THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

GAME group seminary

"Czwartki dla Młodych w IFJ PAN"

Unveiling the Invisible: Discover the Tiny Particles That Shape Our Universe

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Analysis background

- **Working with different MC generators for p-p, Pb-p and PbPb beams;**
- **Mostly SM prediction and BSM Lagrangians;**
- **Multi-purpose generic detectors;**

Diffractive contribution

- Exclusive and diffractive $\gamma\gamma$ production in PbPb collisions at the LHC, HE-LHC and FCC;
- Exclusive and diffractive $\mu^+\mu^-$ production at LHC;
- Top quark pair production in the exclusive processes at LHC at low and high luminosity(pu=50,200);

Standard Model/Beyond

- Higgs boson production in photon-photon interactions with proton, light-ion, and heavy-ion beams at current and future colliders;
- Production of axionlike particles in PbPb collisions at the LHC, HE-LHC and FCC;

Vector Meson production

- Exclusive vector meson production in electron-ion collisions at the EIC, LHeC and FCC-eh;
- Coherent and incoherent J/Ψ photoproduction in PbPb collisions -LHC, HE-LHC and FCC;
- DVCS at LHC and FCC;

Past / Present / Future

Recent Past

Top quark pair production in the exclusive processes at the LHC
Victor P. Gonçalves, Daniel E. Martins, Murilo S. Rangel, and Marek Tasevsky
Phys. Rev. D **102**, 074014 – Published 21 October 2020

Challenging exclusive top quark pair production at low and high luminosity LHC
Daniel E. Martins, Marek Tasevsky, and Victor P. Gonçalves
Phys. Rev. D **105**, 114002 – Published 2 June 2022

Investigating the exclusive toponium production at the LHC and FCC
Reinaldo Francener (Campinas State U.), Victor P. Goncalves, Daniel E. Martins (Cracow, INP)
e-Print: 2502.03295 [hep-ph]

Collaboration with AFP group
Qualification task: Efficiency of Time of Flight detector(ToF) at run III and vertex matching module (AFP, ATLAS Inner detector)

Present

ATLAS collaboration

Diffractive top production analysis with ATLAS Forward Proton detector - Purely leptonic channel

Future

Diffractive top production analysis with ATLAS Forward Proton detector - Semileptonic (lepton + jets) channel

(EoI)-Diffractive bbbar production analysis with ATLAS Forward Proton detector

A Lagrangian to rule them all...

The Standard Model of particle physics

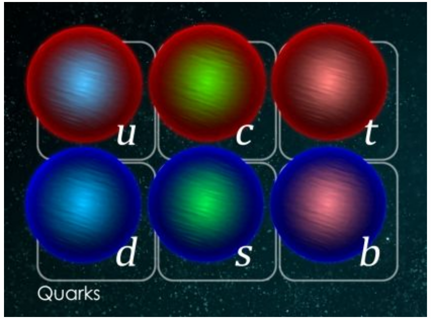
Habakkuk 2:2
The Lord answered me, "Write the vision, and make it plain on tablets, that he who runs may read it"

- The heart of the Standard Model lies the principle of **local gauge invariance**, i.e, the Lagrangian of the theory **remain invariant** under local (space-time dependent) transformations of **internal symmetries**.

- **Mam. Noether's theorem**: each continuous symmetry of the action corresponds to a conserved quantity.

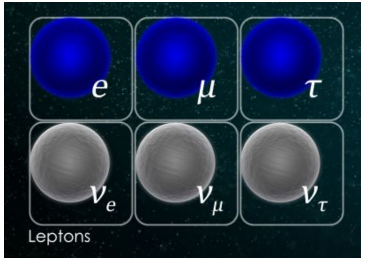
- **Local gauge invariance** enforces the existence **of interaction fields (gauge bosons)** associated with each symmetry generator.

Standard Model - Remarks



Quantum Chromodynamics
Interactions between quarks and gluons.
Color charge: **Red**, **Green**, **Blue.**
Mediated by 8 gluons
Confinement & asymptotic freedom.

