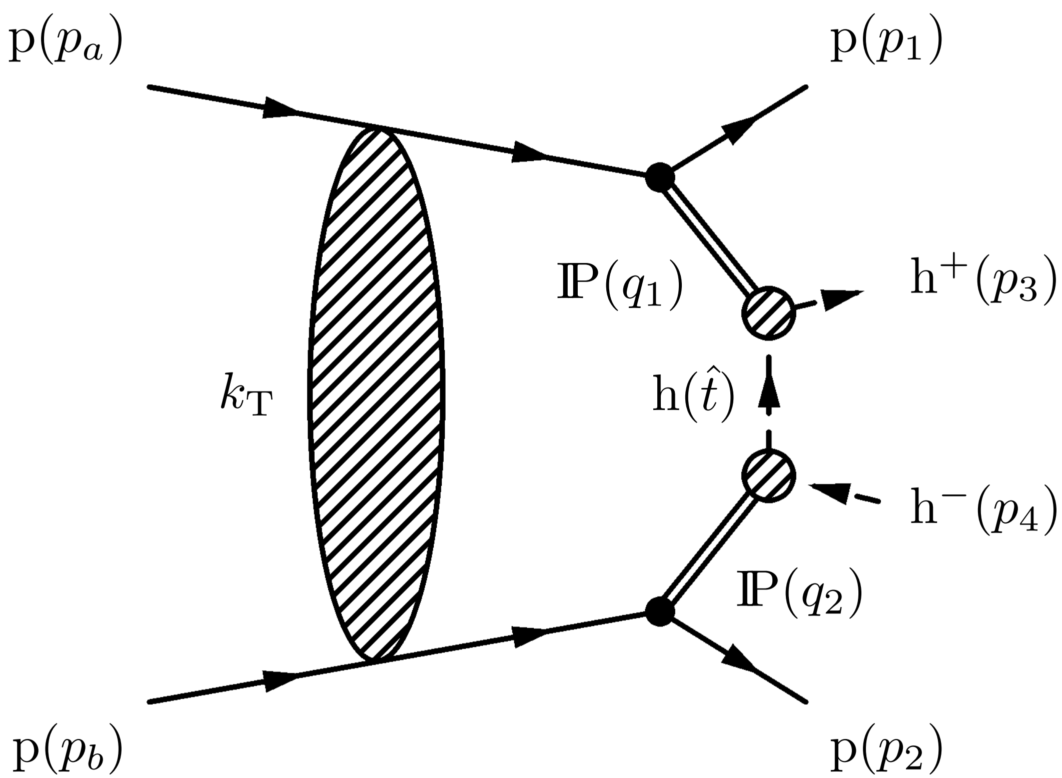
  $$M_{ik}(t_i, s_{ik}) = i s_{ik} C_{\mathbb{P}} \left(\frac{s_{ik}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_i)-1} \exp\left(\frac{B_{\mathbb{P}}}{2} t_i\right)$$

  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 $|\mathcal{M}|^2/s^2$

Theory – nonresonant continuum – interference!



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

- 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	
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	

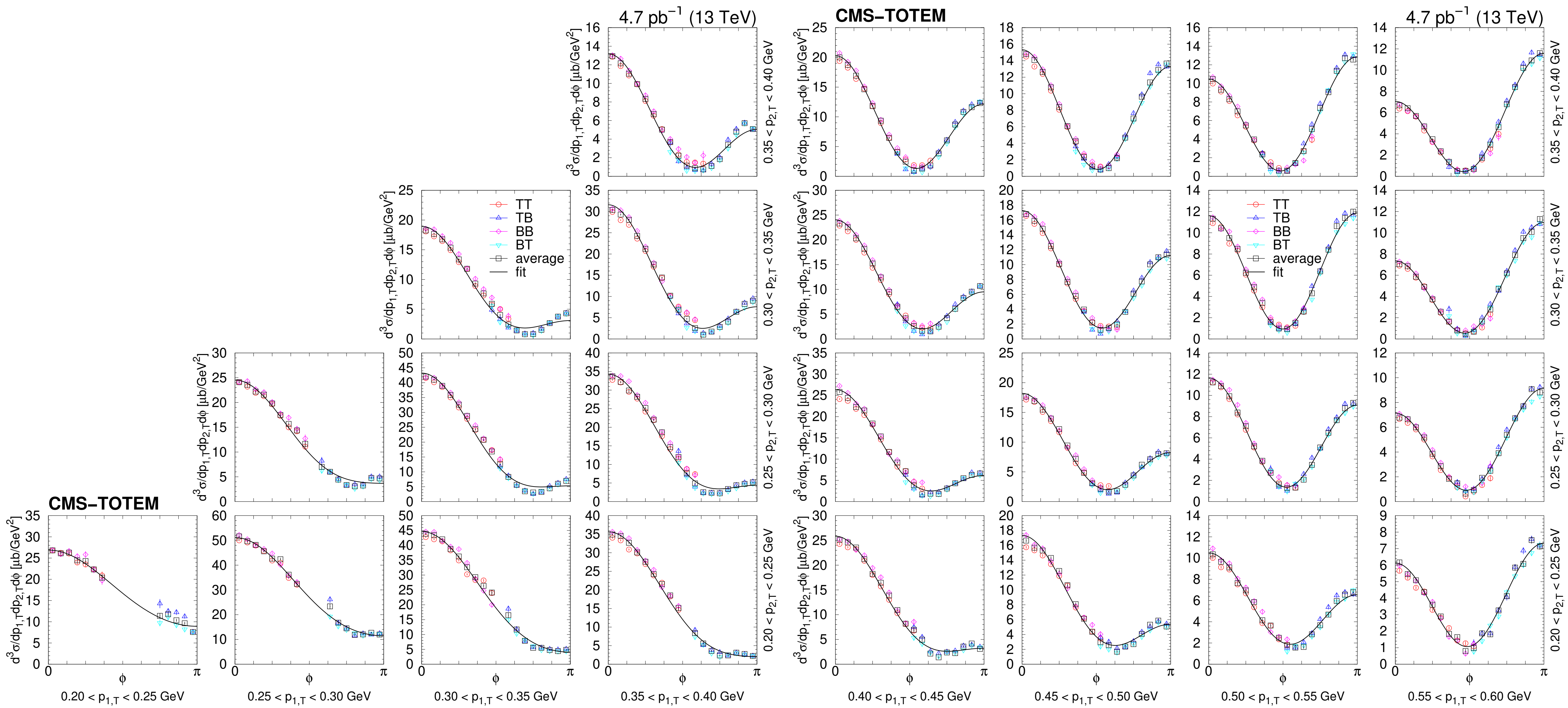
- Pomeron-proton(eigenstate) coupling
  - One-channel model: $F_p(t) = \exp(B_{\mathbb{P}}/2 \cdot t)$
  - Two-channel model:
    $F_i(t) = \exp\left[-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}\right]$

- Pomeron-meson coupling

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

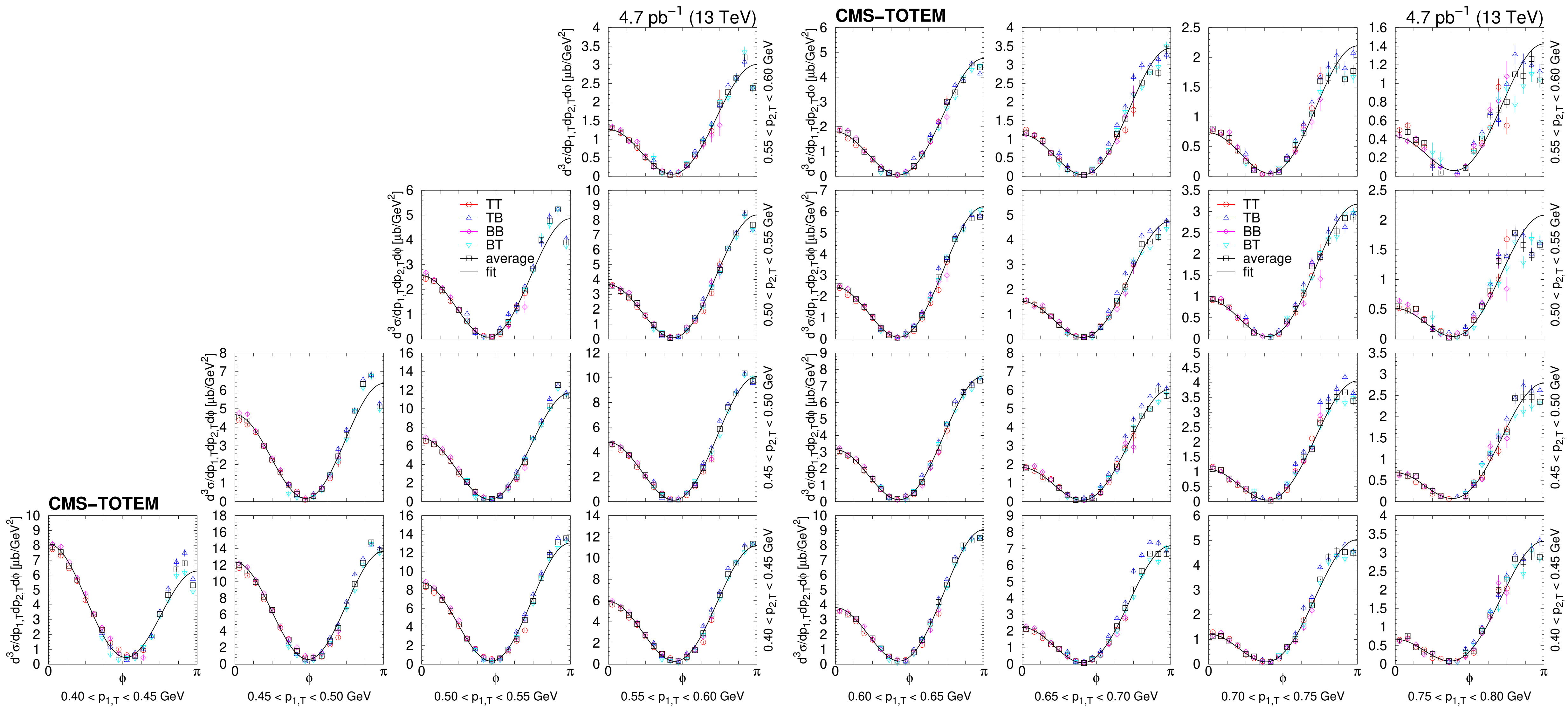
Now using a new generator with proper physics content, from scratch in C++

