

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

Dr. Javier Murillo
Universidad de Sonora

2026 Annual Meeting (RADPyC)

Centro de Estudios Avanzados (CINVESTAV)
México City, México

17-19 May 2026



1) **Photon EPA fluxes**

- i) Proton and nuclear cases
- ii) Effect on UPC dynamics

2) **Large rapidity gap pA interactions**

- i) pomeron-A and angantyr
- ii) CMS probe with pPb

3) **Toponium probes**

- i) EFT and NRQCD η_t models phenomenologies
- ii) Spin correlation observables
- iii) $t\bar{t}$ background rejection analysis

4) **Summary**

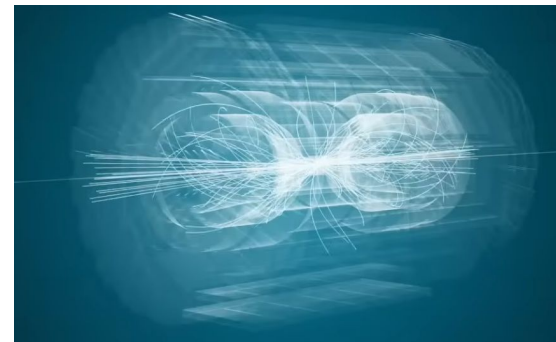
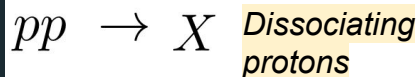


Photo-induced processes and non-dissociating hadrons

Cross section factorisation in pp collisions

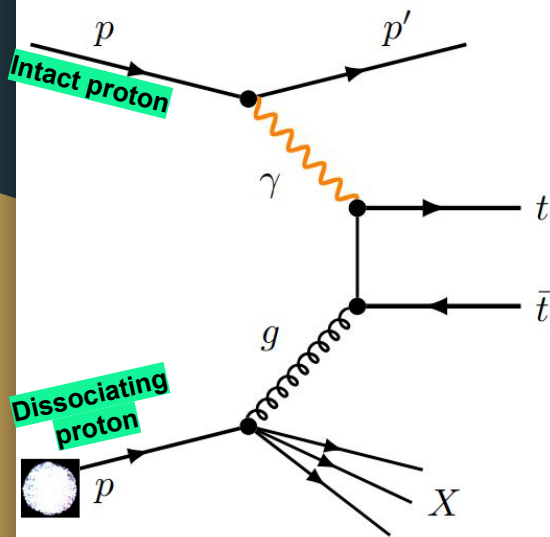
- Ordinary central collisions



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

Proton PDFs

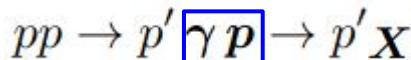
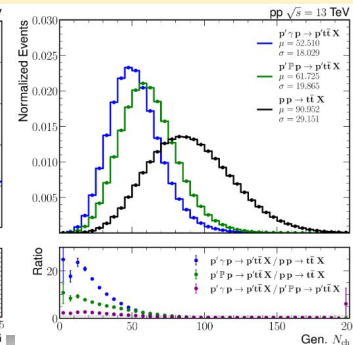
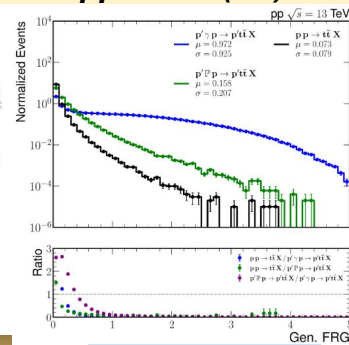
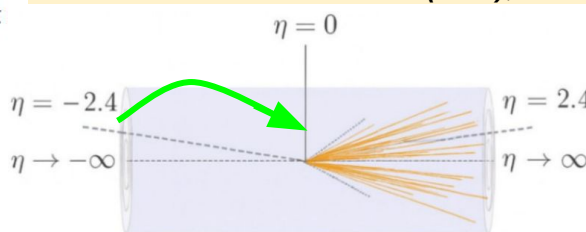
- Equivalent photon approximation (EPA) and UPC's



$$\sigma = \sum_j \int d\omega dx_2 \boxed{\left. \frac{dN}{d\omega} \right|_{p_1}} f_{j/p}(x_2, Q^2) \hat{\sigma}_{\gamma j \rightarrow X}(\omega, x_2, Q^2)$$

Photon flux

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



Rapidity gap
and lower particle production

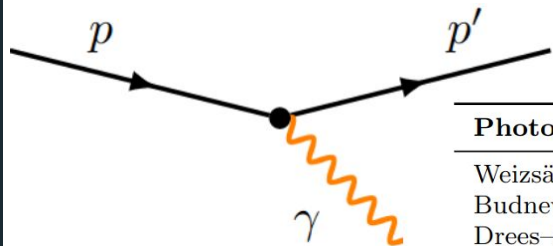
Larger Rapidity gap

Reduced part. multiplicities

Photo-induced processes and non-dissociating hadrons

$$pp \rightarrow p' \boxed{\gamma} p \rightarrow p' X$$

- 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



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

~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

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

W.W. : Point like

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

Budnev: Electromagnetic form factors

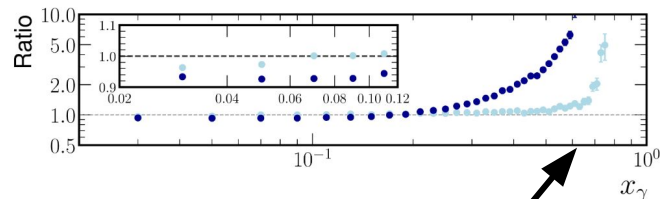
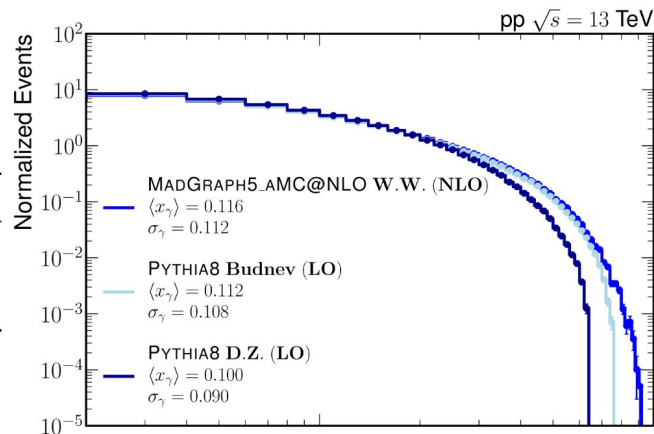
$$f_{\gamma/p}(x) = \frac{\alpha}{2\pi x} [1 + (1-x)^2] \left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3} \right)$$