Weak Interaction
Responsible for **beta decay**, neutrino interactions
Gauge bosons: **W^+, W^-, Z^0**
Part of the **Electroweak theory**



$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

At higher energies
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

- $SU(3)_C$: color charge → gluons (strong force). The strong interaction confines quarks in hadrons, requiring a non-Abelian gauge group with self-interacting bosons — this is well-modeled by $SU(3)_C$.
- $SU(2)_L$: weak isospin → W^+, W^-, Z^0 bosons. The weak interaction is chiral (it acts only on left-handed fermions), motivating a non-Abelian group like $SU(2)_L$.
- $U(1)_Y$: weak hypercharge → photon after symmetry breaking. Electromagnetism is a long-range Abelian interaction, suitably described by $U(1)$.

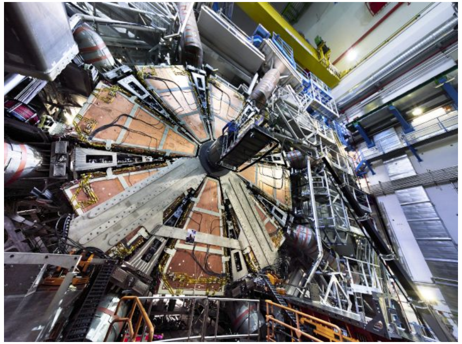
Hypercharge
Governs the **electromagnetic interaction** (after symmetry breaking).

Experimental apparatus

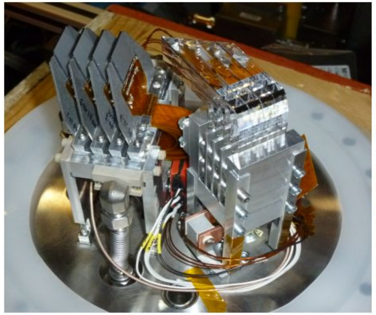
The LHC (2000s-present)

- **The Large Hadron Collider (LHC)**: Began operations in 2008, the LHC is the world's most powerful particle accelerator, enabling experiments with record-breaking energy levels.
- **The Higgs Boson Discovery**: In 2012, ATLAS and CMS experiments confirmed the existence of the Higgs boson, key to explaining particle mass, earning a Nobel Prize.
- **Ongoing Research**: CERN continues to explore new physics, from **dark matter to extra dimensions**, and is enhancing the LHC for even higher energy collisions. The **Future Circular Collider** (FCC) is the best candidate to follow its legacy.

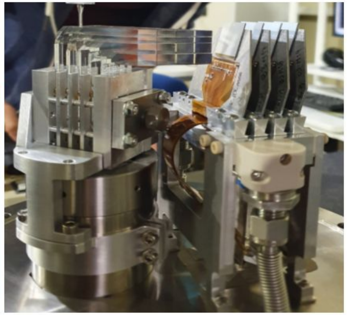
ATLAS



AFP-ATLAS



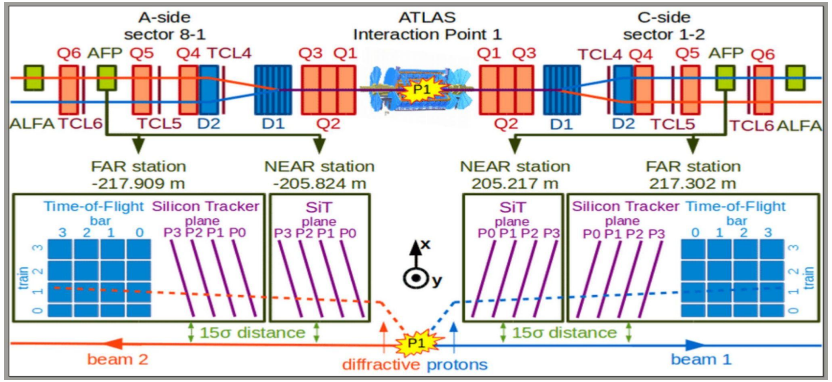
Run II



Run III

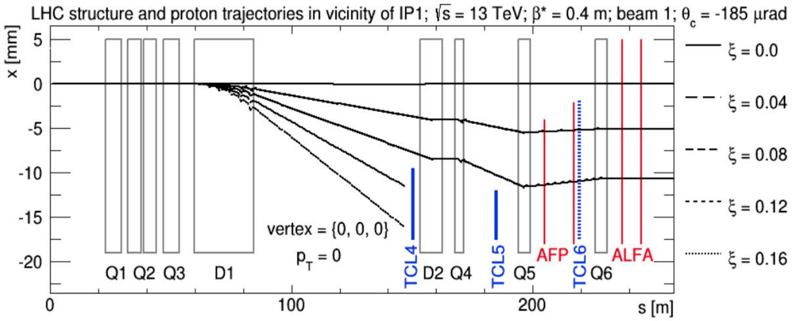
Atlas Forward Detector (AFP)