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



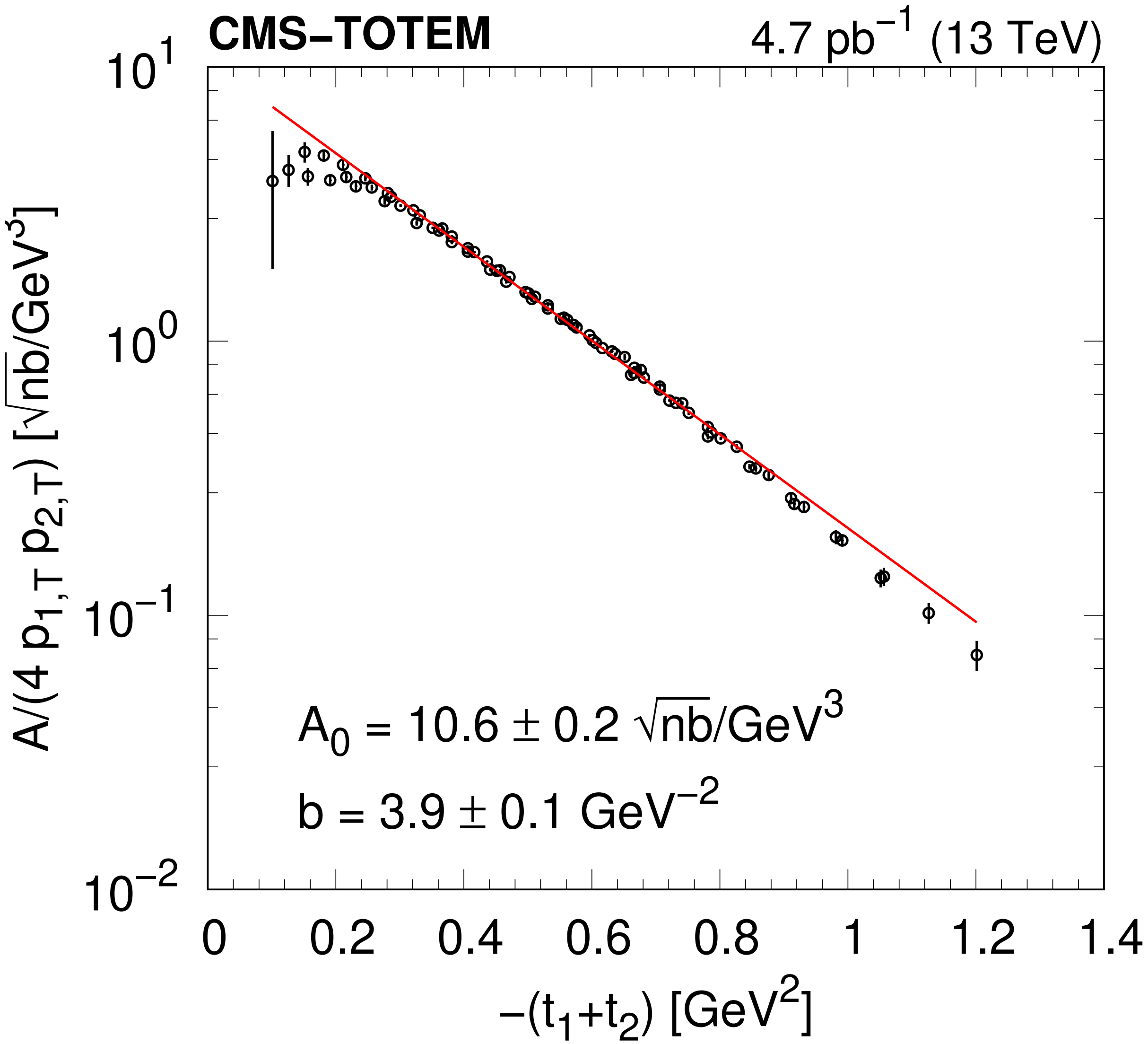
As a function of $\phi_{\mathbf{pp}}$ in $(p_{1,T}, p_{2,T})$ bins, in units of [μb/ GeV^2], if $0.35 < m_{\pi\pi} < 0.65\,\mathrm{GeV}$

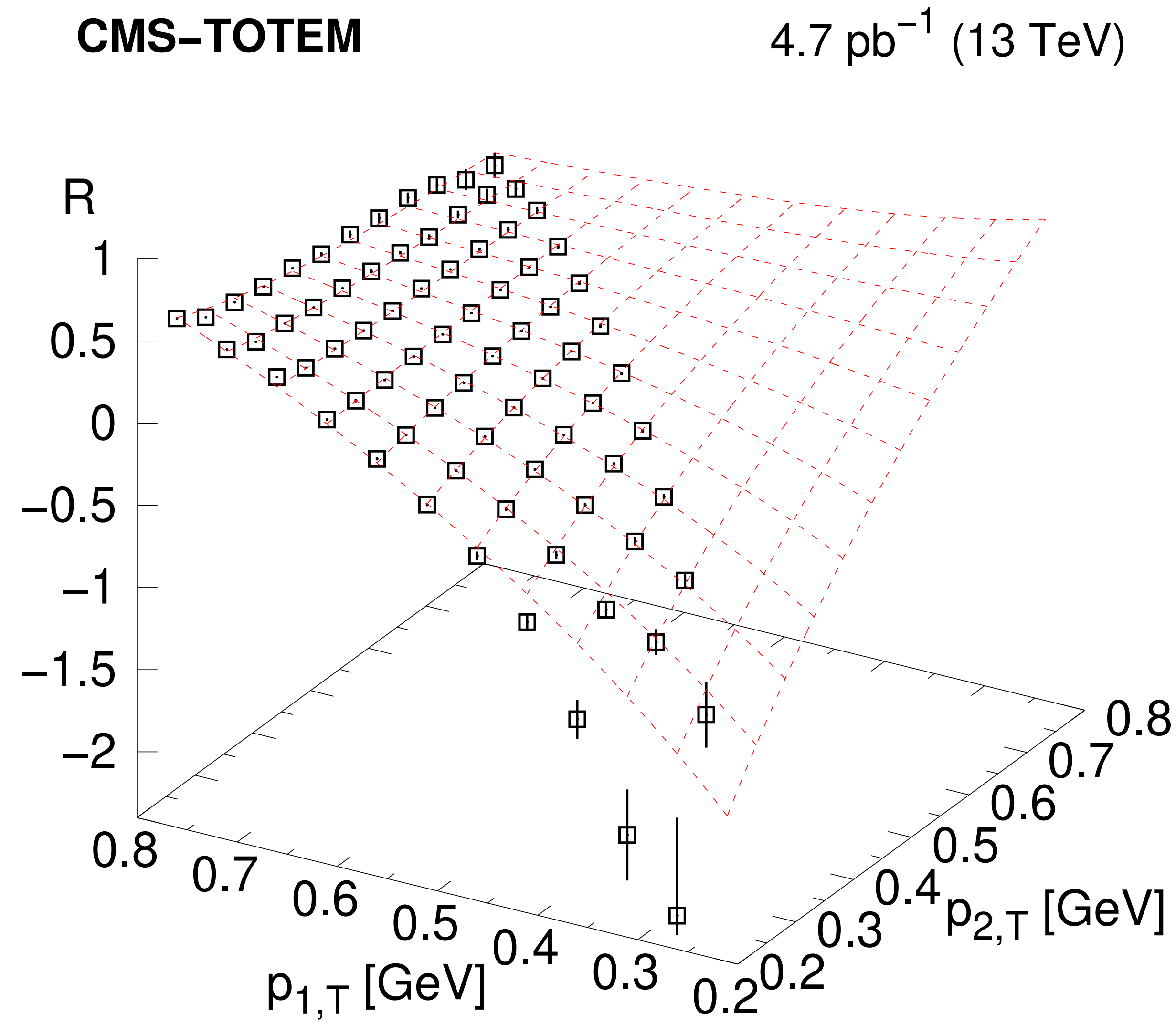
Measurements – nonresonant $d^3\sigma/dp_{1,T}dp_{2,T}d\phi_{pp}$