D. Z. : Dipole form factors

Sampled photons

$$\text{in } x = E_{ph}/E_p$$

energy fraction range

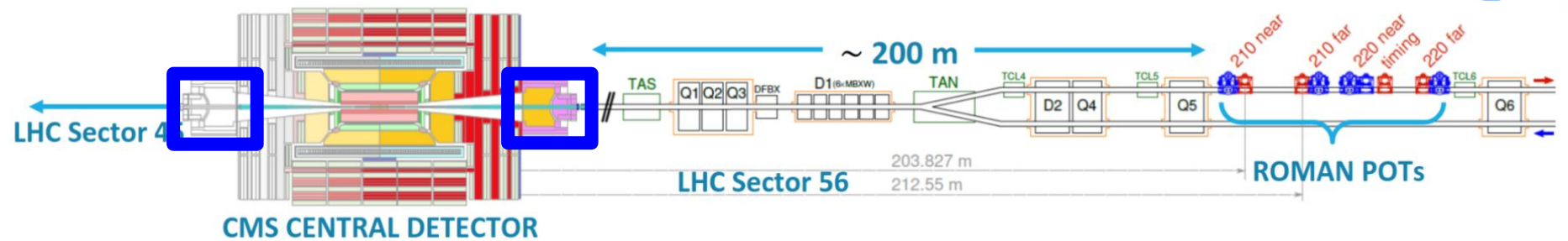
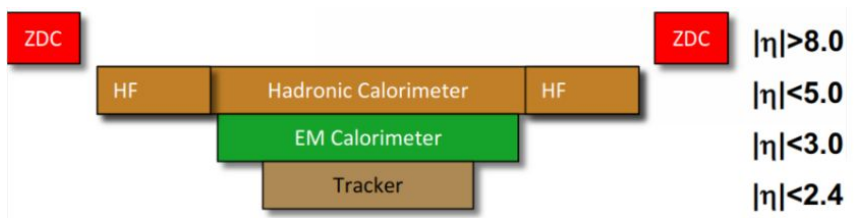
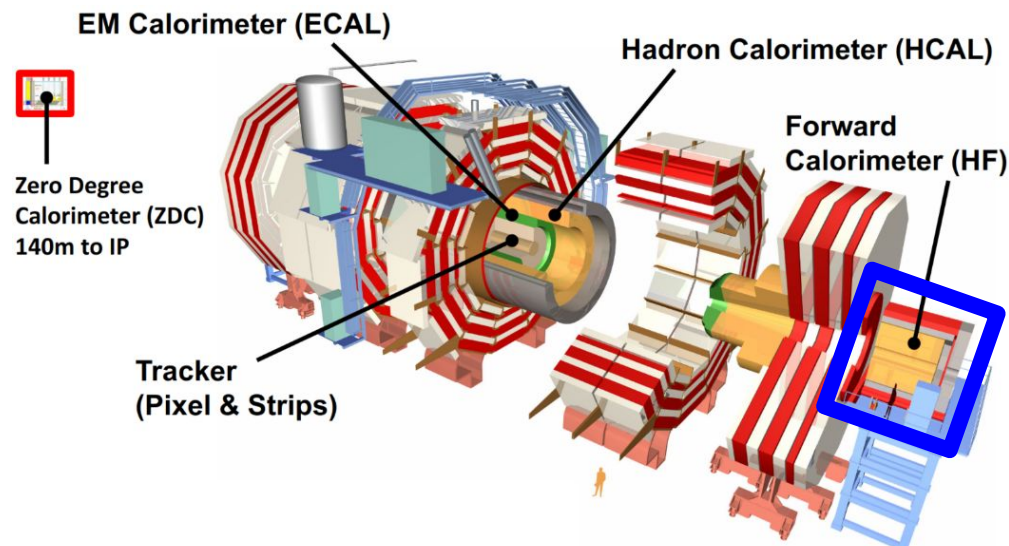


DZ and Budnev suppressing high virtualities and x fractions

Forward detectors

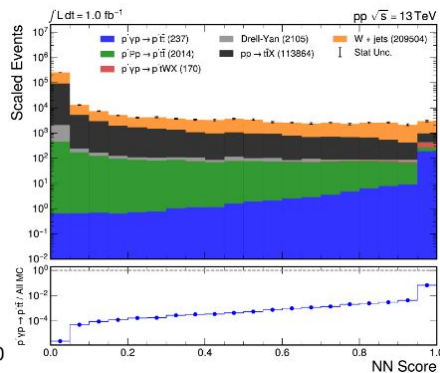
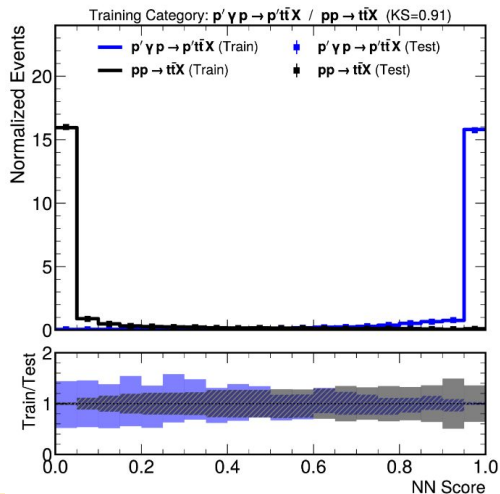
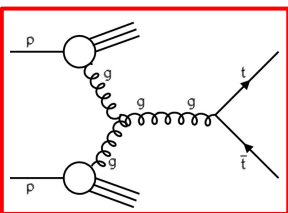
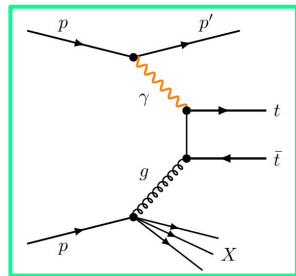
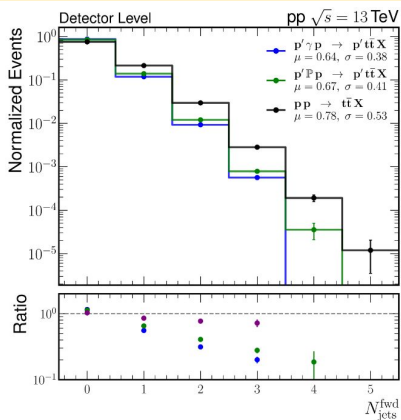
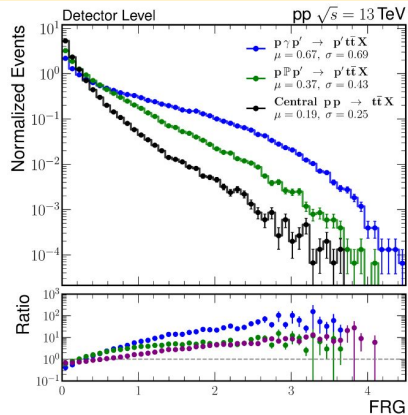
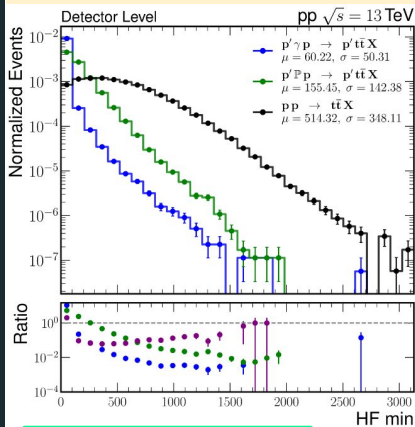
- ▶ Zero Degree (ZDC) and Hadronic Forward (HF) calorimeters for Pb and protons respectively
- ▶ CMS Particle Flow energies to constrain activity as a function of η
- ▶ CT-PPS spectrometer for pp runs

- Analysis can be guided by recorded activity as function of pseudorapidity
- Or it can rely on proton tagging



