Angular observables for nuclear photon fluxes, pomeron-A interactions and toponium probes at the LHC

Dr. Javier Murillo
Universidad de Sonora

EMMI Workshop
Mining for gluon saturation at the LHC and the future EIC

GSI, Darmstadt

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Overview

1) ***Photon EPA fluxes***
   i) Proton and nuclear cases
   ii) Effect on UPC dynamics and ttbar production

2) ***Large rapidity gap pA interactions*** (*semiexclusive*)
   i) pomeron-A and angantyr
   ii) CMS probe with pPb data

3) ***Toponium probes***
   i) EFT and NRQCD η_t models phenomenologies
   ii) Spin correlation observables
   iii) ttbar background rejection analysis

4) ***Summary***

Photo-induced processes and non-dissociating hadrons

- **Ordinary Central Collisions**

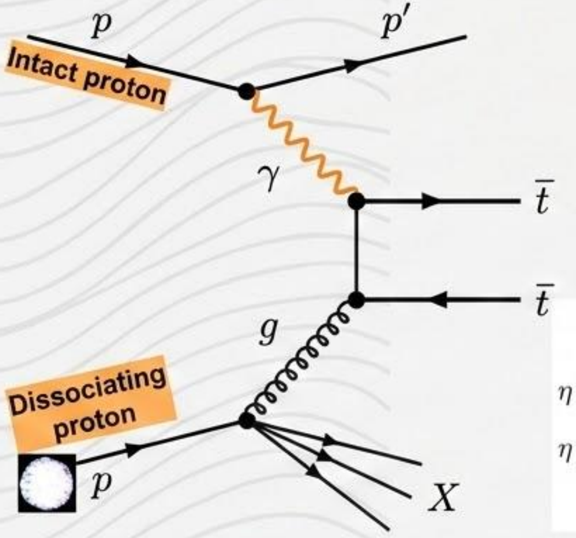
$pp \to X$ Dissociating protons

Equivalent Photon Approximation (EPA) and UPC's

Proton PDFs

$$\sigma = \sum_{i,j} \int dx_1\, dx_2 \boxed{f_{i/p}(x_1, Q^2)\, f_{j/p}(x_2, Q^2)}\, \hat{\sigma}_{ij \to \chi}(x_1, x_2, Q^2)$$

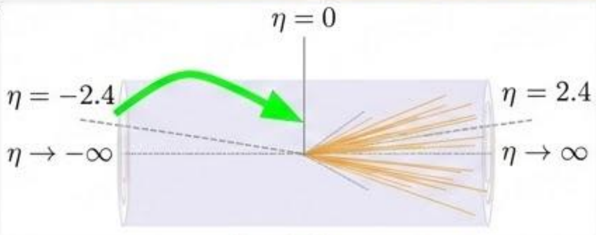
- **Equivalent photon approximation (EPA) and UPC's**



Photon flux

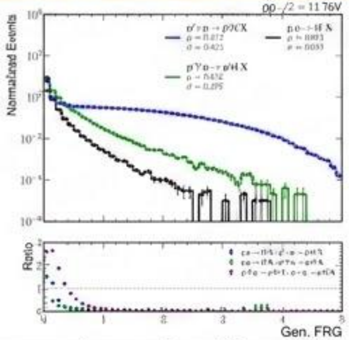
$$\sigma = \sum_{j} \int d\omega\, dx_2 \boxed{\left.\frac{dN}{d\omega}\right|_{p1}} f_{j/p}(x_2, Q^2)\, \hat{\sigma}_{\gamma j \to \chi}(\omega, x_2, Q^2)$$

- Photon source replaced by equivalent flux of quasi-real photons with energy ω
- **Weizsäcker–Williams (WW)**, **Drees–Zeppenfeld (DZ)** and **Budnev** EPA formalisms

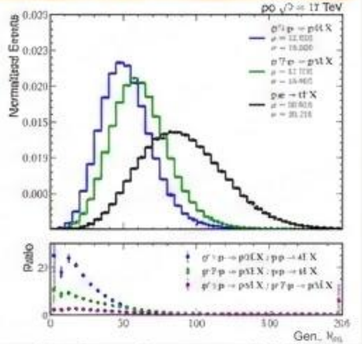


$pp \to p'\, \gamma\, \boldsymbol{p} \to p'\, \boldsymbol{X}$

Rapidity gap
and lower particle production



Larger Rapidity gap

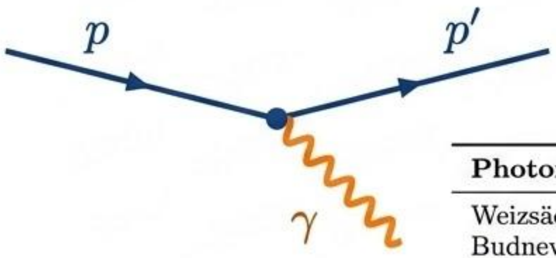


Reduced part. multiplicities

Cota Rodriguez, A., V. Corral, J.A. & Murillo Quijada, *Eur. Phys. J. C* **86**, 228 (2026)

Photo-induced processes and non-dissociating hadrons $pp \to p' \boxed{\gamma\, p} \to p' X$

- *Equivalent photon approximation (EPA) and **UPC's***
- ***Weizsäcker-Williams (WW)**, **Drees-Zeppenfeld (DZ)** and **Budnev** EPA formalisms with different photon virtuality and proton form factor considerations*



$$\sigma_{p'\gamma p} = 1.395 \pm 0.006\ (\mathrm{stat}) \pm \boxed{0.129\ (\mathrm{syst})}\ \mathrm{pb}$$

~9.2%

Photon Flux	Low(%)	Mid(%)	High(%)
Weizsäcker–Williams	58.87	40.06	1.08
Budnev	60.30	38.83	0.87
Drees–Zeppenfeld	62.98	36.82	0.20

Photon fluxes

$$f_{\gamma/p}(x) = \frac{\alpha}{2\pi}\left[\frac{1+(1-x)^2}{x}\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right) - 2m_p^2 x\left(\frac{1}{Q^2_{\min}} - \frac{1}{Q^2_{\max}}\right)\right]$$

W.W. : Point like

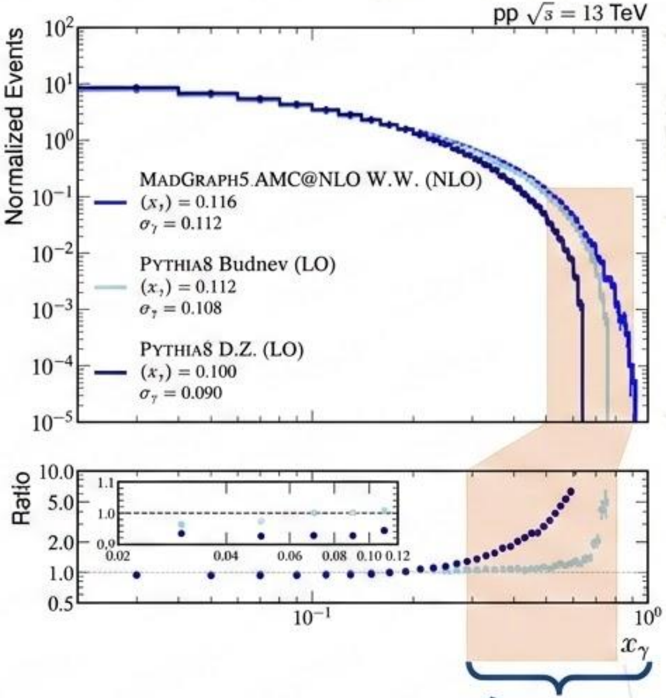
$$\frac{d^2N_\gamma}{dx\, dQ^2} = \frac{\alpha}{\pi}\frac{1}{xQ^2}\left[(1-x)\left(1-\frac{Q^2_{\min}}{Q^2}\right)F_E(Q^2) + \frac{x^2}{2}F_M(Q^2)\right]$$