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

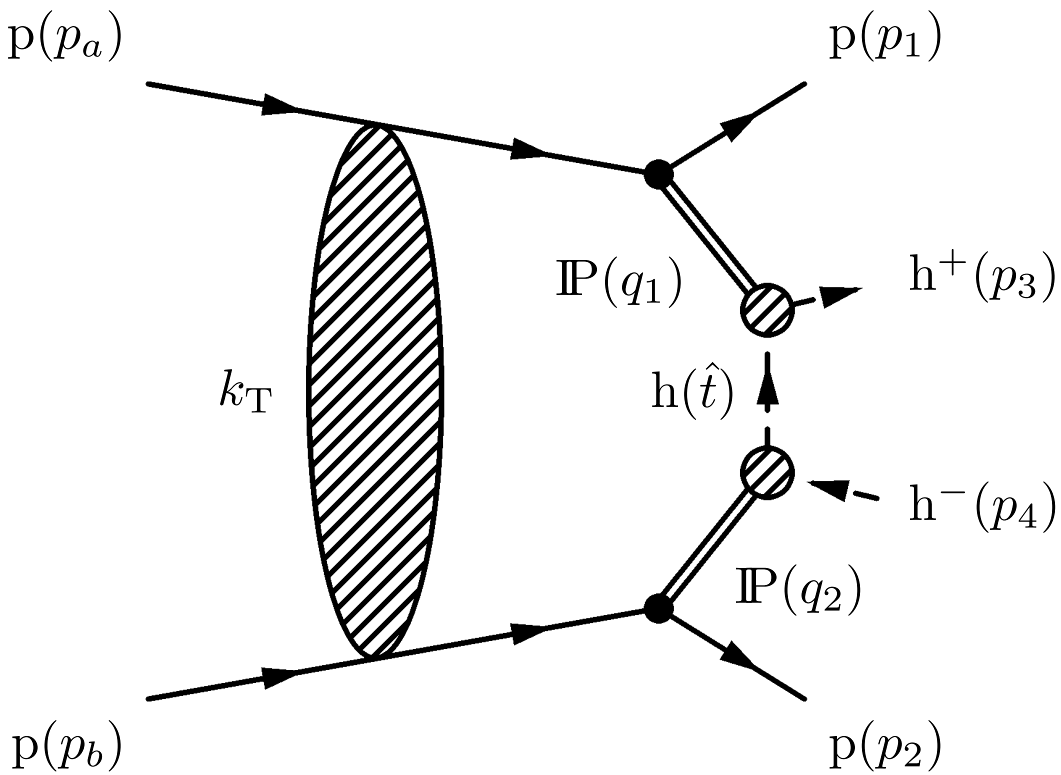
Parameter dependencies



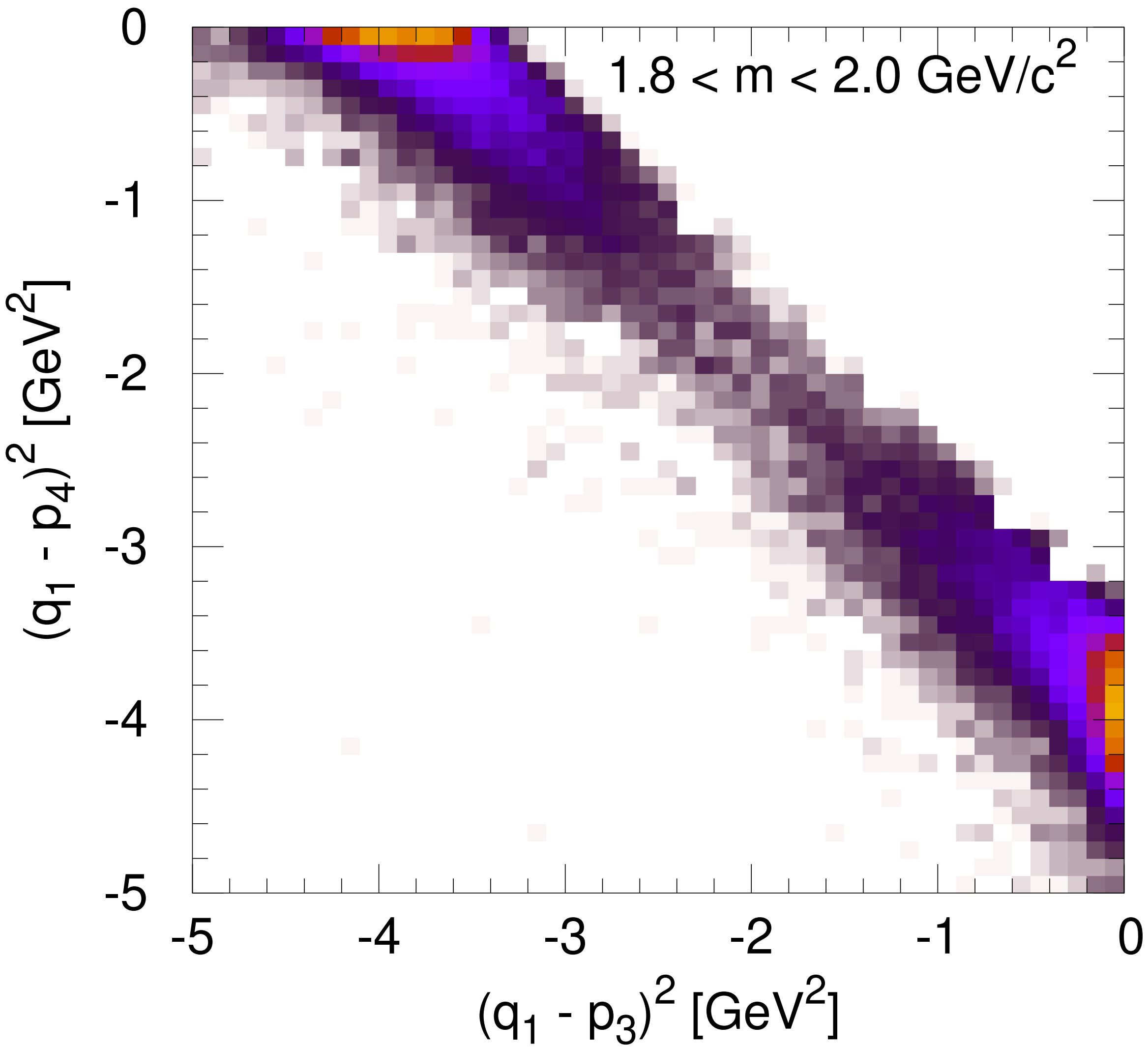


Scaling described by theory-motivated functional forms

Virtual hadron – proof

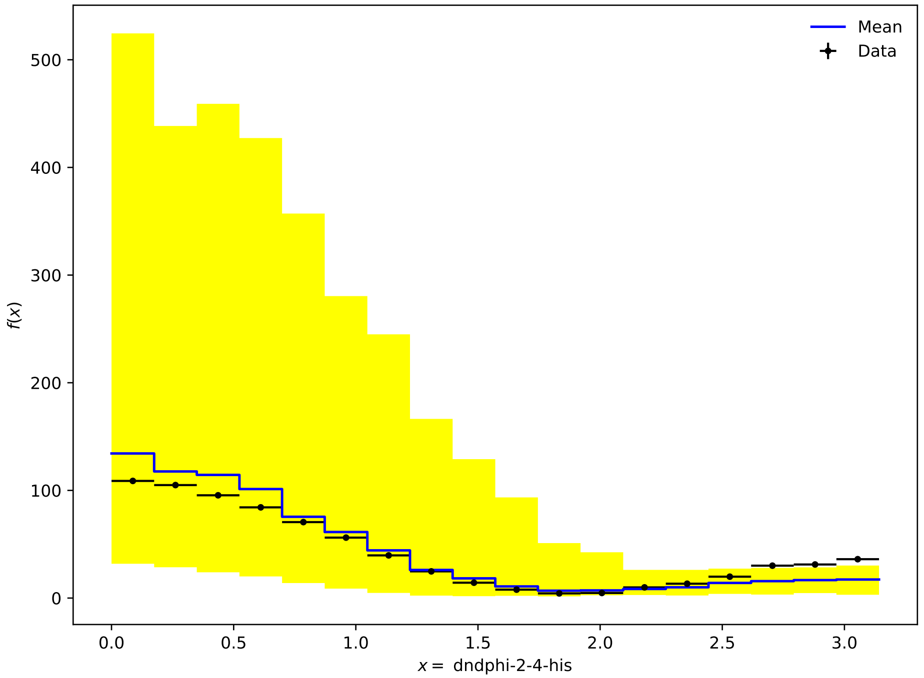


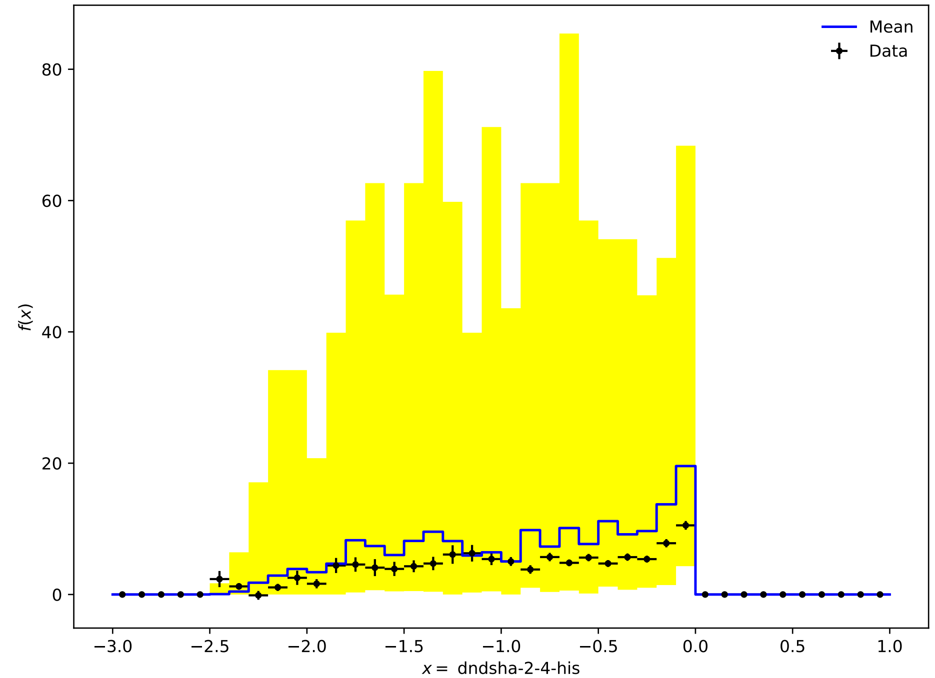
Propagator of virtual hadron:
central hadrons are emitted close to
the direction of the incoming pomeron