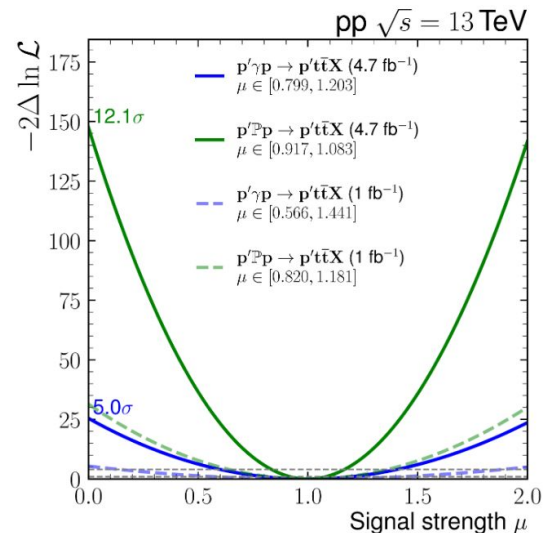
Neural network training for *top-antitop* quarks productions

photoinduced vs central production features



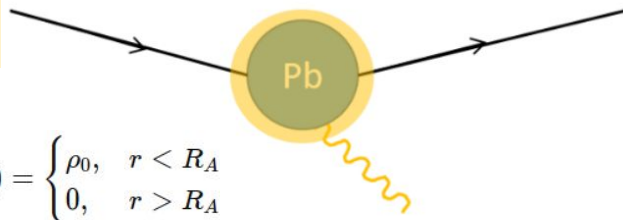
At least 4.7fb^{-1} of low pile up pp data for observation

Alternative scenario for HL-LHC



Current analysis with data using standard pp runs affected by large pileup levels

Nuclear EPA fluxes



- **Hard sphere approximation**

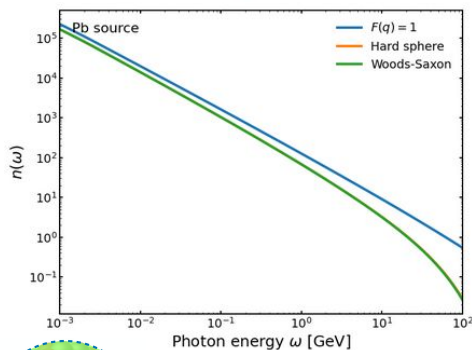
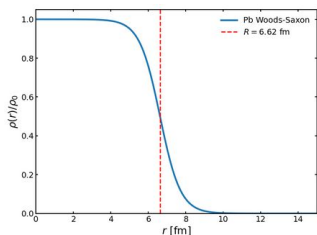
$$\rho(r) = \begin{cases} \rho_0, & r < R_A \\ 0, & r > R_A \end{cases}$$

Uniform charge distribution

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

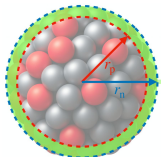
- **Wood-saxon**

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

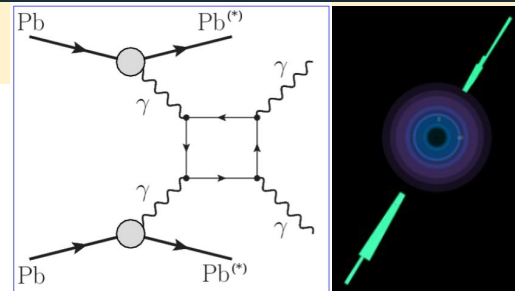
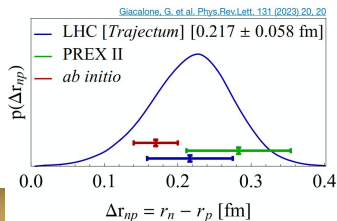


$$F(\mathbf{q}) = \frac{1}{Z_e} \int d^3r \rho(r) e^{i\mathbf{q}\cdot\mathbf{r}}$$

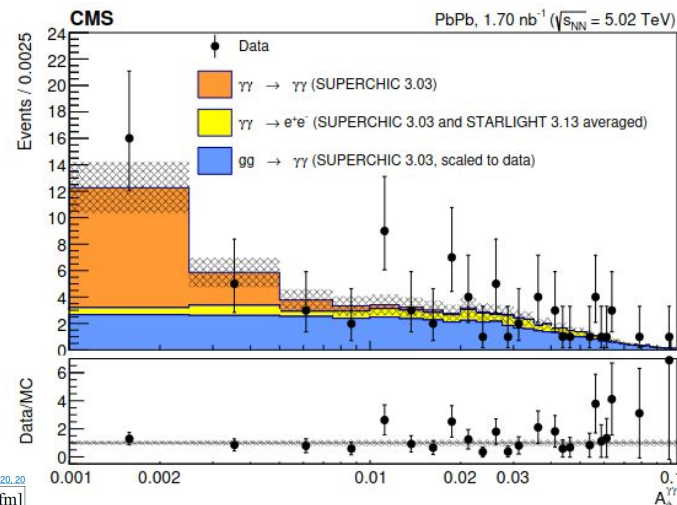
$$N(\omega, b) = \frac{Z^2\alpha}{\pi^2\omega} \left| \int d^2q_{\perp} \frac{\mathbf{q}_{\perp}}{q_{\perp}^2 + \omega^2/\gamma^2} F(q) e^{i\mathbf{q}_{\perp}\cdot\mathbf{b}} \right|^2$$



Proton and neutron independent densities;
neutron skin

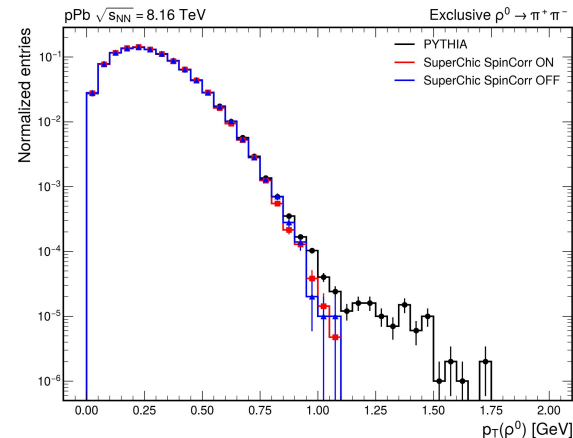
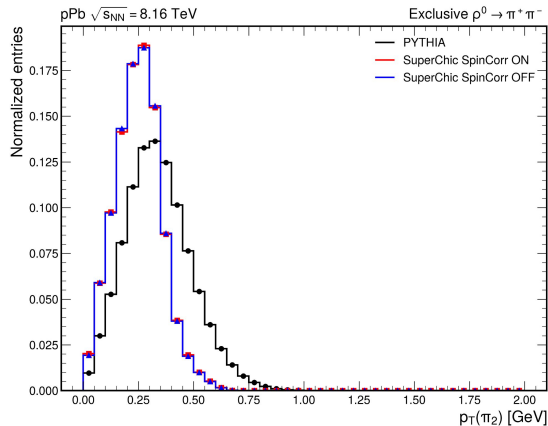
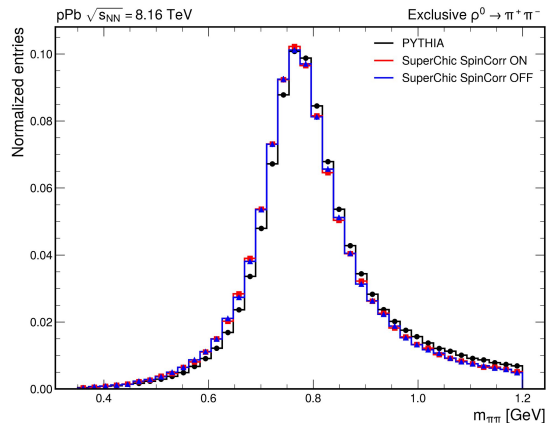