Budnev: Electromagnetic form factors

$$f_{\gamma/p}(x) = \frac{\alpha}{2\pi x}[1+(1-x)^2]\left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right)$$

D. Z. : Dipole form factors

Sampled photons in $x = E_{ph}/E_p$ energy fraction range

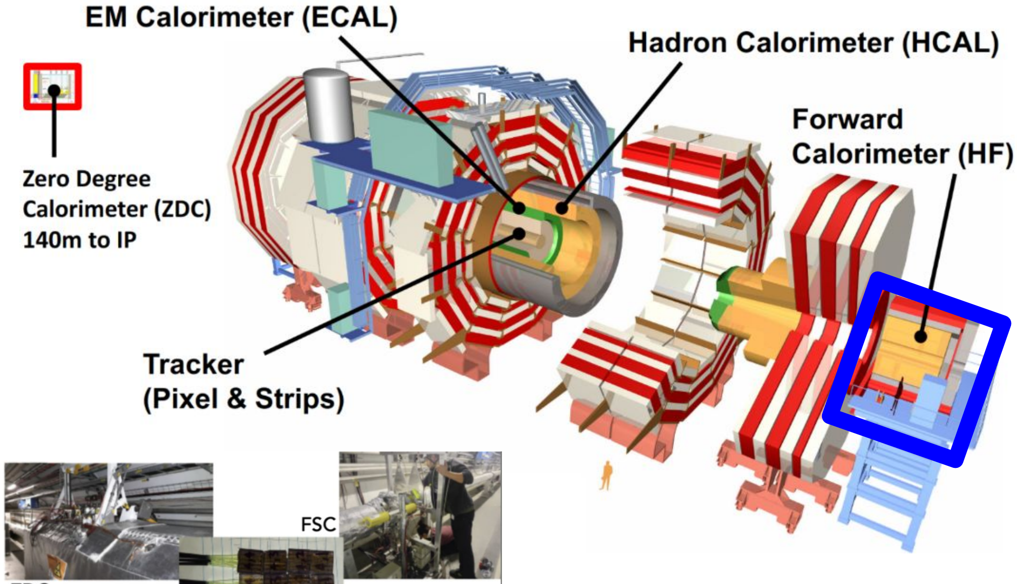


DZ and Budnev suppressing high virtualities and x fractions

Cota Rodríguez, A., V. Corral, J.A. & Murillo Quijada, *Eur. Phys. J. C* ***86****, 228 (2026)*

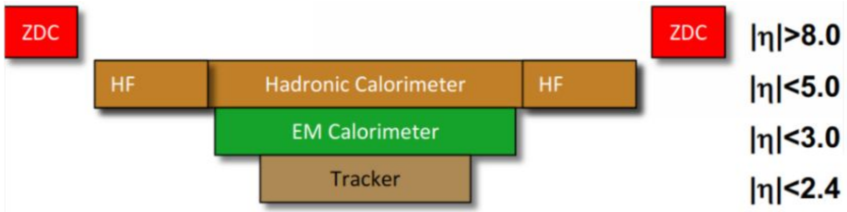
Forward detectors

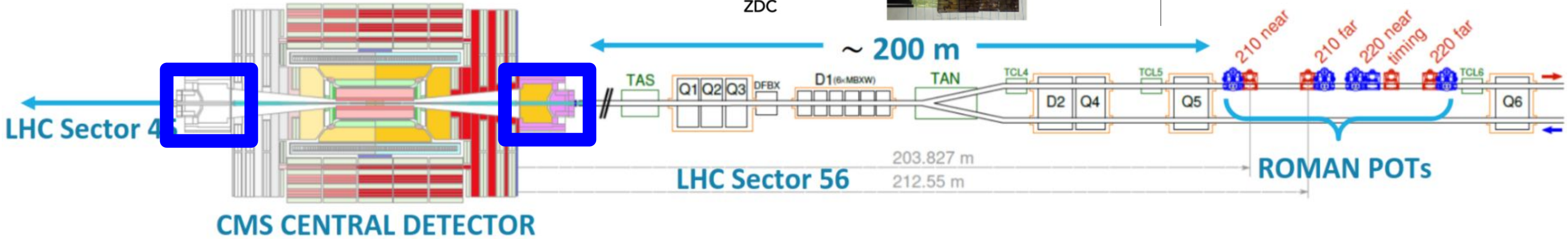
- Zero Degree (ZDC) and Hadronic Forward (HF) calorimeters for Pb and protons respectively
- CMS Particle Flow energies to constrain activity as a function of η
- CT-PPS spectrometer for pp runs



- Analysis can be guided by recorded activity as function of pseudorapidity

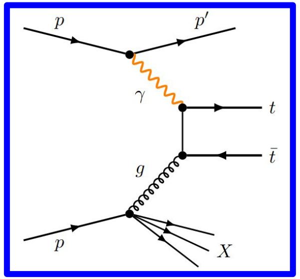
- Or ir can rely on proton tagging

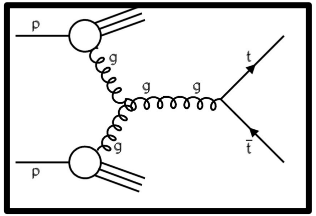


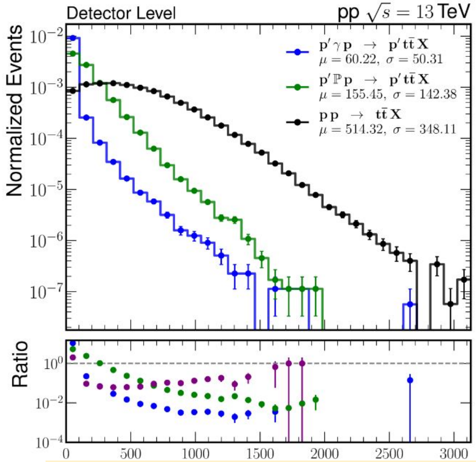


Photoinduced *vs* ***central production*** *features*

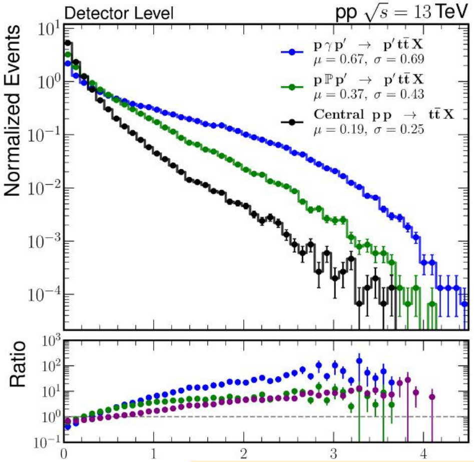
Neural network training for ***top-antitop*** *quarks productions*







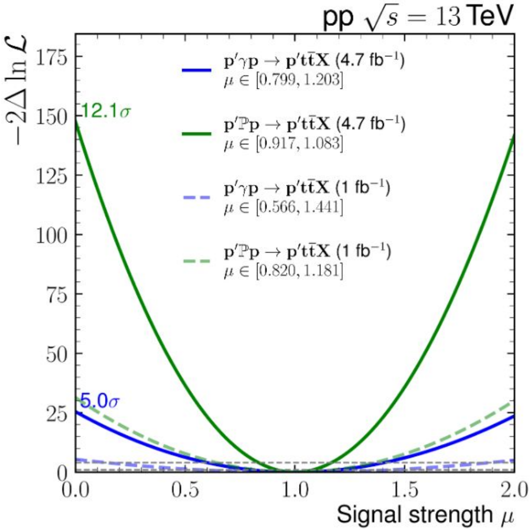
Smallest HF energy (+ or - side)