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

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

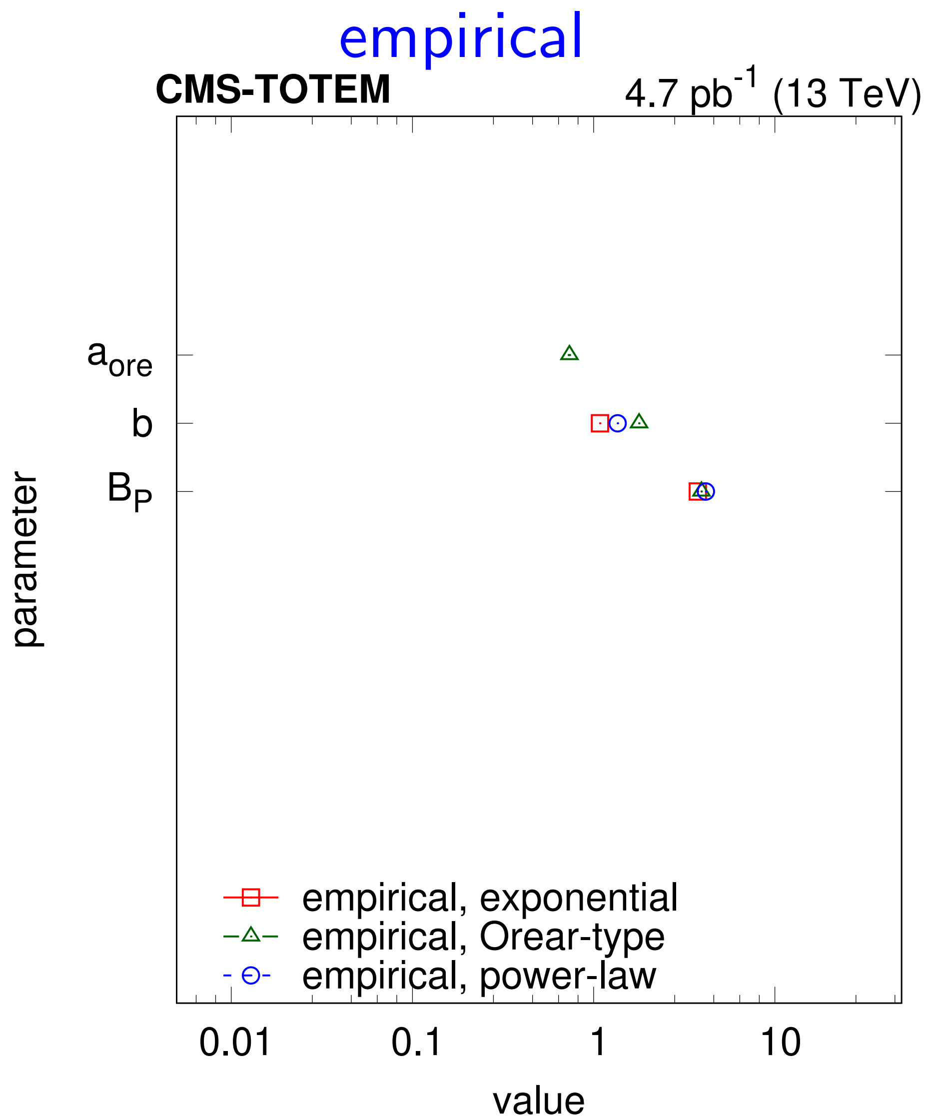
Tuned separately for the parametrisations of the $\mathbb{P}$-meson form factor

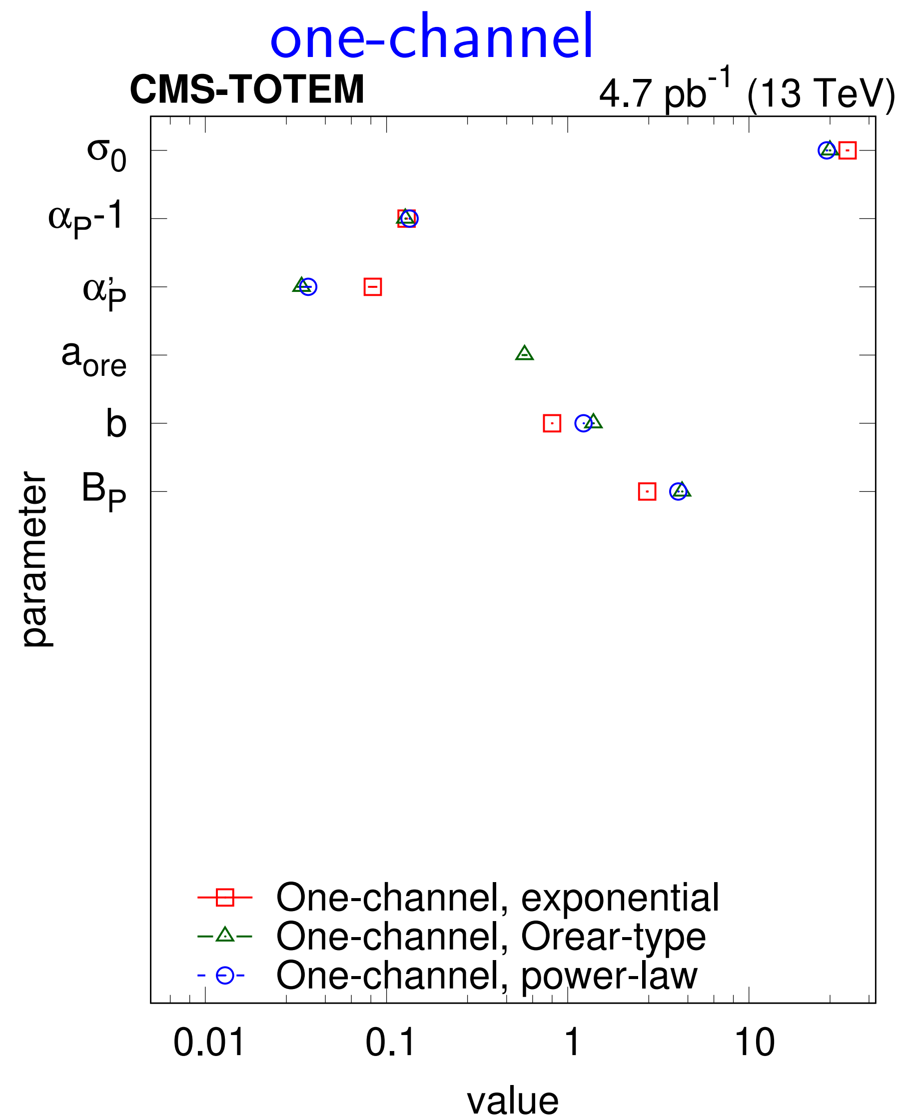
Model tuning – result

Parameter	Exponential	Orear-type	Power-law
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
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001
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
$\Delta\|a\|^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004
χ^2/dof	5741/5786	6415/5785	7879/5786