Light-by-light scattering

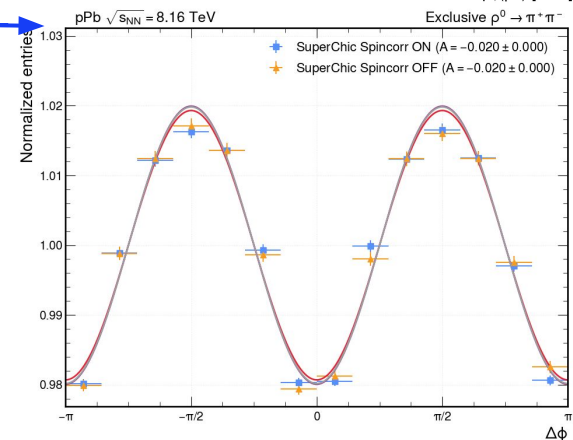
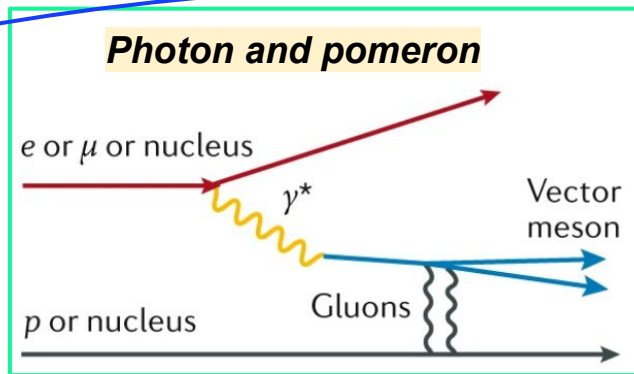
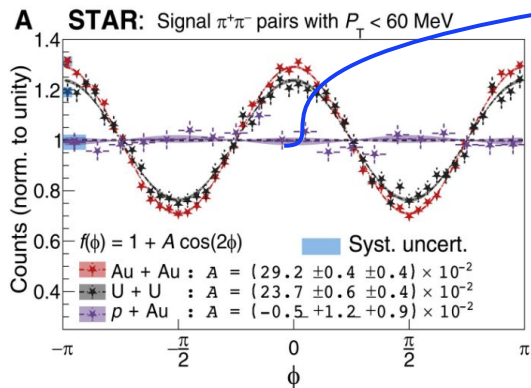


Superchic including wood saxon
and skin treatment

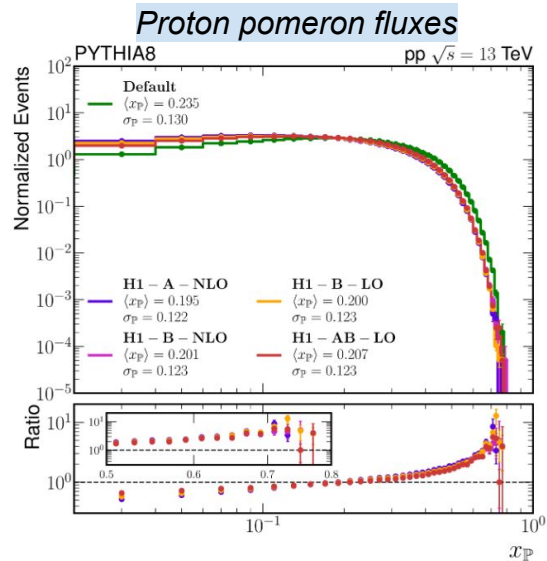
Exclusive vector meson photoproduction within pPb



Modulations and proton probing

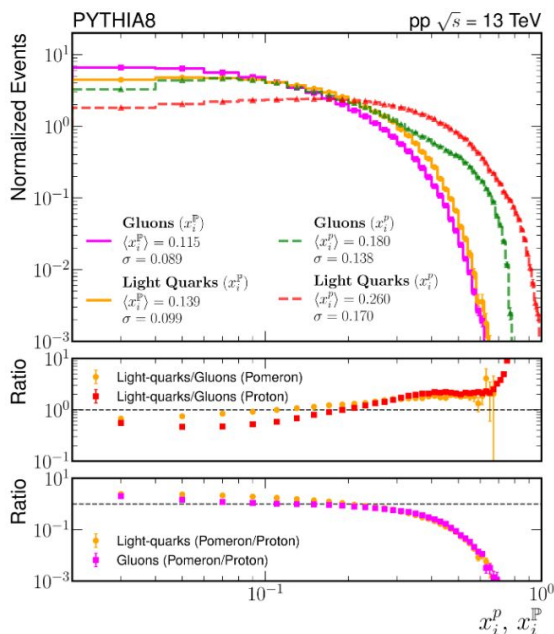


Pomeron neutral fluxes



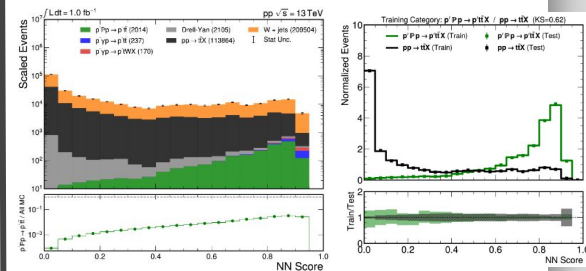
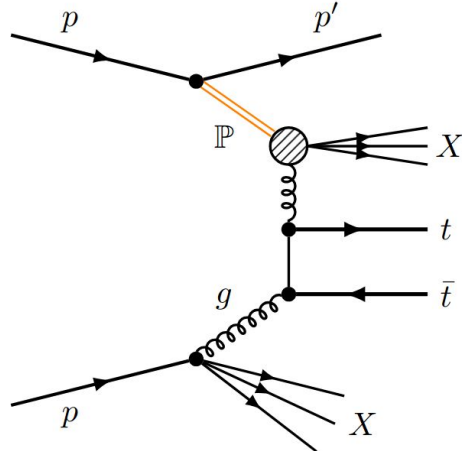
$$\xi \equiv x_{\mathbb{P}} = \frac{E_{\mathbb{P}}}{E_{\text{beam}}}$$

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

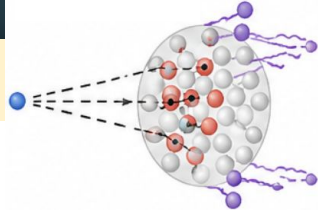


Data Driven Fit	Pomeron Flux	Pomeron Set
Default	1	6
H1-A-NLO	6	3
H1-B-NLO	7	6
H1-B-LO	7	4
H1-AB-LO	8	6