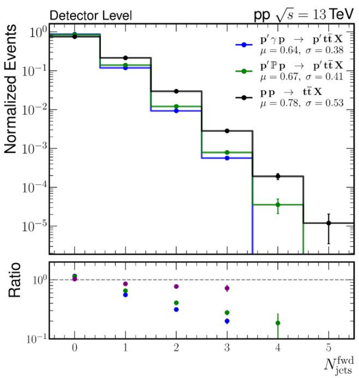


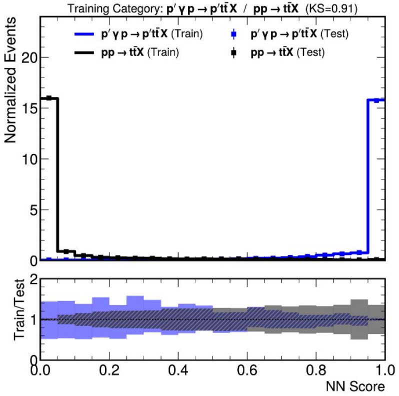
Forward rapidity gap

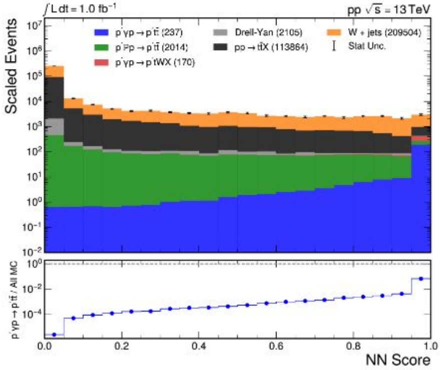
At least 4.7fb^{-1} of low pile up pp data for observation

Alternative scenario for HL-LHC





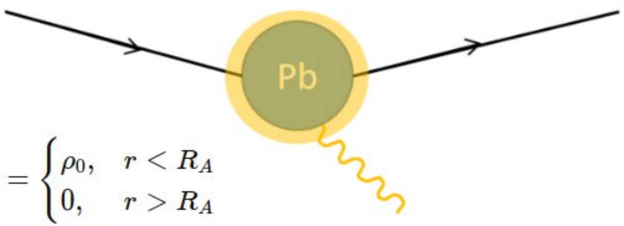




Current analysis with standard pp runs affected by **large pileup levels**

Cota Rodríguez, A., V. Corral, J.A. & Murillo Quijada, J.A.. Eur. Phys. J. C ***86****, 228 (2026)*

Nuclear EPA fluxes



- **Hard sphere approximation**

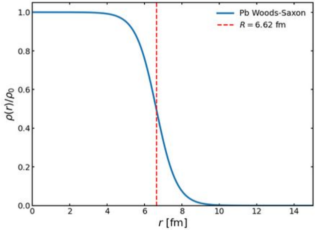
$$\rho(r) = \begin{cases} \rho_0, & r < R_A \\ 0, & r > R_A \end{cases}$$

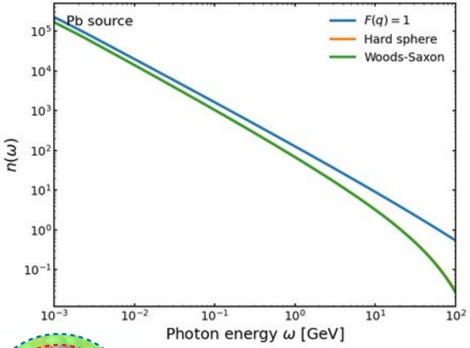
Uniform charge distribution

$$n(\omega) = \frac{2Z^2\alpha}{\pi\omega}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right] \quad \xi = \frac{\omega\, b_{\min}}{\gamma} \quad \omega_{\max} \sim \frac{\gamma}{b_{\min}}$$

- **Wood-saxon**

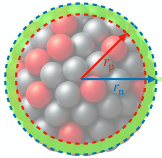
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$



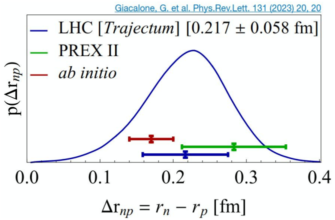


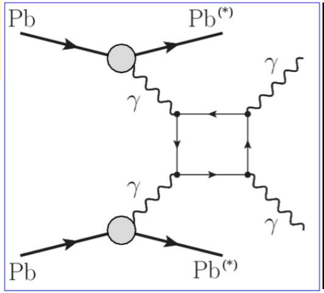
$$F(\mathbf{q}) = \frac{1}{Ze}\int d^3r\, \rho(r) e^{i\mathbf{q}\cdot\mathbf{r}}$$

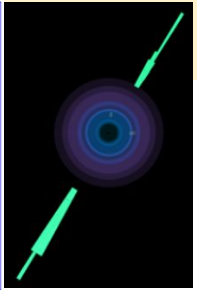
$$N(\omega, b) = \frac{Z^2\alpha}{\pi^2\omega}\left|\int d^2q_\perp \frac{\mathbf{q}_\perp}{q_\perp^2 + \omega^2/\gamma^2} F(q) e^{i\mathbf{q}_\perp\cdot\mathbf{b}}\right|^2$$



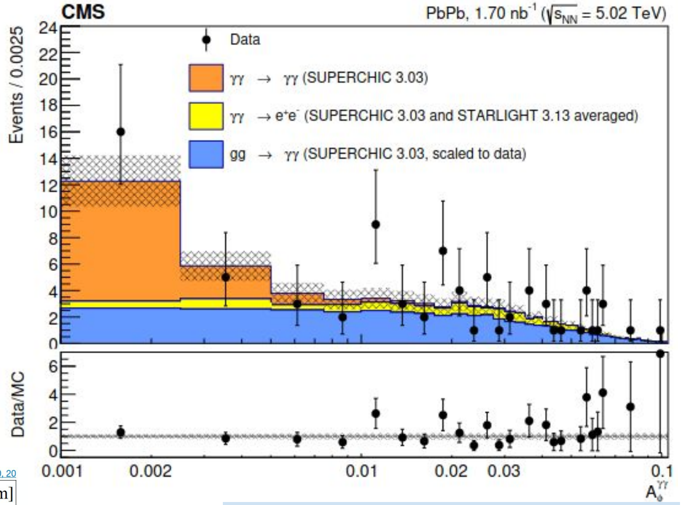
Proton and neutron independent densities; **neutron skin**