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

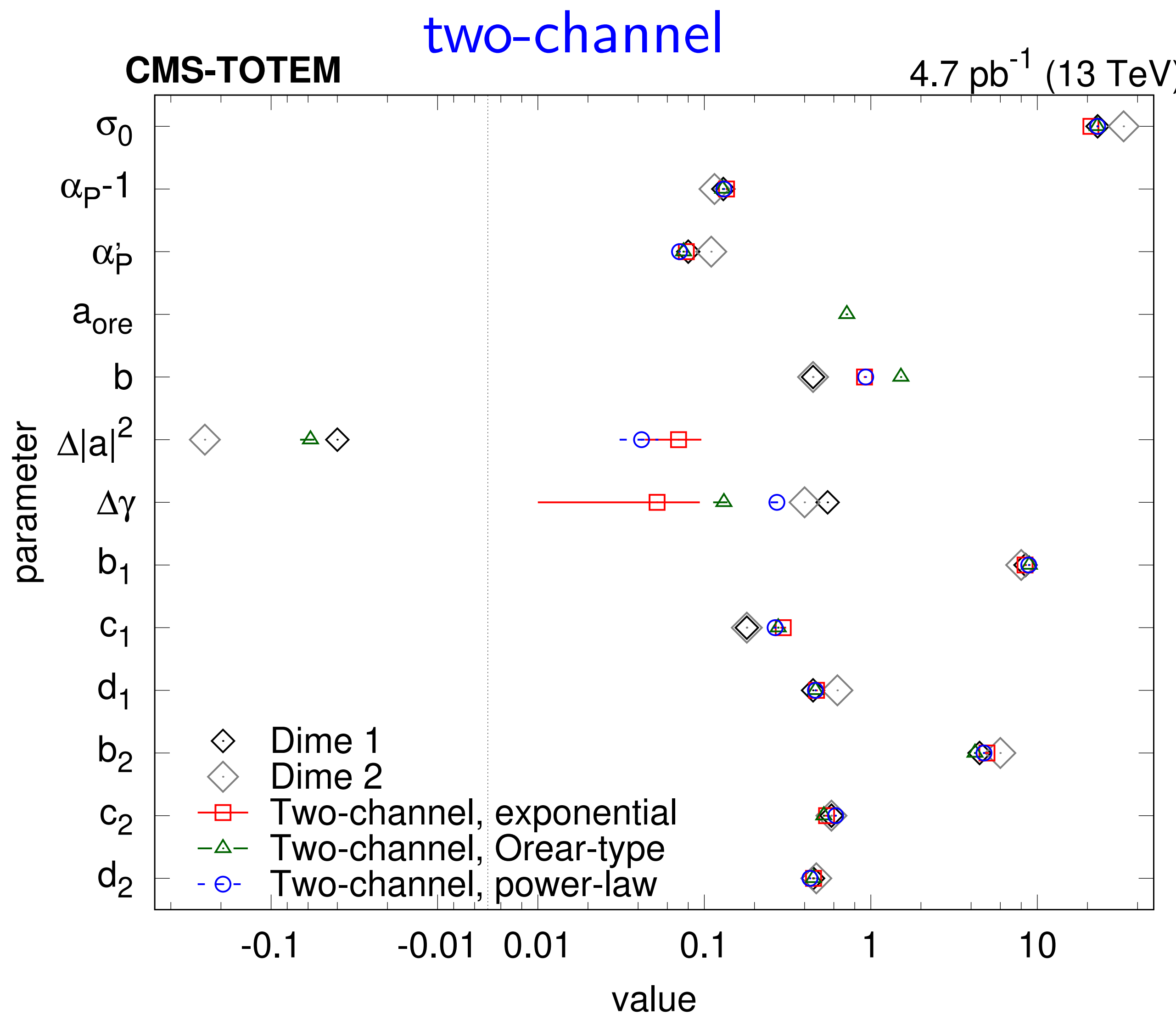
Model tuning – result





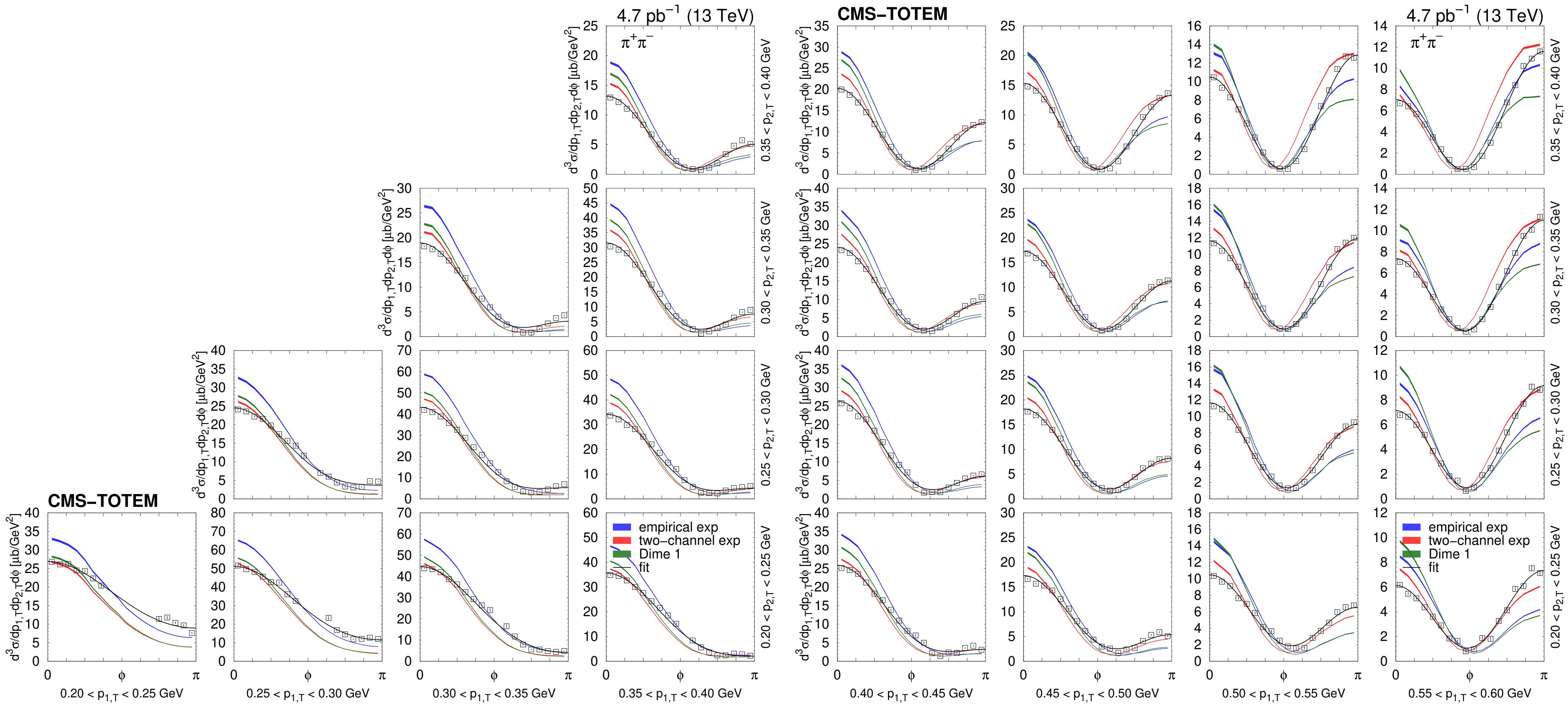
Best fit with two-channel exponential, others are also close

Model tuning – result



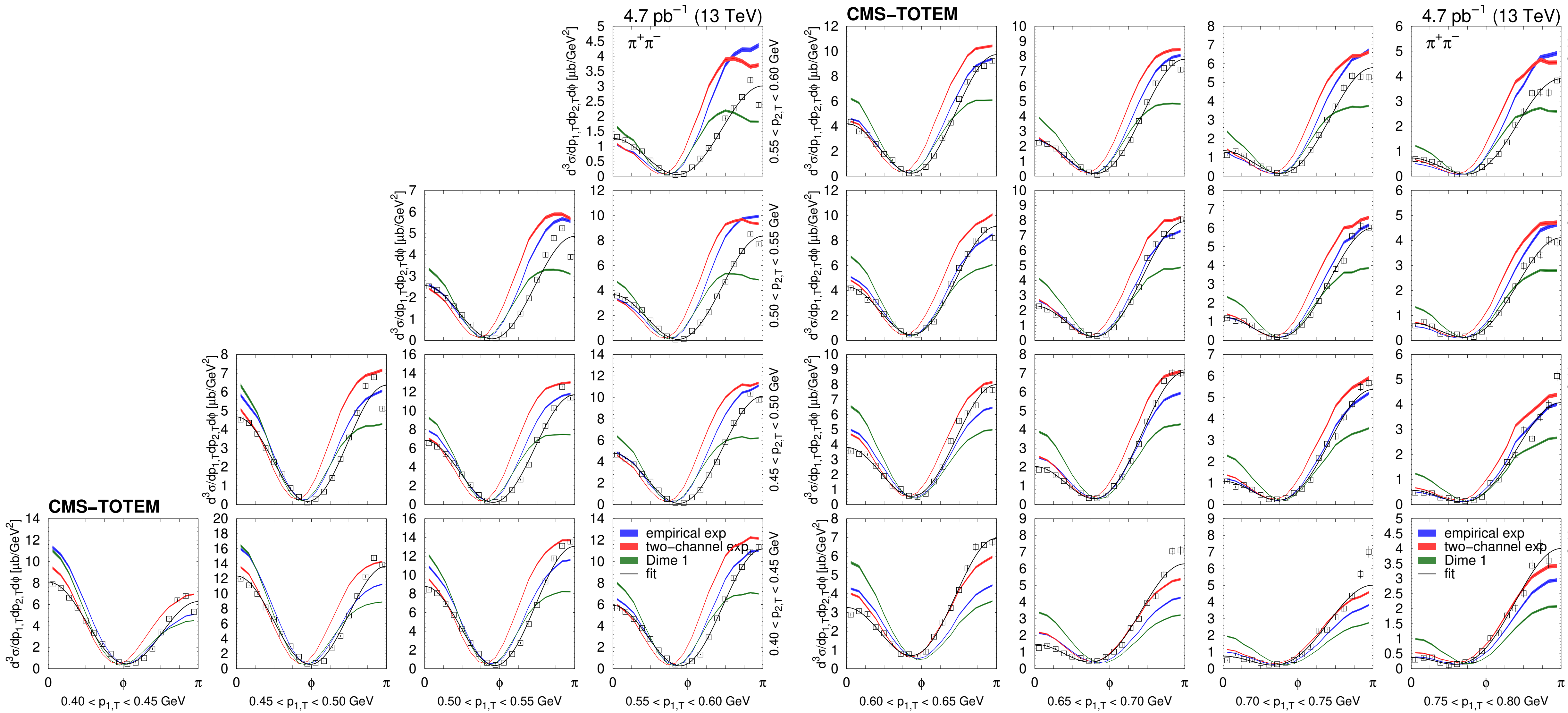
Remarkable agreement with DIME KMR m1 ("soft model 1", although with **unexpected** eigenstate weights ($a_1 \approx a_2$) and eigenstate-pomeron coupling ($\gamma_1 \approx \gamma_2$)!