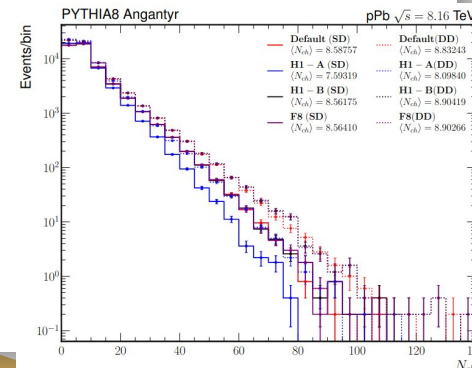
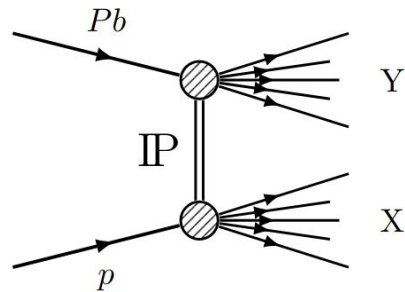
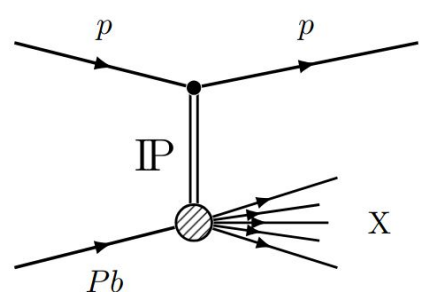
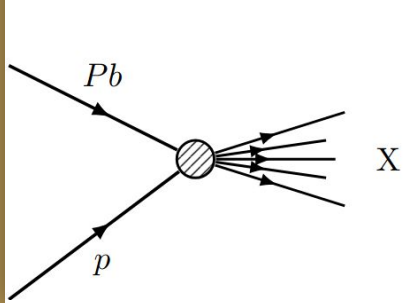
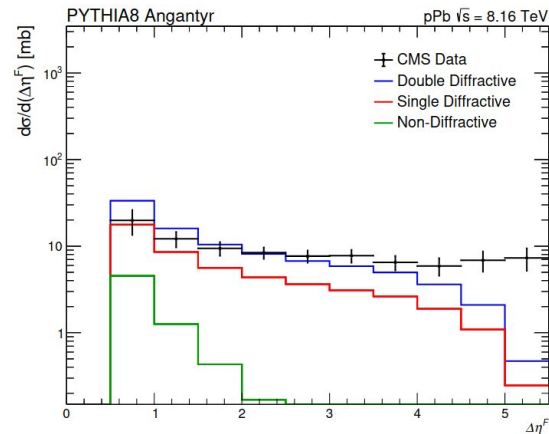
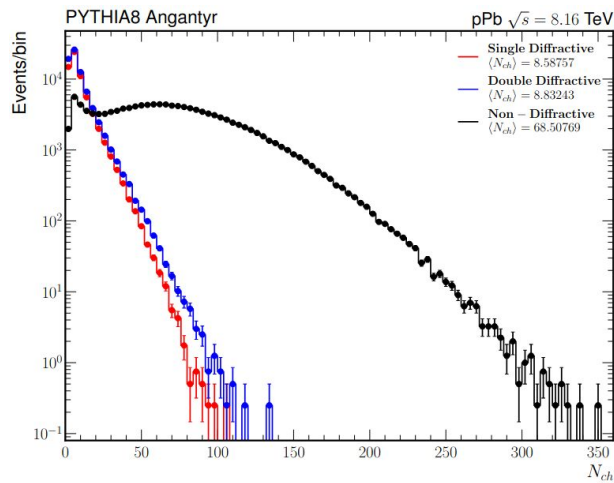
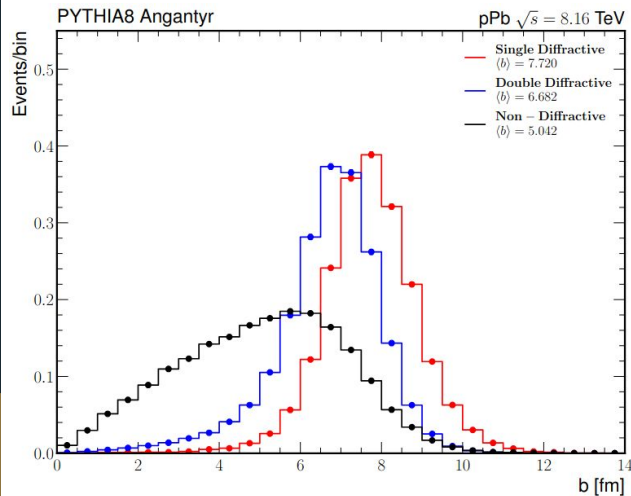
Pomeron treatment as hadron with own PDF



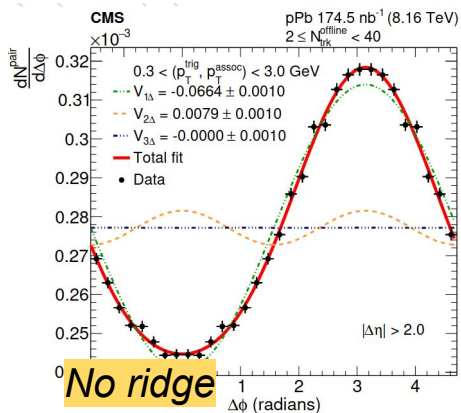
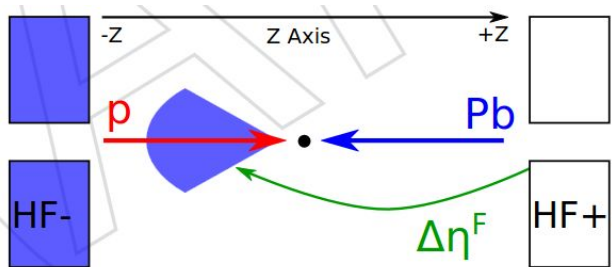
Pomeron-Nucleus interaction and Angantyr model



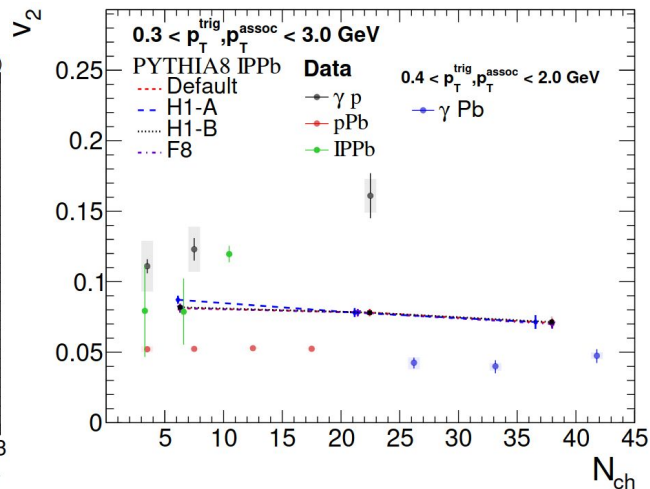
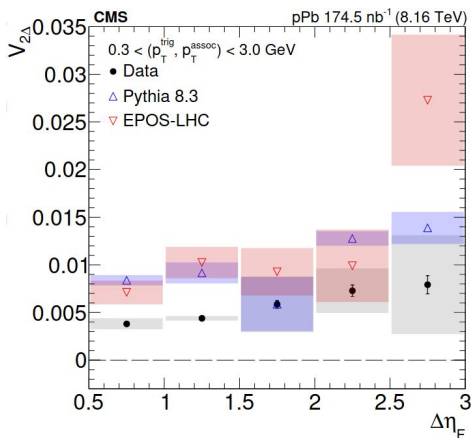
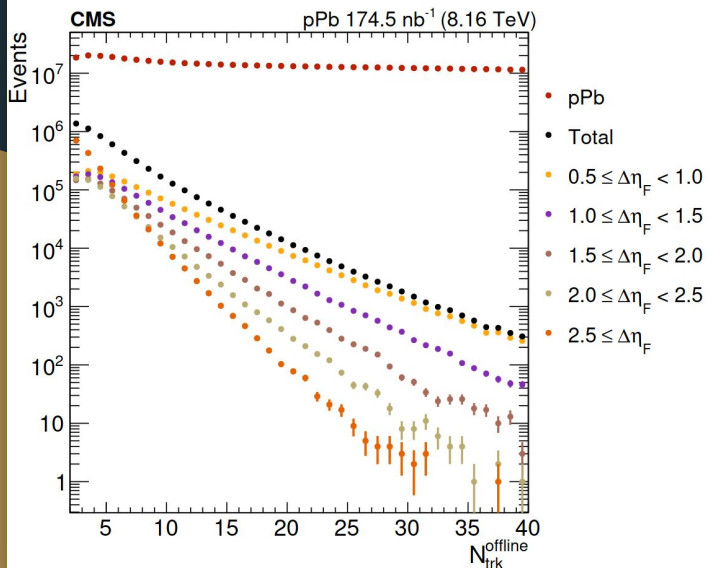
- **LHCP slides** $\mathbb{P} + \text{Pb} \rightarrow X$. within pPb collisions