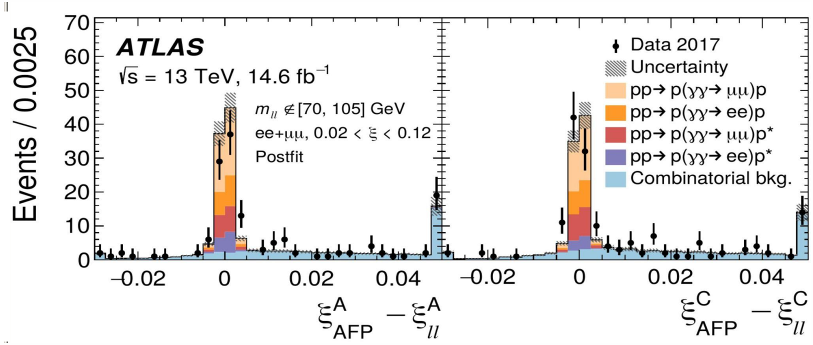
- Two Roman pot vacuum-sealed stations on either side of the interaction point;
- Far stations additionally house ToF detectors: **pile-up suppression via the vertex location from relative timing of protons on A- and C-sides**;



$$\xi = 1 - \frac{E_{proton}}{E_{beam}}$$

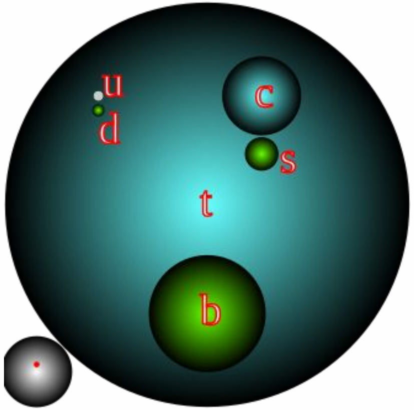
- **High energy loss → Filtered by collimators**;
- **Small energy loss → Close to the beam;**





Why top quarks?

- Its mass close to the electroweak symmetry-breaking scale.



- Its large mass implies it couples strongly to the Higgs boson.
- Sensitive probe of the mechanism behind mass generation.