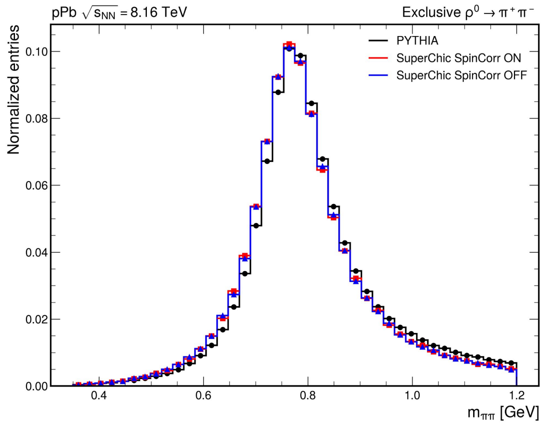


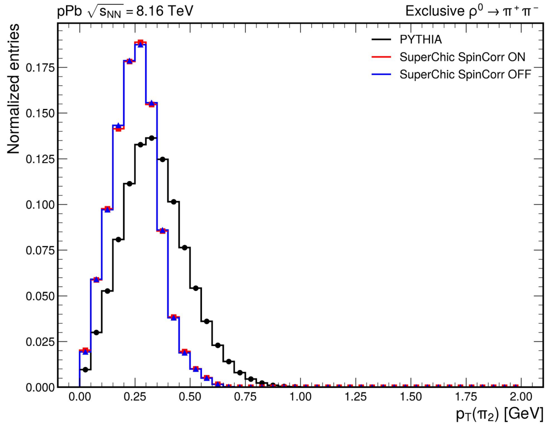
Light-by-light scattering

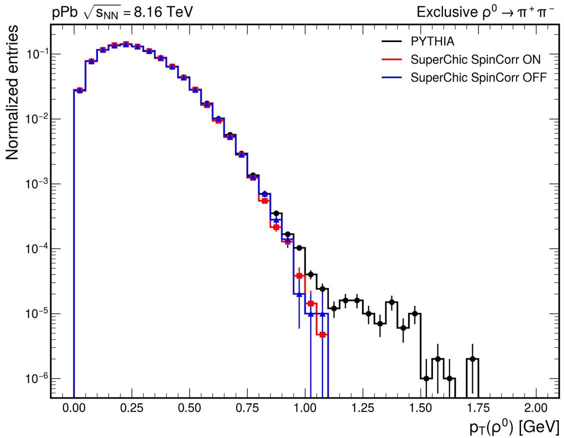


Superchic including wood saxon and skin treatment

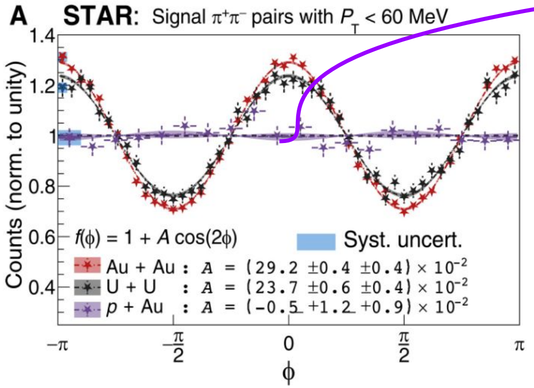
Exclusive vector meson photoproduction within pPb and angular modulations



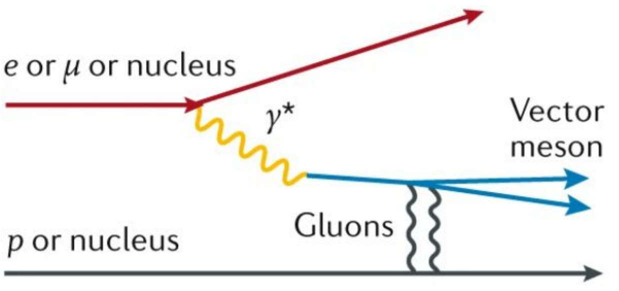


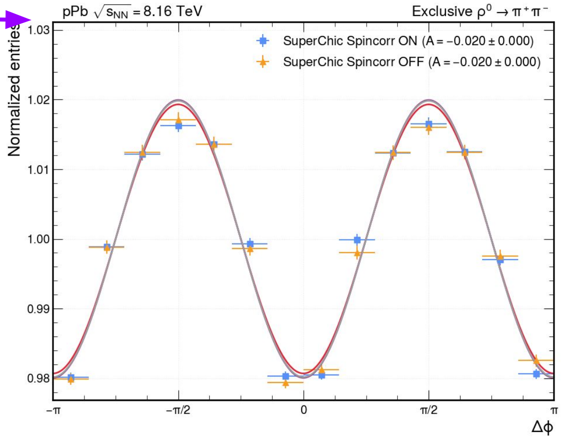


- ***Modulations and proton probing***



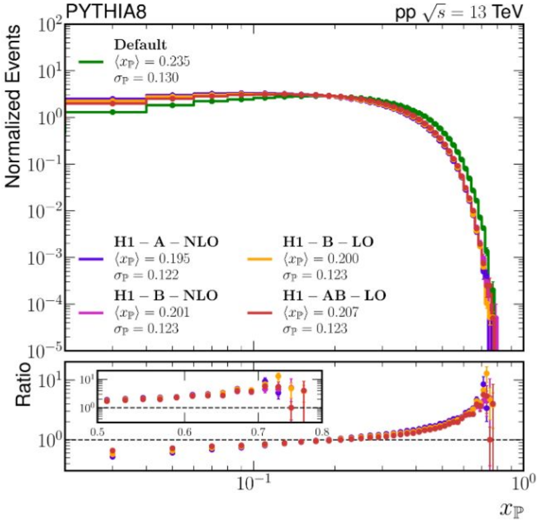
Photon and pomeron

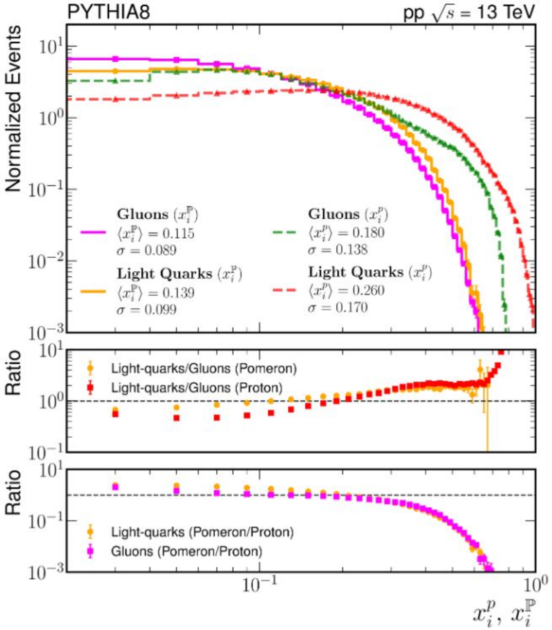




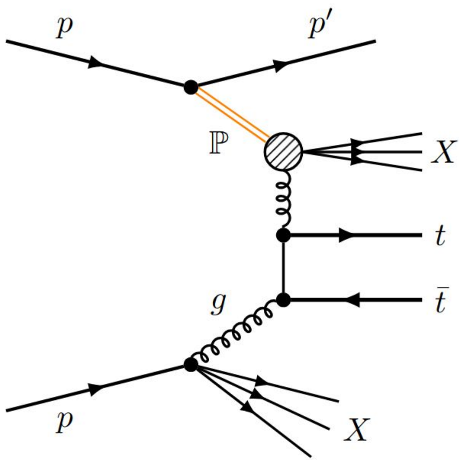
Pomeron *neutral fluxes*

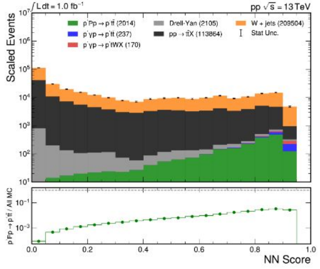
Proton pomeron fluxes

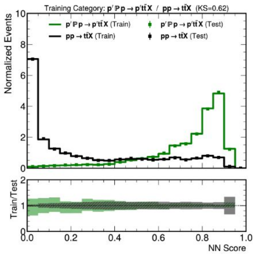




Pomeron treatment as hadron with own PDF







$$\xi \equiv x_{\mathbb{P}} = \frac{E_{\mathbb{P}}}{E_{\text{beam}}}$$

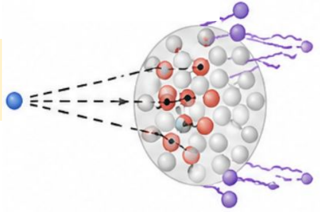
$$\underbrace{f_{i/p}^{D}(x, Q^2; \xi, t)}_{\text{DPDF}} = \underbrace{f_{\mathbb{P}/p}(\xi, t)}_{\text{pomeron flux}} \times \underbrace{f_{i/\mathbb{P}}(\beta, Q^2)}_{\text{parton distribution of pomeron}}$$

Ingelman–Schlein

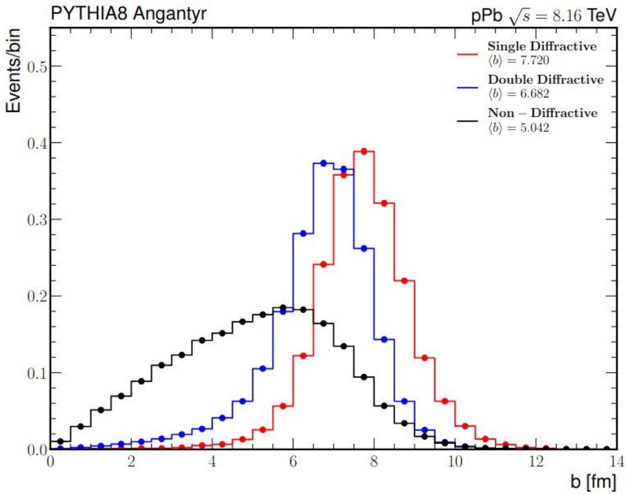
Data Driven Fit	Pomeron Flux	Pomeron Set
Default	1	6
H1-A-NLO	6	3
H1-B-NLO	7	6
H1-B-LO	7	4
H1-AB-LO	8	6