Large rapidity gap pA interactions

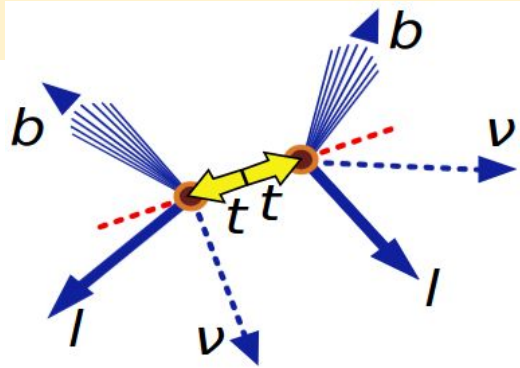


- Smaller v_2 flow anisotropy than gamma-p but larger than pPb
- POM-Pb data consistent with PYTHIA model with need to investigate higher N_{trk}

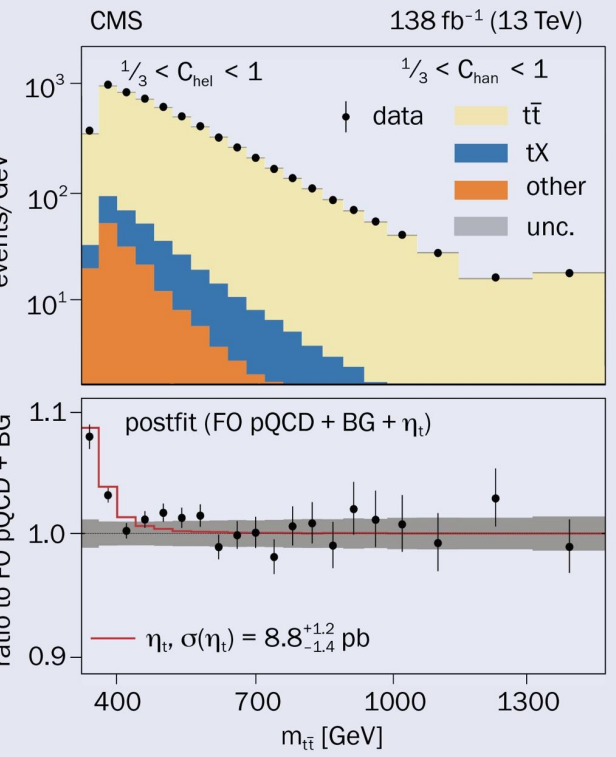


Observation of a pseudoscalar excess at the top quark pair production threshold

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



CMS-TOP-24-007

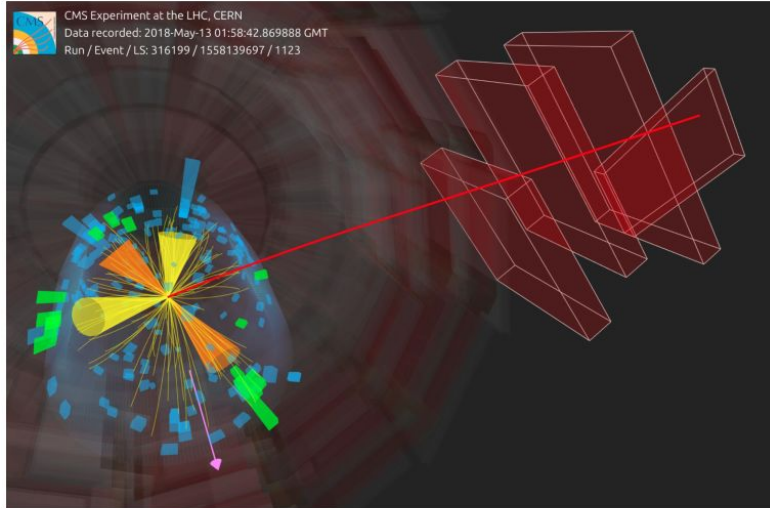
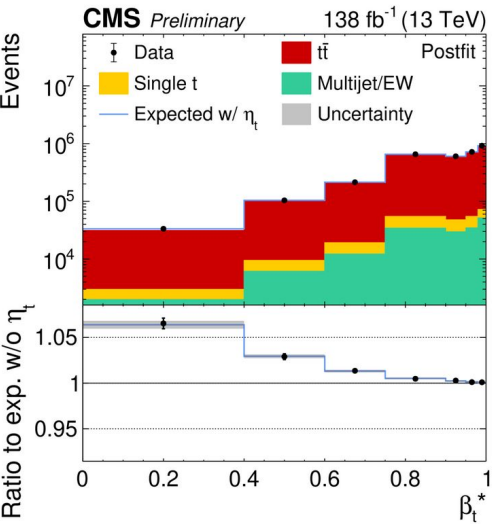
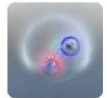


CMS-TOP-25-002

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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.