Top compositeness

Anomalous couplings

Top partners in composite Higgs or Little Higgs models

Heavy-ion PbPb (pPb) measurement

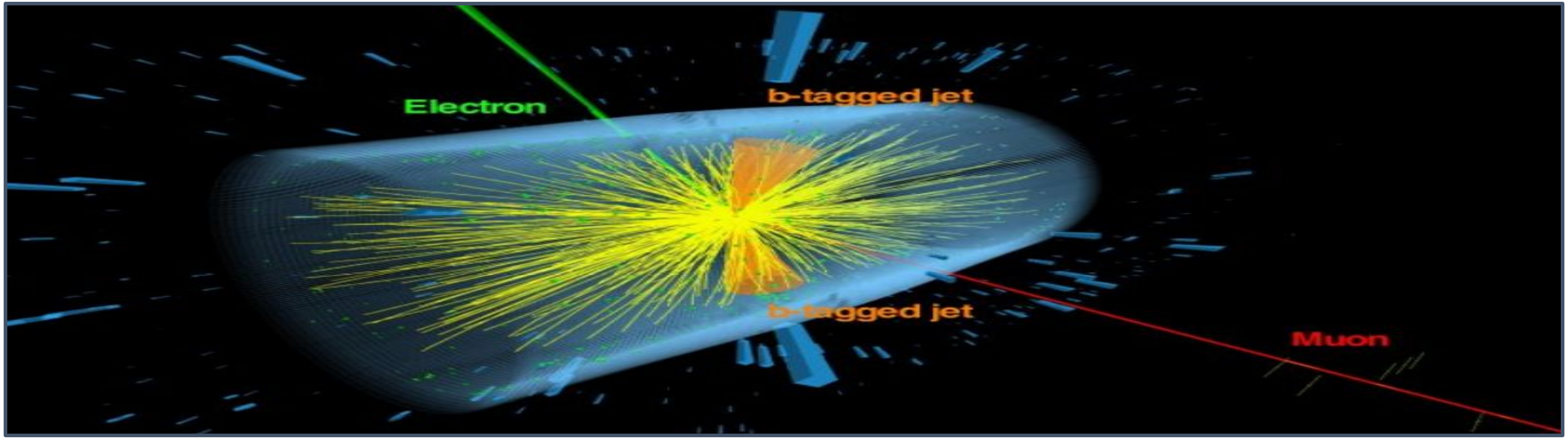
Extra dimensions

Diffractive top quark production at the LHC (e.g., via photon-pomeron or pomeron-pomeron fusion) - novel way to test color-singlet exchange mechanisms

- Precision measurements of top quark properties (e.g., mass, Yukawa coupling) - essential to understanding the **vacuum stability** of our universe.
- Top–antitop spin correlations in production and decay can be used to test **quantum entanglement** at high energies.

Top quark physics: properties

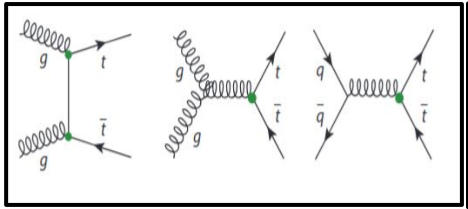
- Top quarks has a mass of approximately **173 GeV/c^2** and carries an electric charge of **+⅔e**.
- Its **discovery in 1995** by the **CDF** and **DØ** collaborations at Fermilab completed the quark sector of the SM.
- <u>**Decay characteristics:**</u>
  Predominantly into a W boson and a bottom quark (b), with a mean lifetime of about **5×10^{-25} seconds**, decaying **before** it can hadronise.



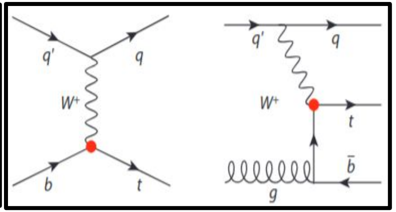
Top Physics: Decay channels

- Top decays through the **electroweak interaction into a W boson and (usually) a bottom quark**.