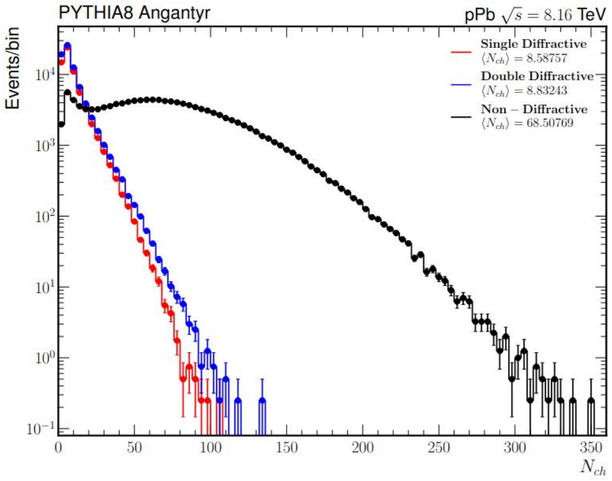
*Cota Rodríguez, A., V. Corral, J.A. & Murillo Quijada, J.A.. Eur. Phys. J. C **86**, 228 (2026)*

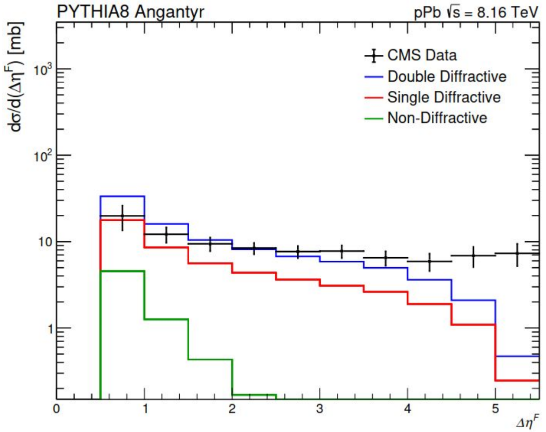
*Pomeron-Nucleus interaction and **Angantyr model***

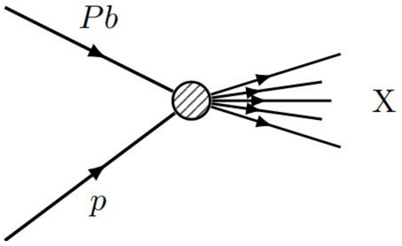


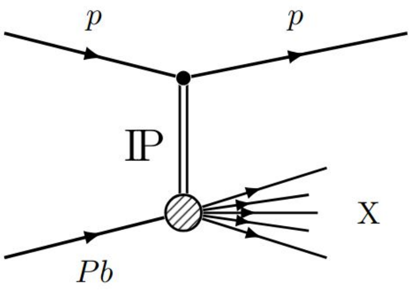
$\mathbb{P} + \mathrm{Pb} \rightarrow X$ *within pPb collisions*

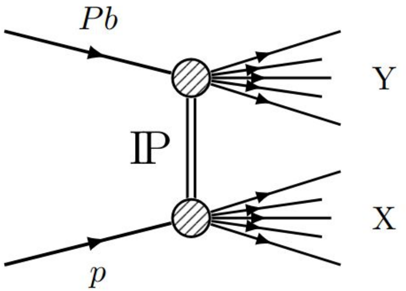


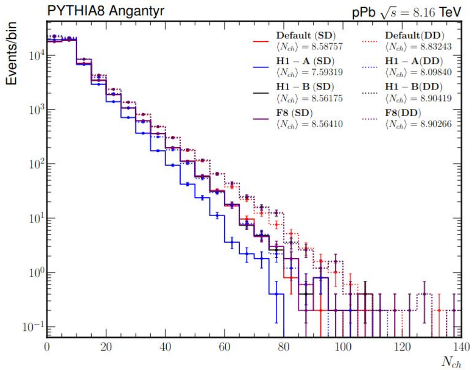








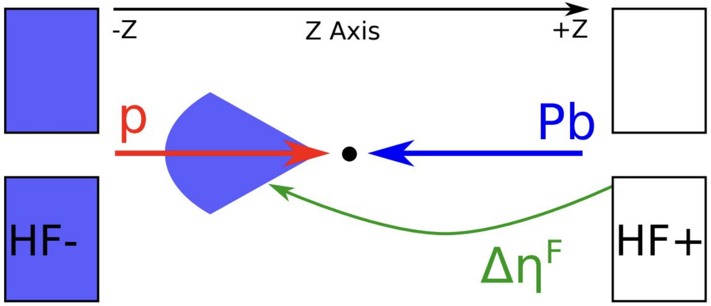


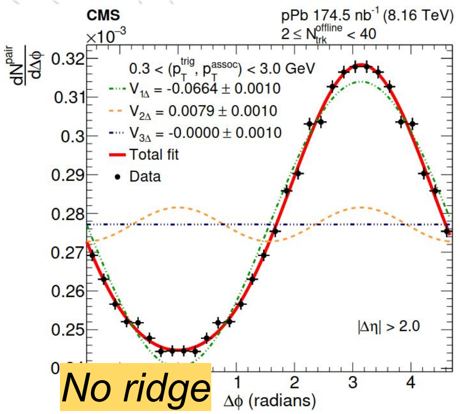


*Jesus A. V. Corral, Cota Rodríguez, A. & Murillo Quijada, J.A. Azimuthal anisotropies within non-perturbative pomeron schemes and nuclear Pb ion interactions and their discrimination against non-diffractive noise, Submitted to **PLB***