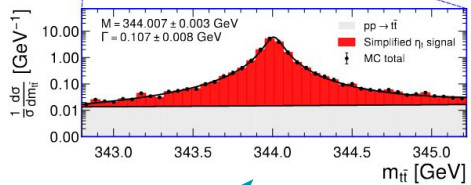
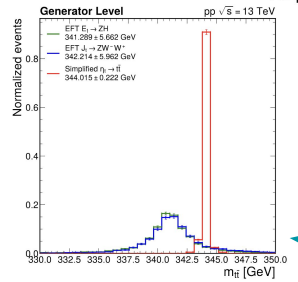
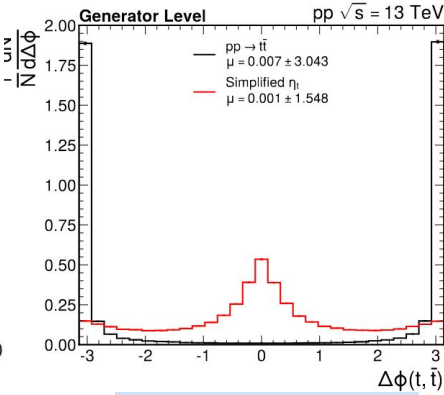
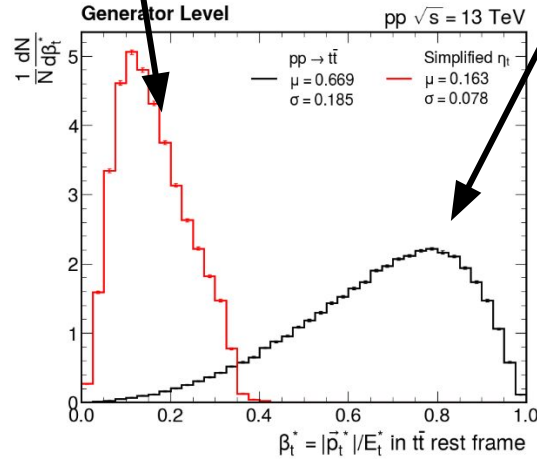
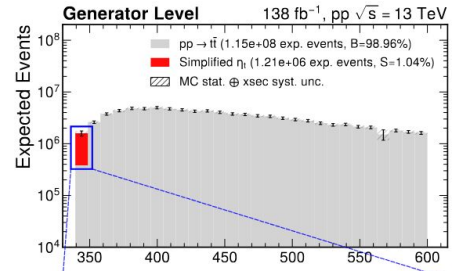
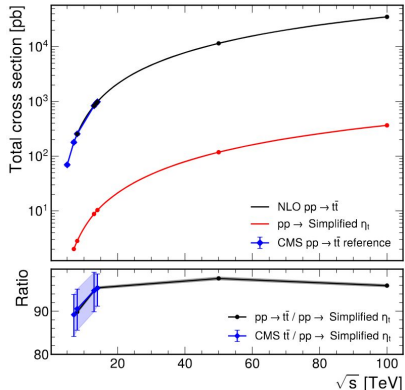
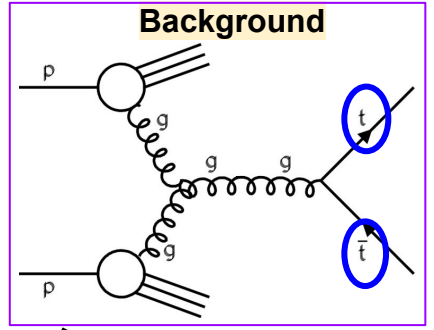
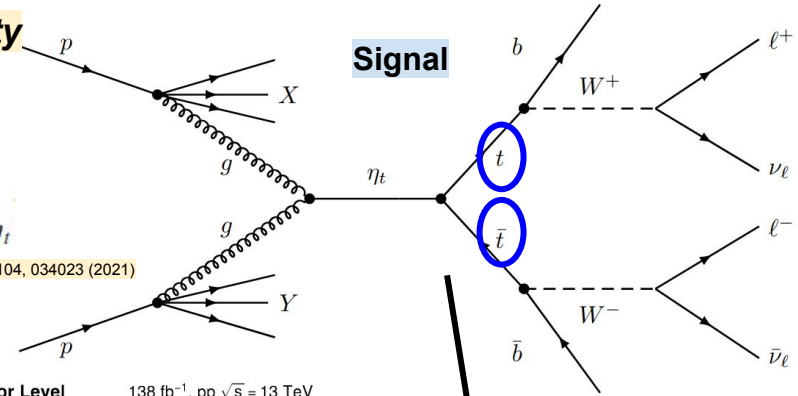
Observation of a pseudoscalar excess at the top quark pair production threshold

A simplified EFT toponium model: $\eta_t \rightarrow t\bar{t}$ decays

Effective lagrangian density

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

PHYSICAL REVIEW D 104, 034023 (2021)



With and without $2m_t$ threshold restriction

Cota Rodriguez, A., V. Corral, A. Paredes, J.A. & Murillo Quijada, J.A. Toponium decays spin correlations and deep learning performance for background rejection, in submission to JHEP

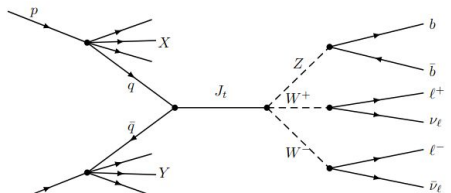
Toponium top pair decays closer azimuthally

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

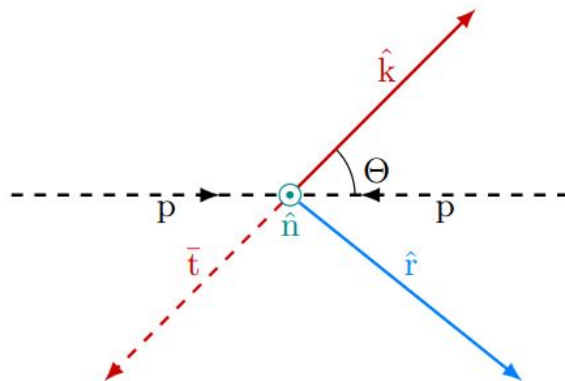
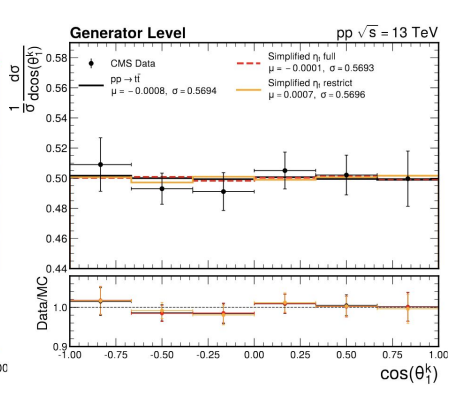
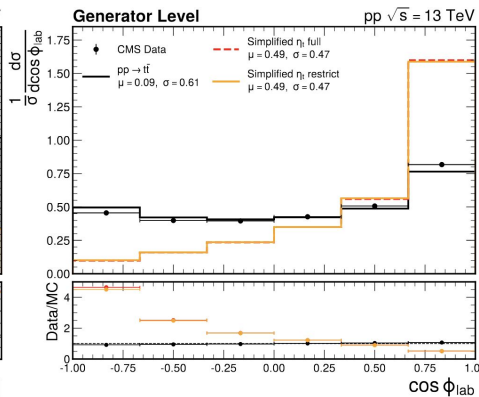
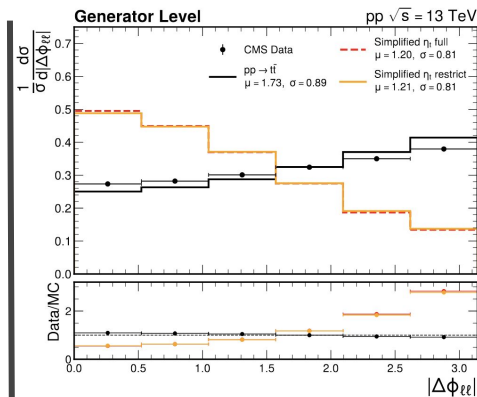
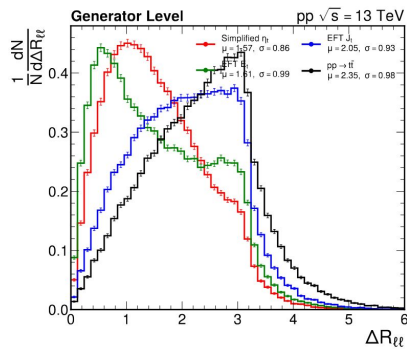
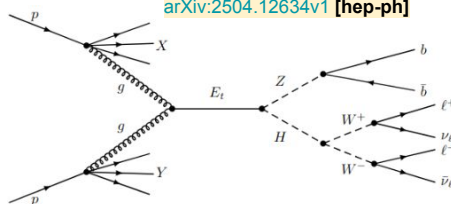
NRQCD toponium model:

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

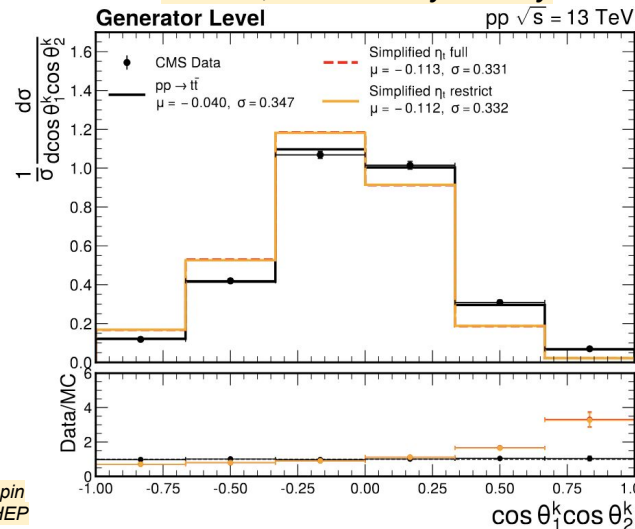
- Scalar and vector mesons
- No $t\bar{t}$ in final state
- same $bl^+\nu_l l^- \bar{\nu}_l \bar{b}$ topology



arXiv:2504.12634v1 [hep-ph]

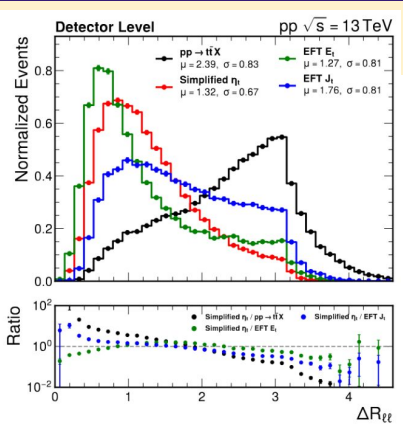
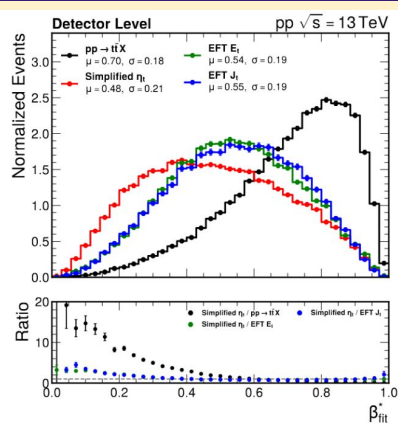
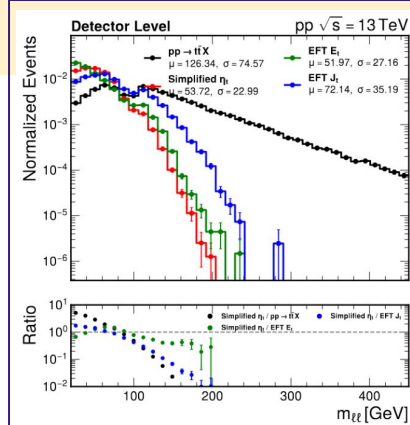
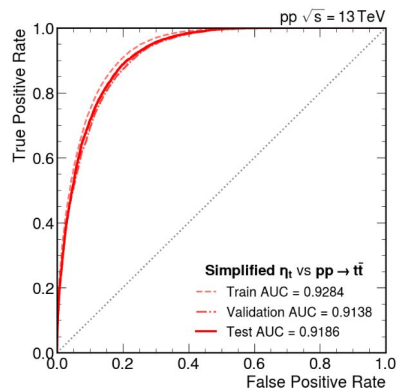
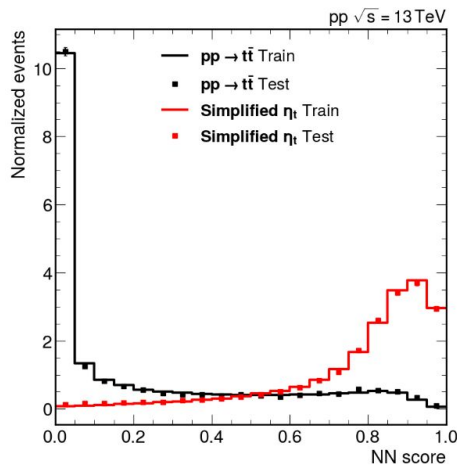


P-even, CP-even symmetry

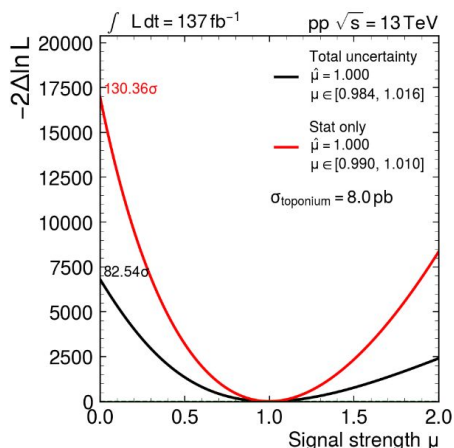


Cota Rodríguez, A., V. Corral, A. Paredes, J.A. & Murillo Quijada, J.A. Toponium decays spin correlations and deep learning performance for background rejection, in submission to JHEP

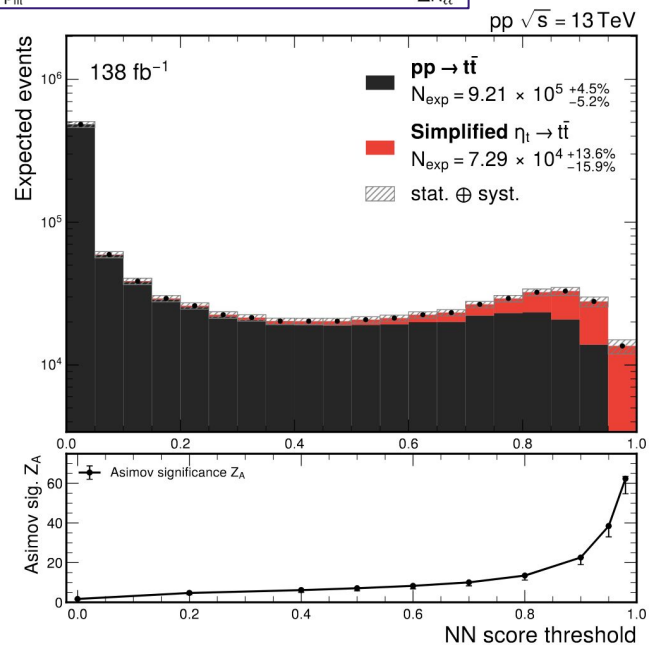
Neural network training



Neural network training identifying most discriminating observables



Improved sensitivity



- **Ongoing efforts to investigate γ / pomeron induced events**

- $\gamma p \rightarrow \text{top} + \text{antitop}$ process with large pile up contribution in standard pp collisions
 - Parallel 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 $t\bar{t}$ 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

LHC

60 collisions / 25ns
or 2.4 billion collisions / second

HL-LHC

200 collisions / 25ns
or 8 billion collisions / second