$d\sigma/d\phi$ – $\pi^+\pi^-$



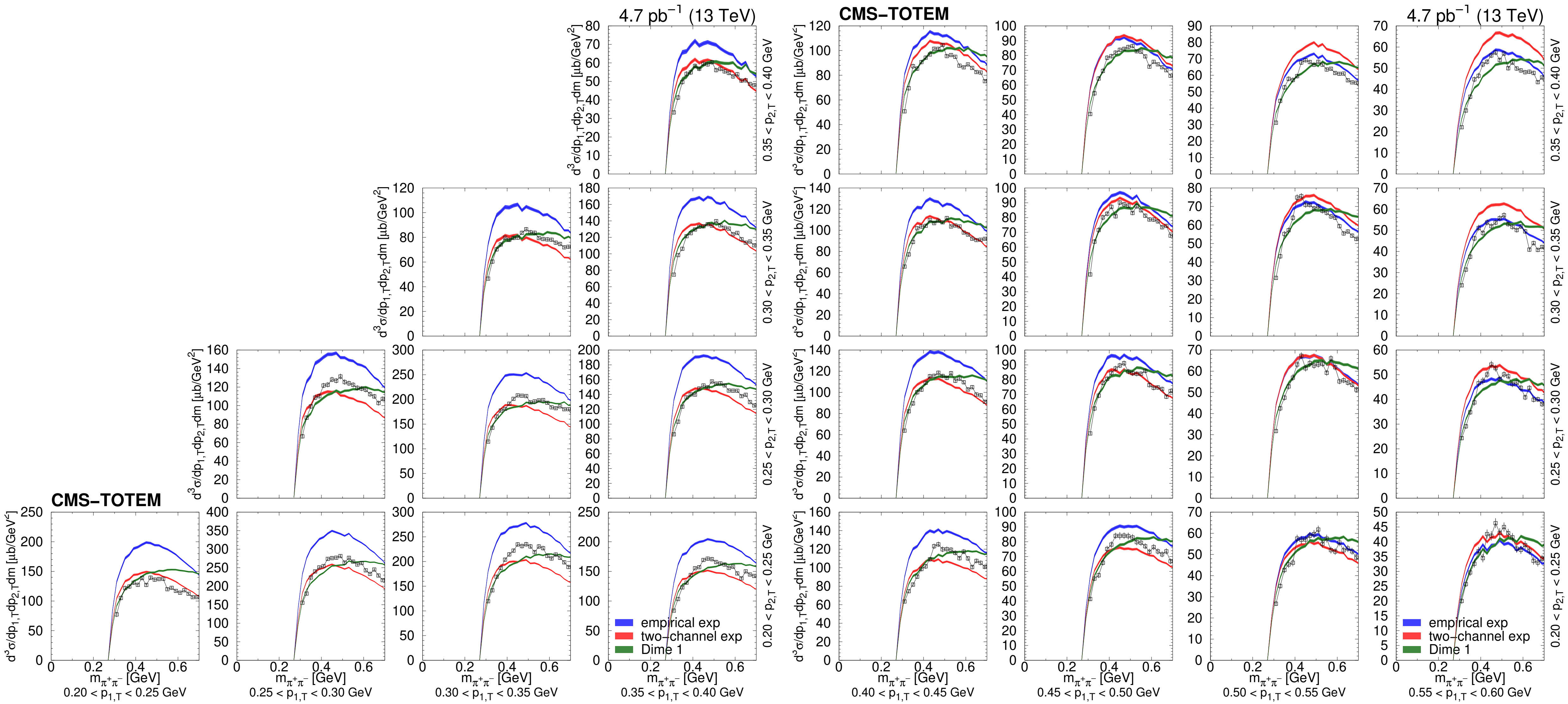
Looks good

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



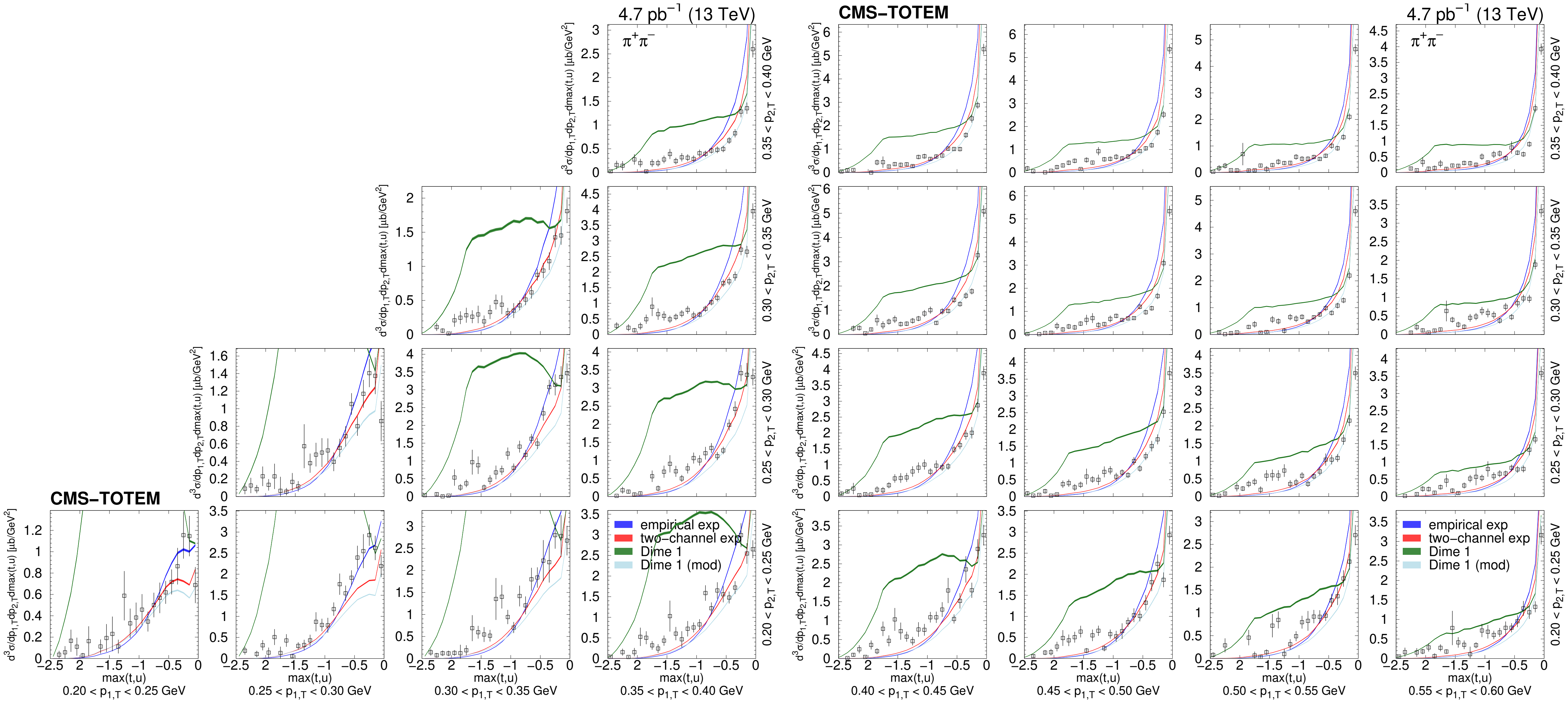
Maybe a ground-state proton is enough? But then what about $\mathrm{d}\sigma/\mathrm{d}t$

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



Looks good

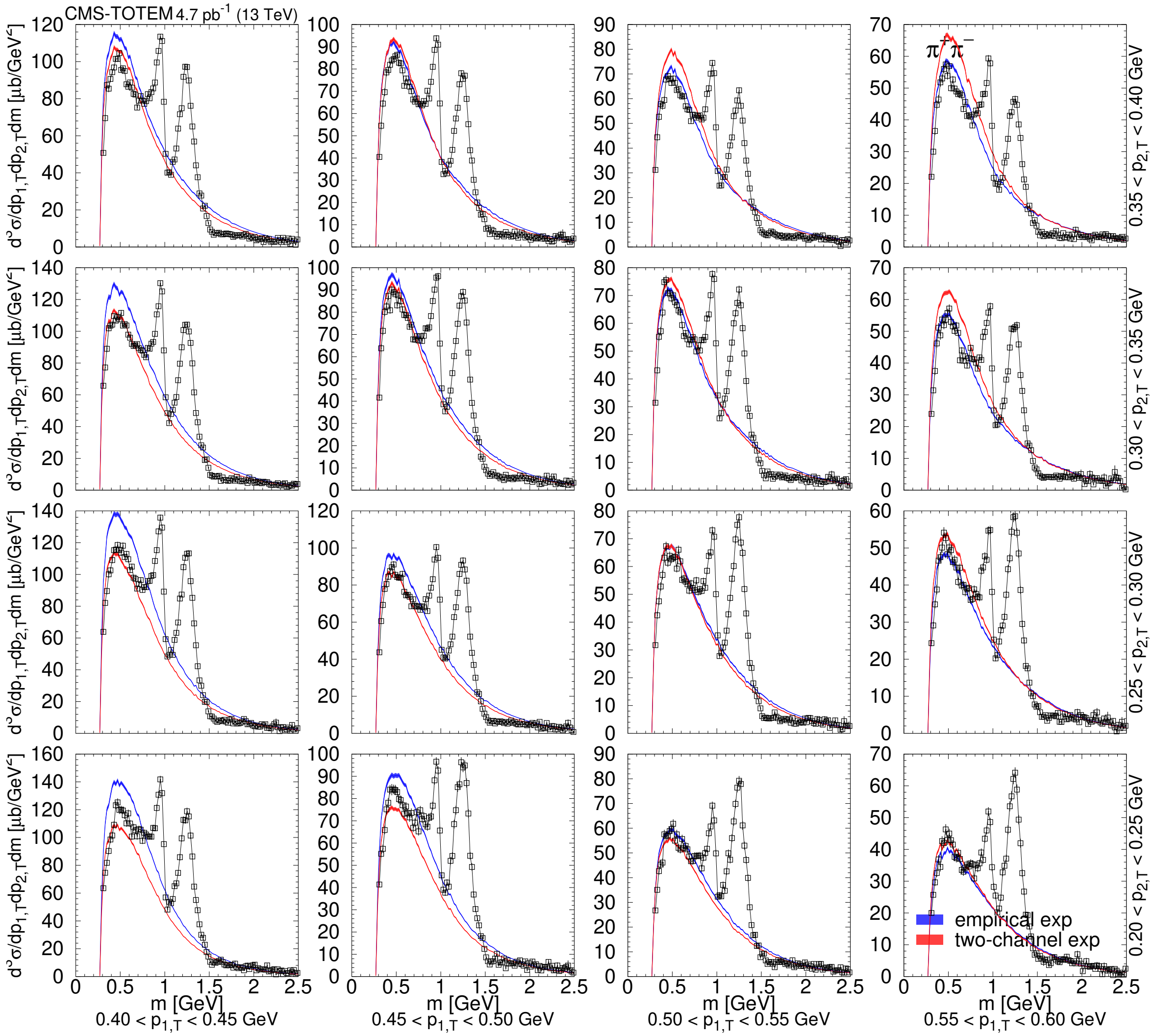
$\mathrm{d}\sigma/\mathrm{d}\max(\hat{t},\hat{u})\ -\ \pi^+\pi^-$