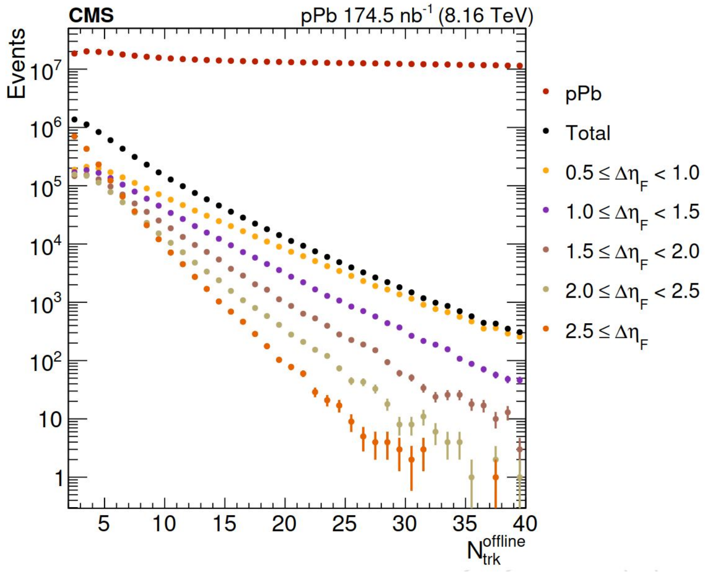
Large rapidity gap pA interactions

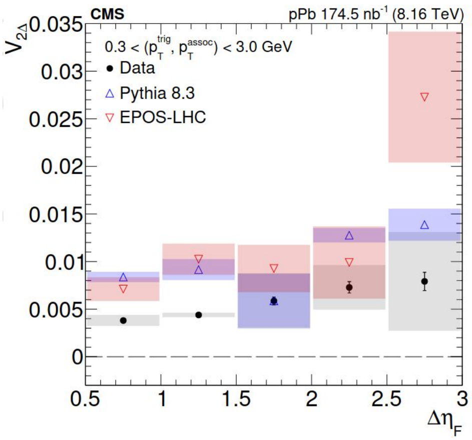
CMS-PAS-HIN-22-004

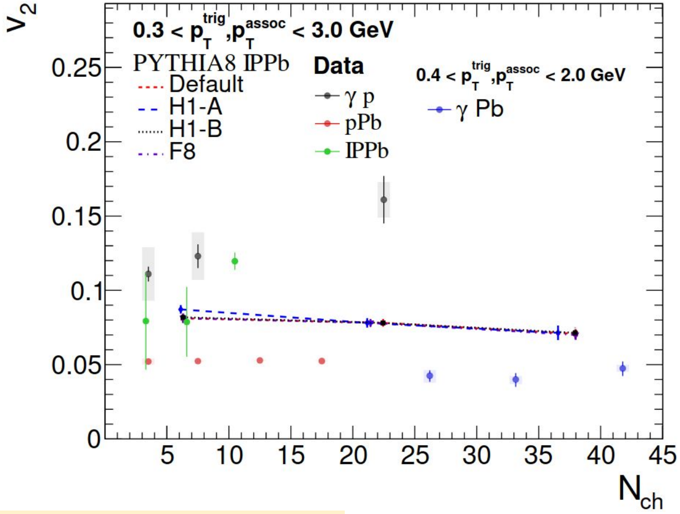




- *Smaller v2 flow anisotropy than gamma-p but larger than pPb*
- *POM-Pb data consistent with PYTHIA model with need to investigate higher Ntrk*

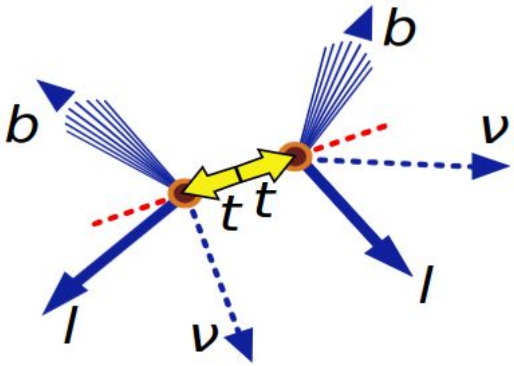






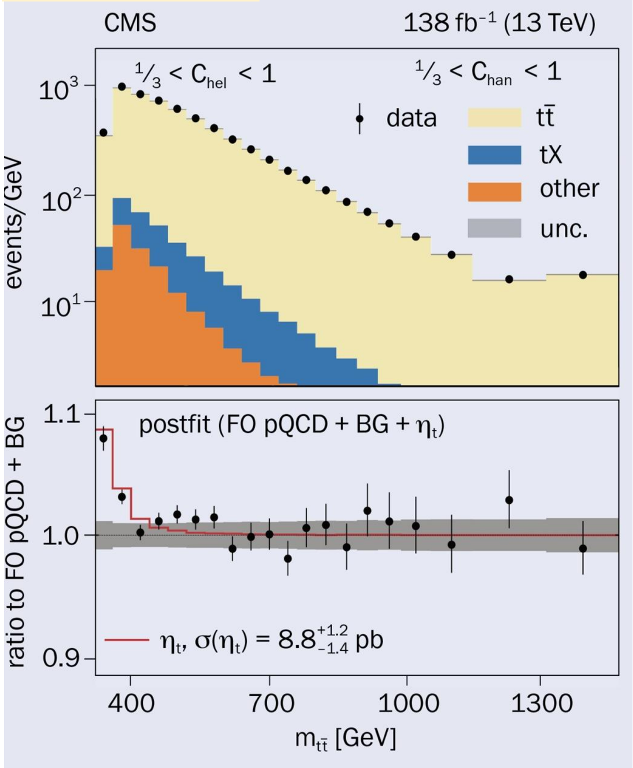
Moises Leon Coello et al. Dependence of two-particle azimuthal correlations on the forward rapidity gap width in pPb collisions at √ s NN = 8.16 TeV, Submitted to Physical Review C.

Observation of a pseudoscalar excess at the top quark pair production threshold



- Extreme top quark properties; reduced lifetime < hadronization timescale
- Bound states with top flavor, not previously considered

CMS-TOP-24-007



CMS-TOP-25-002

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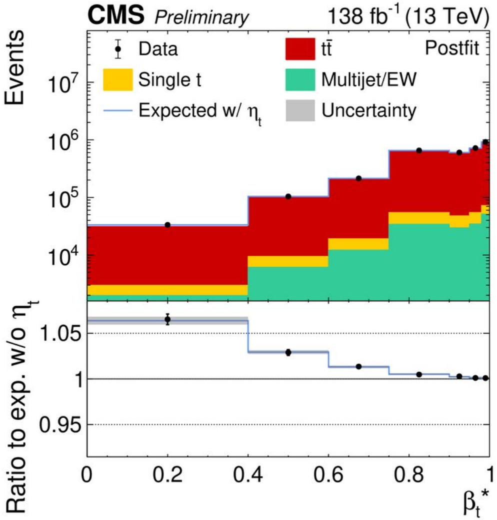
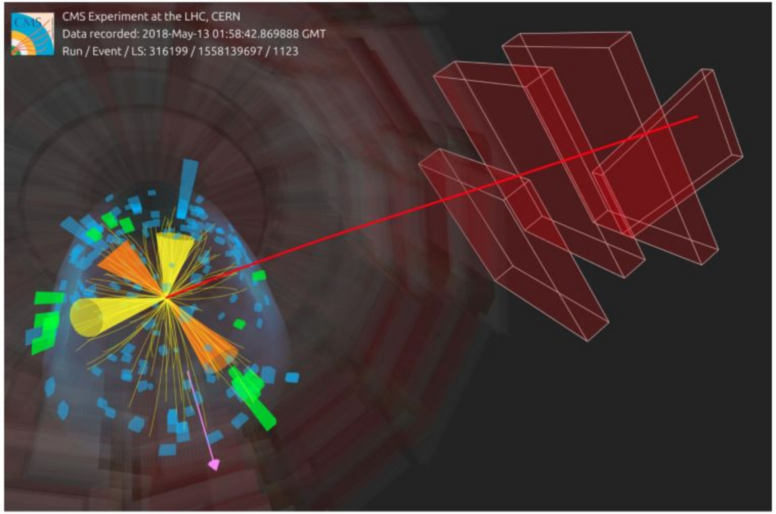
CMS strengthens the case for toponium – Home

CMS strengthens the case for toponium. A new independent measurement by the CMS experiment at the LHC is consistent with the existence of...





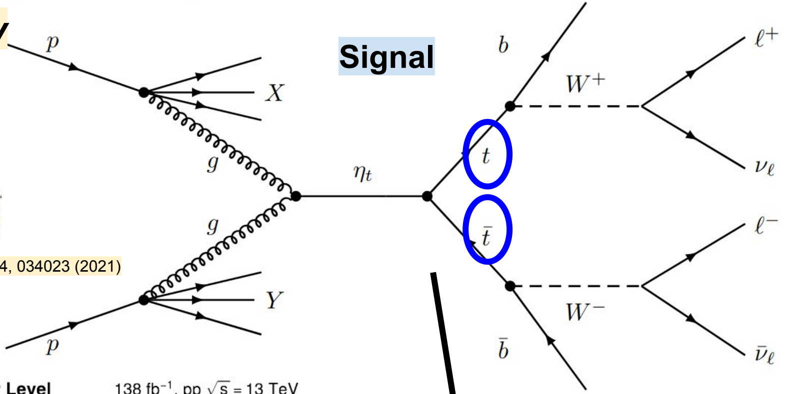
The CMS experiment provides the first confirmation of the excess observed in top quark-antiquark production that is consistent with the short-lived bound state – toponium – decaying to a lepton + jets final state.

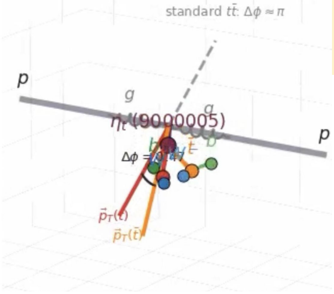
Observation of a pseudoscalar excess at the top quark pair production threshold

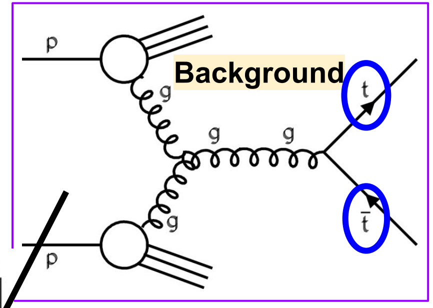
- *A simplified EFT toponium model:* $\eta_t \to t\bar{t}$ decays
  - ***Effective lagrangian density***

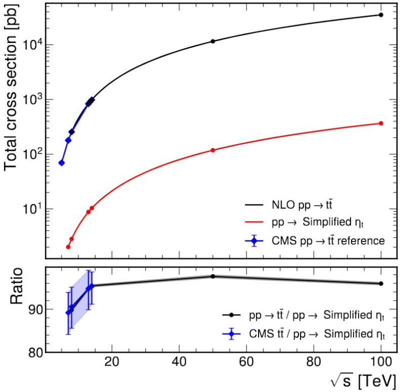
$$\mathcal{L}_{\eta_t} = \frac{1}{2}\partial_\mu \phi_{\eta_t} \partial^\mu \phi_{\eta_t} - \frac{1}{2} m_{\eta_t} \phi_{\eta_t}^2 - \frac{1}{4} g_{gg\eta_t} \phi_{\eta_t} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} - i g_{tt\eta_t} \phi_{\eta_t}$$

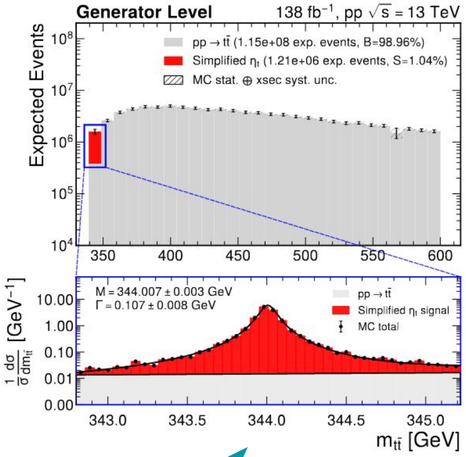
PHYSICAL REVIEW D 104, 034023 (2021)

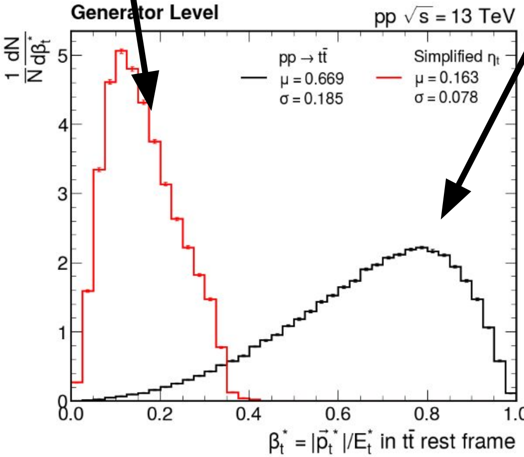


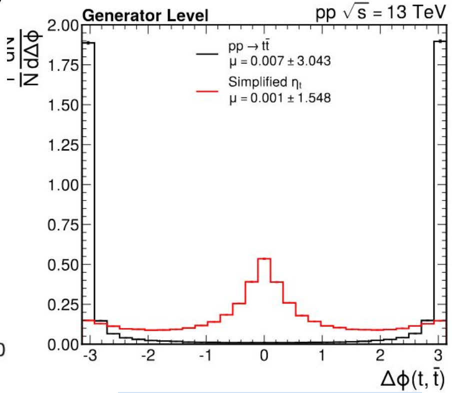


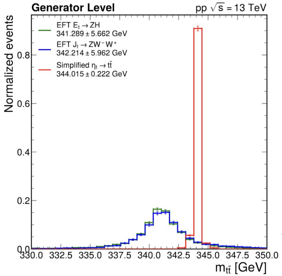












With and without $2m_t$ threshold restriction

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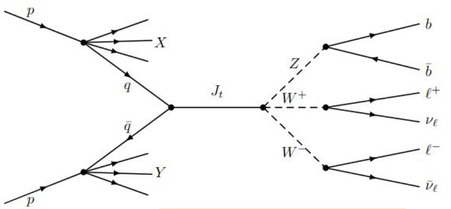
Toponium top pair decays closer azimuthally

Observation of a pseudoscalar excess at the top quark pair production threshold

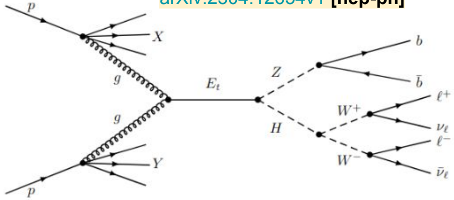
NRQCD toponium model:

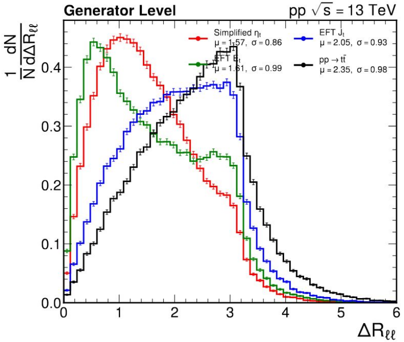
$\eta_t \rightarrow \mathrm{ZH}$ and $J_t \rightarrow \mathrm{ZW^+W^-}$ decays

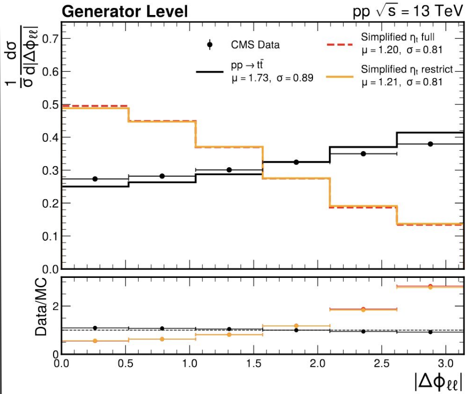
- *Scalar and vector mesons*
- *No $t\bar{t}$ in final state*
- *same $bl^+\nu_l l^- \bar{\nu}_l \bar{b}$ topology*