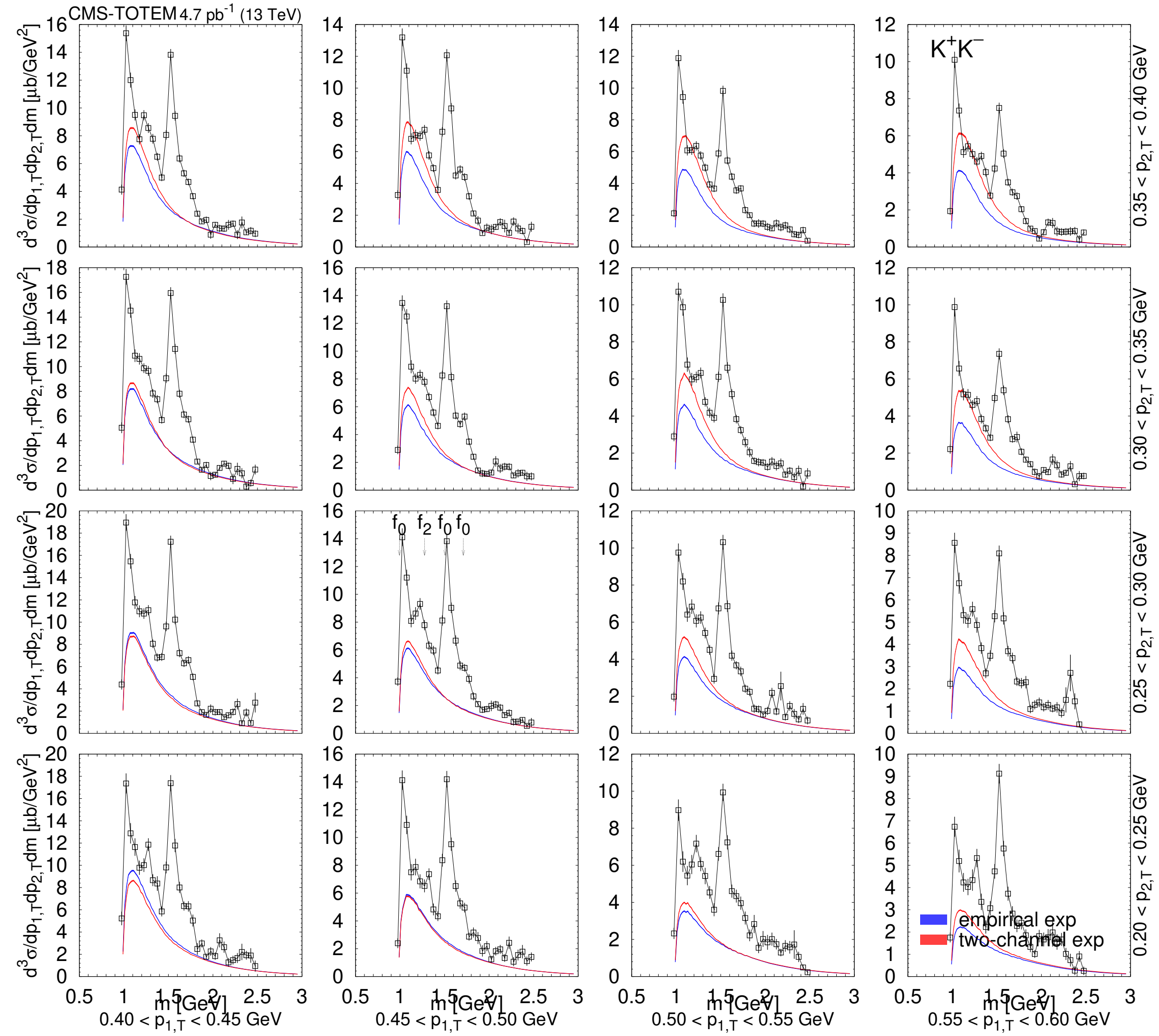
Original DIME tune is quite off

Resonances

$\pi^+\pi^-$



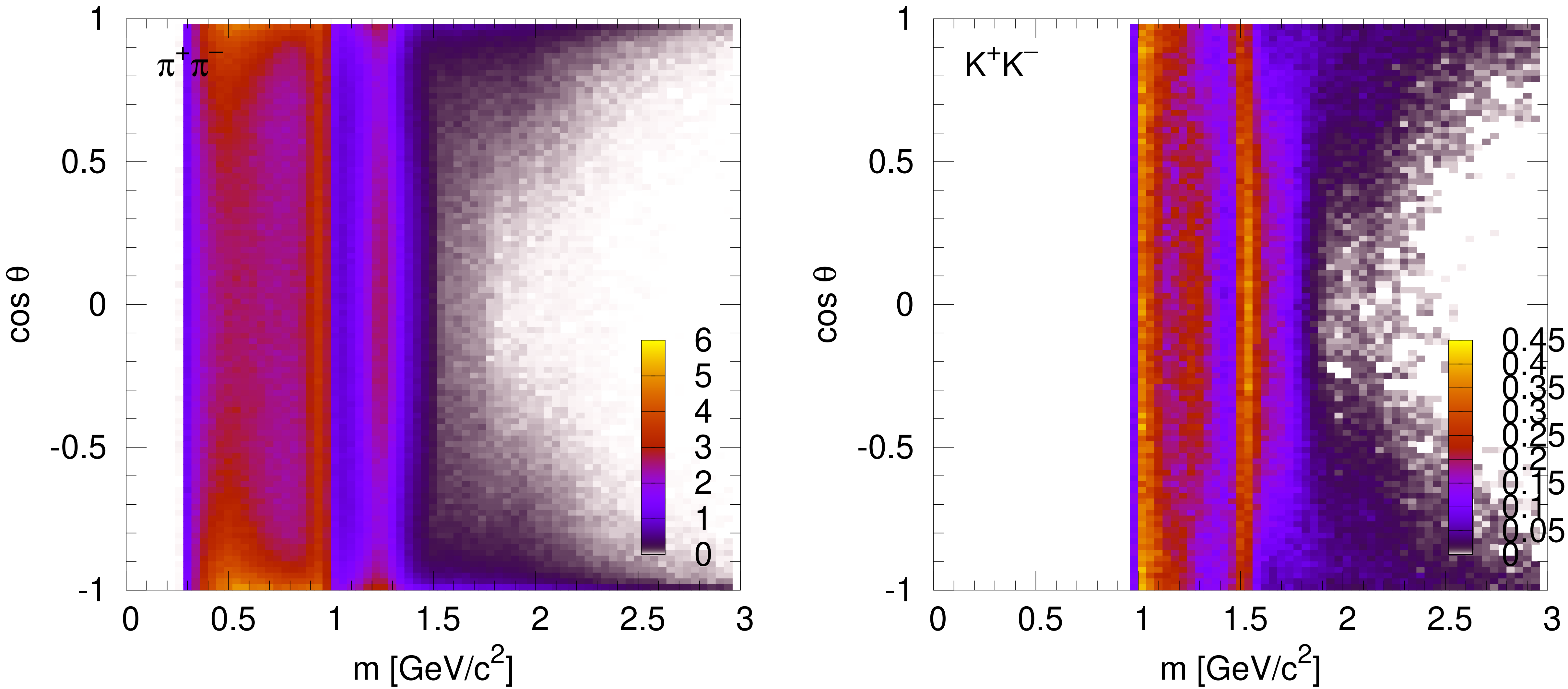
K^+K^-



Mass spectra and decay spherical harmonics – precision and spin/parity

$f_0(980)$, $f_2(1270)$, $f_0(1370)$, $f_0(1500)$, $f_2'(1525)$, $f_0(1710)$, $f_J(2xxx)$, and others

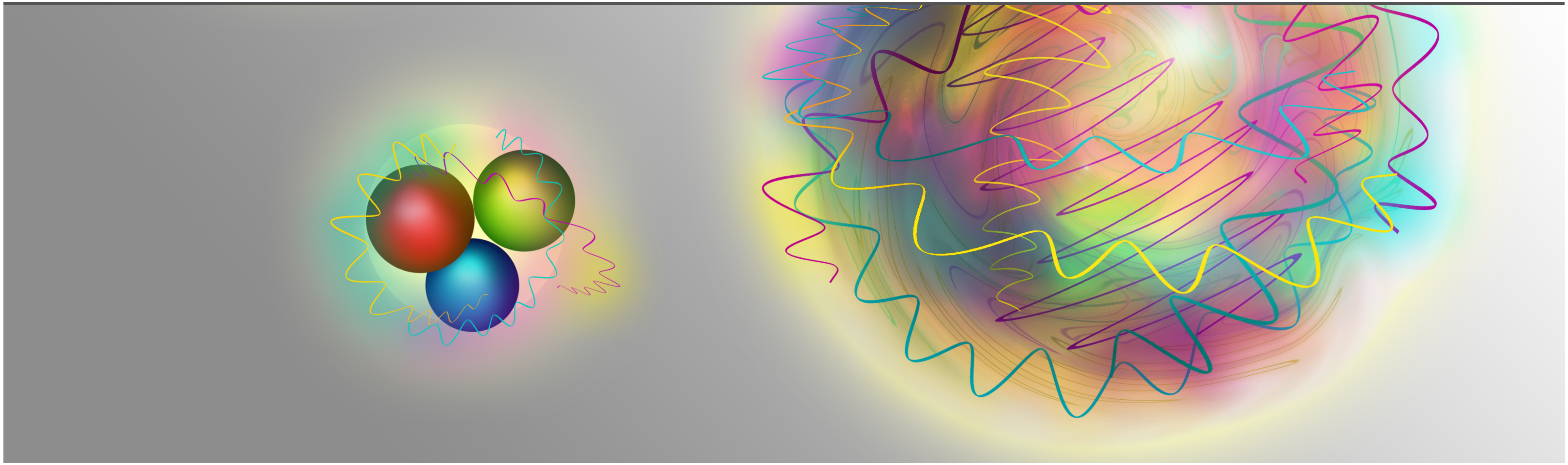
Central exclusive production – polar angle



Angular distribution depends on mass – connected to spin!

$f_0(980)$ is spin-0 (S-wave), $f_2(1270)$ is spin-2 (D-wave)

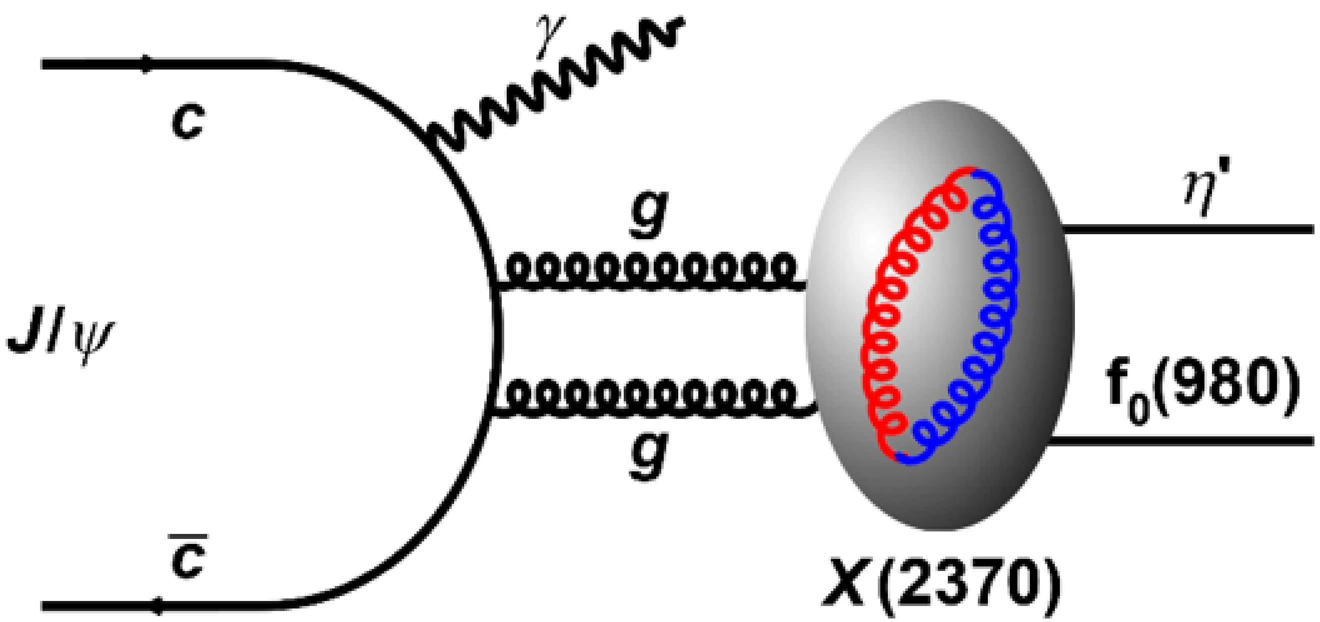
Glueballs?