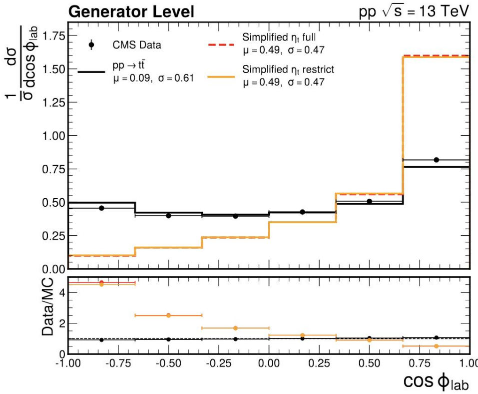


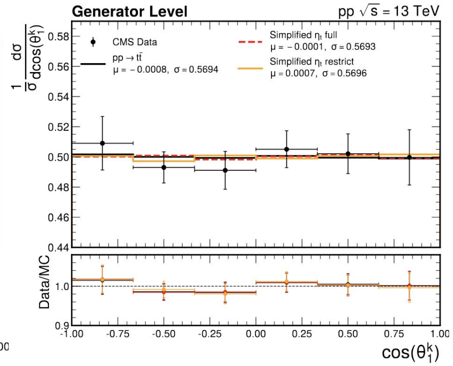
arXiv:2504.12634v1 **[hep-ph]**



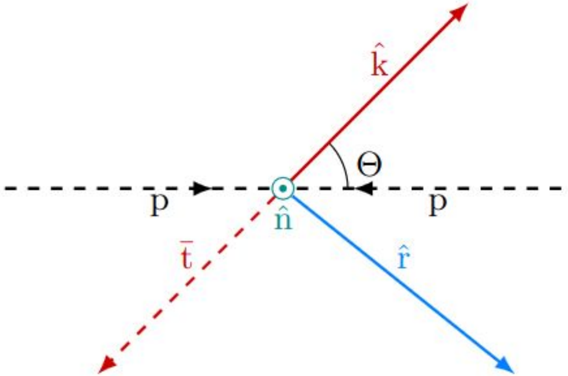


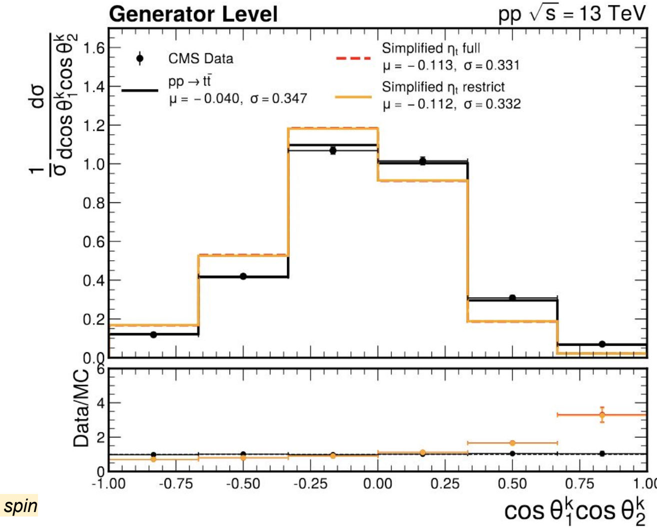






P-even, CP-even symmetry





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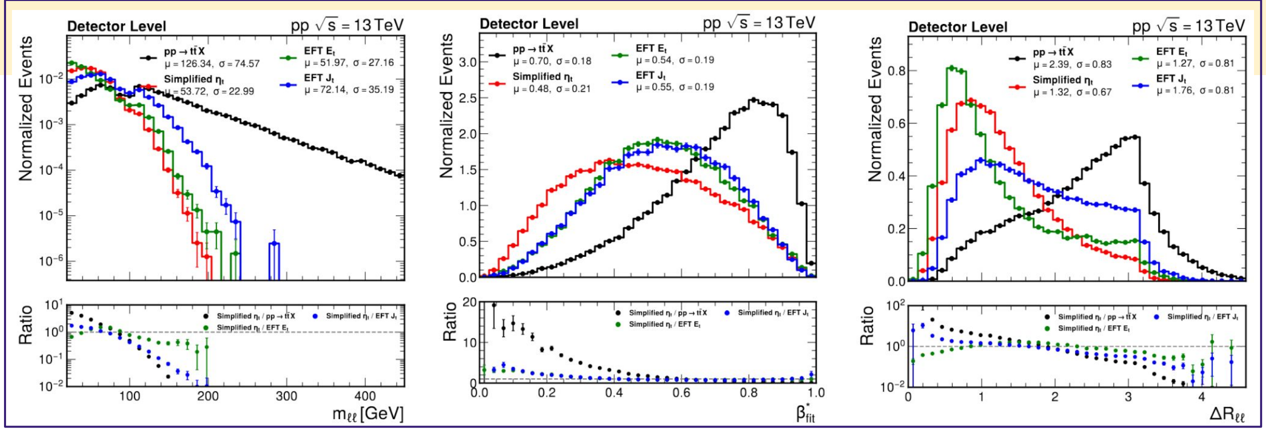
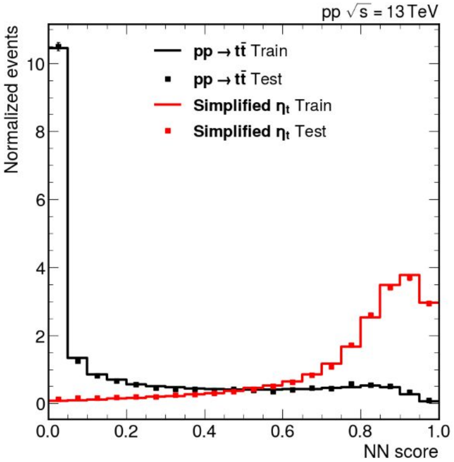
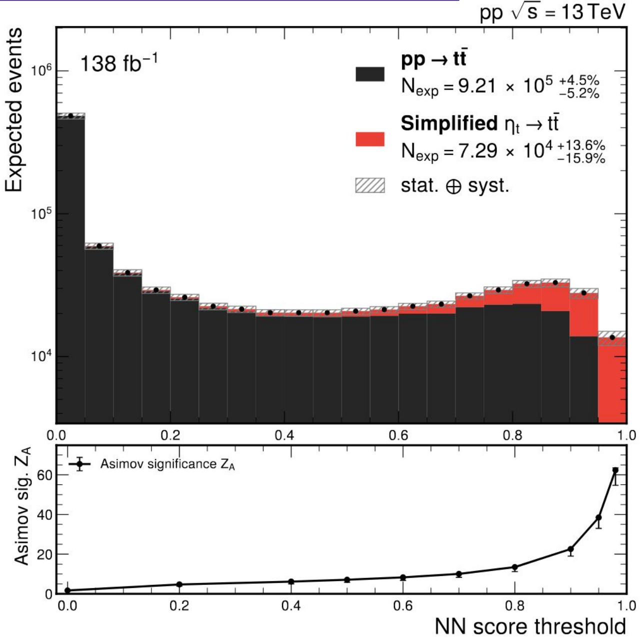
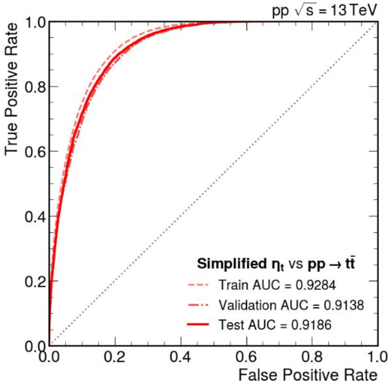
Neural network training

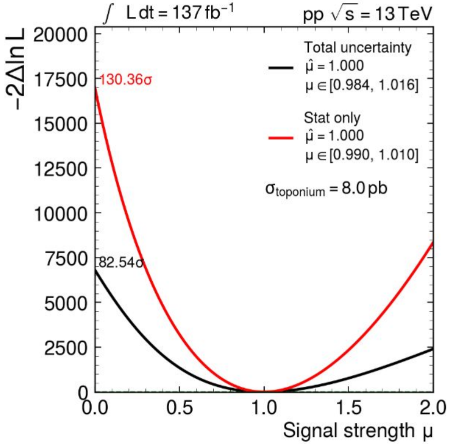




Neural network training identifying most discriminating observables







Improved sensitivity

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Summary and Outlook

- **Ongoing efforts to investigate γ / pomeron induced events**
  - **γp $\rightarrow$ top + antitop process** with large pile up contribution in standard pp collisions
    - Paralel probes with low pile up pp data
  - **Vector meson production** used to investigate origin of azimuthal modulations and for nuclear/hadron structure probing
    - Investigating modulation in pA case with A as photon source
  - **Pomeron-Nucleus interactions** are investigated using Angantyr method and pomeron data driven PDFs
    - Studies can be extended to other lighter nuclei
    - Predictions from MC reference still would need some investigation at high Ntrk
- **Data excess at near to ttbar invariant mass threshold**
  - NRQCD and simplified EFT models phenomenologies has been studied
  - Spin correlation features have been proposed as a way to characterize data excess
  - Improved isolation of toponium events can be achieved by using neural network tagger

Thanks