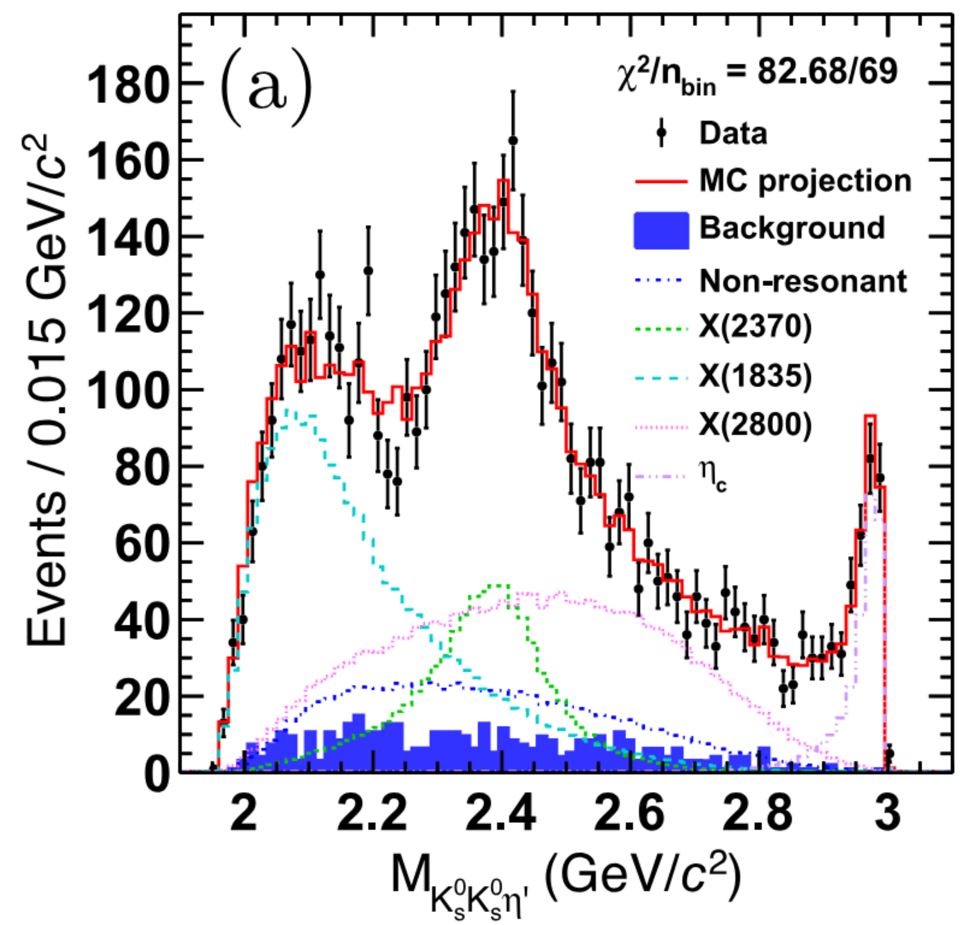
- Details
  - enhanced in gluon-rich environment, such as $\mathbb{P}\mathbb{P}$ scattering, also in gluonic jets
  - how do you recognise them? difficult, pure gluonic states mix with $q\bar{q}$ states
  - no firm mass prediction from lattice calculations

No firm mass prediction from lattice calculations ($1600 - 1700$ MeV/c^2)

Glueball candidates – X(2370)



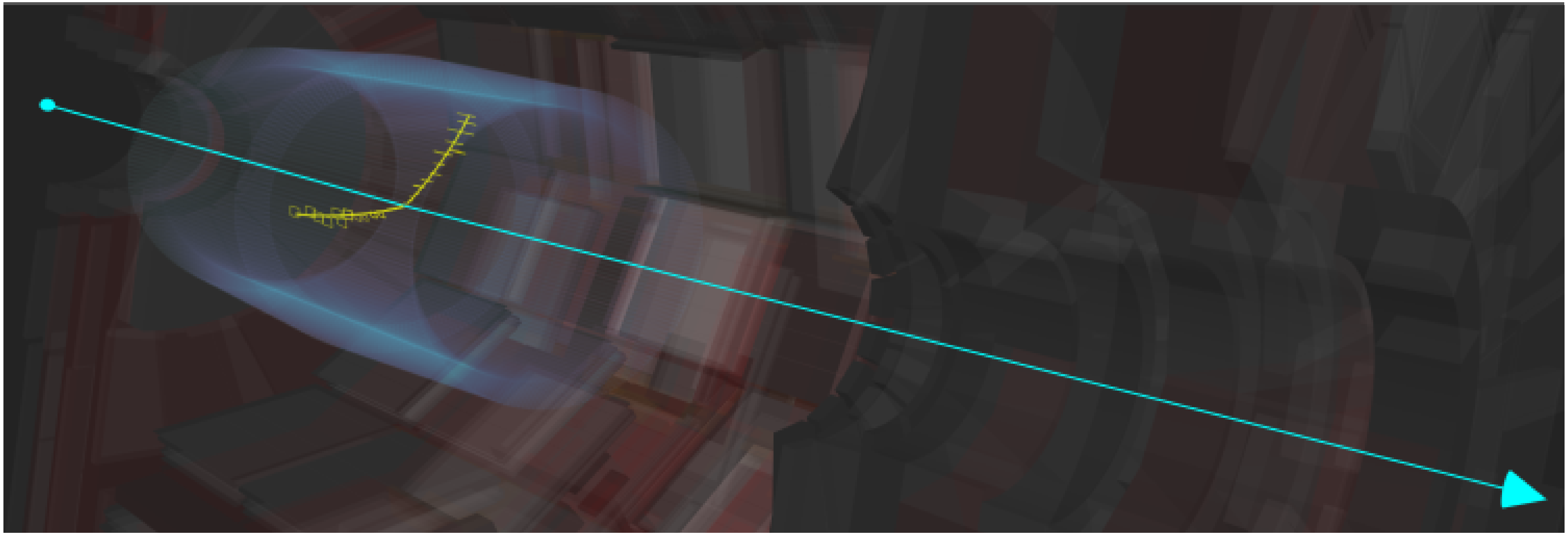
Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a partial wave analysis of the decay $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed. The mass and width of the $X(2370)$ are measured to be $2395 \pm 11(\text{stat})^{+26}_{-94}(\text{syst})$ MeV/c^2 and $188^{+18}_{-17}(\text{stat})^{+124}_{-33}(\text{syst})$ MeV, respectively. The corresponding product branching fraction is $\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to f_0(980)\eta'] \times \mathcal{B}[f_0(980) \to K_S^0 K_S^0] = (1.31 \pm 0.22(\text{stat})^{+2.85}_{-0.84}(\text{syst})) \times 10^{-5}$. The statistical significance of the $X(2370)$ is greater than 11.7σ and the spin parity is determined to be 0^{-+} for the first time. The measured mass and spin parity of the $X(2370)$ are consistent with the predictions of the lightest pseudoscalar glueball.



BESII Collaboration, Phys Rev Lett 132 (2024) 181901

Are there $q\bar{q}$ states nearby?

Forward physics at LHC energies



CMS Collaboration, "In search of the strong interaction: the pomeron"

Thanks

Optical theorem

Incident plane wave along z axis, the scattering amplitude is

$$\phi(\mathbf{r}) \approx e^{ikz} + f(\theta)\frac{e^{ikr}}{r} + \dots$$

For large z and at small angle θ

$$r \approx z + \frac{x^2 + y^2}{2z} = z + \frac{\rho^2}{2z}$$

The intensity

$$|\phi|^2 \approx \left| e^{ikz} + \frac{f(\theta)}{z} e^{ikz} e^{ik\rho^2/2z} \right|^2 = 1 + \frac{f(\theta)}{z} e^{ik\rho^2/2z} + \frac{f^*(\theta)}{z} e^{-ik\rho^2/2z} + \frac{|f(\theta)|^2}{z^2}.$$

Dropping $1/z^2$ term, and with $c + c^* = 2\,\mathrm{Re}\,c$,

$$|\phi|^2 \approx 1 + 2\,\mathrm{Re}\left[\frac{f(\theta)}{z} e^{ik\rho^2/2z}\right]$$

Optical theorem

Integrate the intensity $|\phi|^2$ on the transverse plane

Sum over many fringes of the diffraction pattern
Method of stationary phase: $f(\theta) \to f(0)$

$$\int_A |\phi|^2 \mathrm{d}A \approx A + 2\,\mathrm{Re}\left[\frac{f(0)}{z} \cdot \int_0^{2\pi} \mathrm{d}\theta \int_0^{\infty} \mathrm{d}\rho\, \rho\, e^{ik\rho^2/2z}\right] =$$

$$= A + 2\,\mathrm{Re}\left[\frac{f(0)}{z}\frac{2\pi i z}{k}\right] = A - \frac{4\pi}{k}\,\mathrm{Im}\, f(0)$$

Therefore the loss, the scattering cross section is

$$\underline{\sigma_{\text{tot}} = \frac{4\pi}{k}\,\mathrm{Im}\, f(0)}$$

Theory – propagators and virtual particles

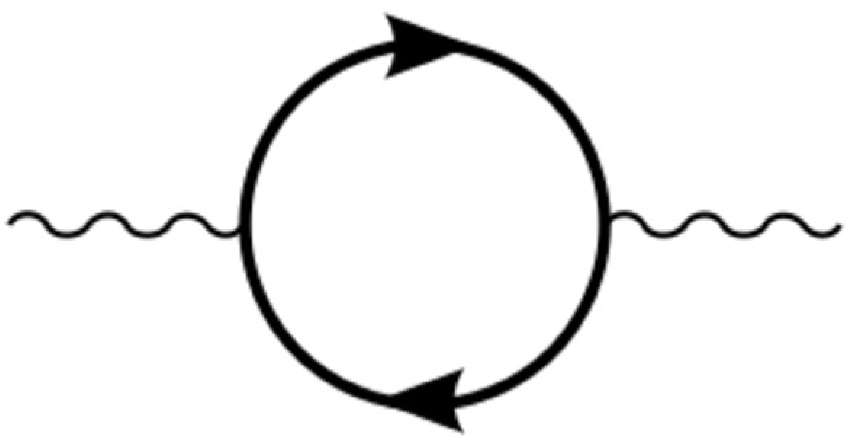
- Propagator
  - specifies the amplitude for a particle to travel from one place to another in a given time, or with a certain energy and momentum
  - for scalars, the propagators are Green's functions for the Klein–Gordon equation

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 + m^2\right) G(x,y) = -\delta(x-y)$$

  - solution, in momentum space is

$$\underline{\underline{\tilde{G}_F(p) = \frac{1}{p^2 - m^2}}}$$

(for resonances, the denom is $p^2 - m^2 + im\Gamma$)



- Virtual particle
  - transient quantum fluctuation, has some of the characteristics of an ordinary particle
  - its existence limited by the uncertainty principle
  - t-channel scattering, vacuum polarisation, etc