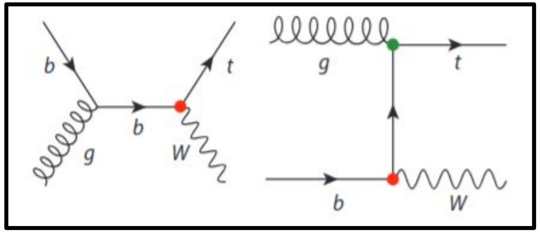
tt production



t-channel



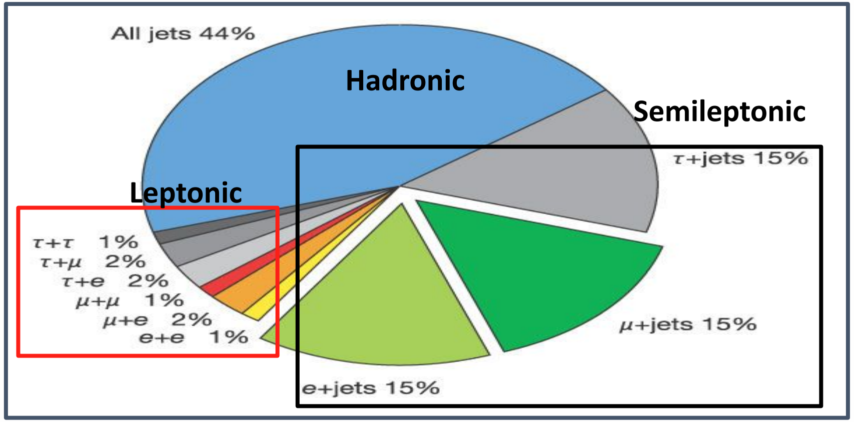
W-associated production



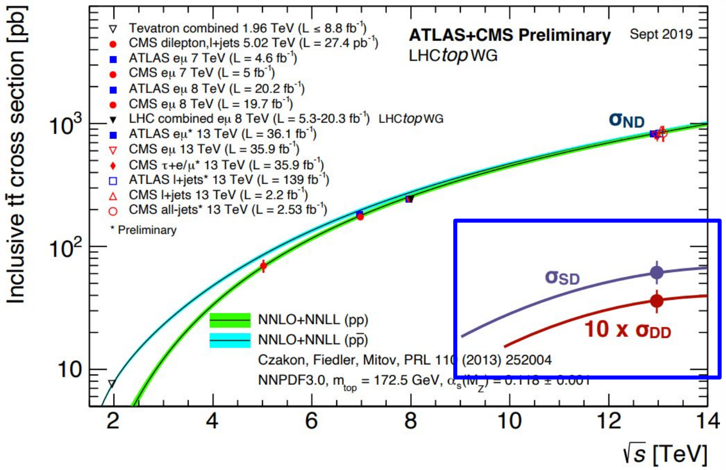
- $t\bar{t}$ production is the **dominant** top quark production and allows to test QCD predictions and constraining parameters;

- The final state topology is given in term of W-boson decay mode;

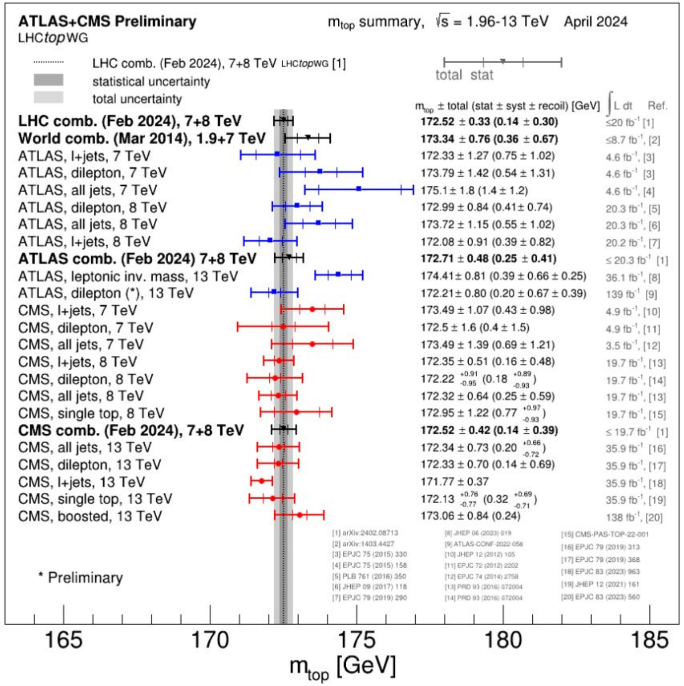
$$W \rightarrow l\nu\ (\sim 30\%)\ /\ qq'\ (\sim 70\%)$$



Top Physics: From Tevatron to LHC



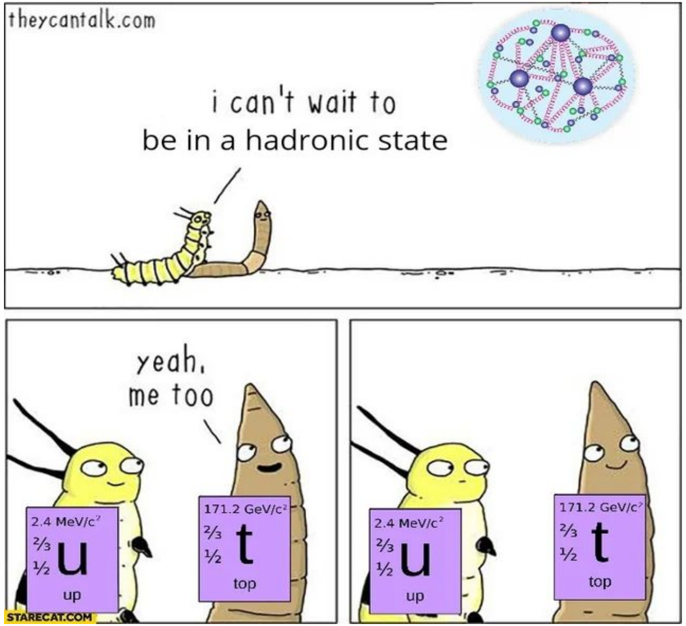
- Top quark properties have already been performed from Tevatron to LHC: **kinematical properties, reconstruction, production cross section.**



- At the Tevatron top quark pairs are mainly produced in **quark-antiquark** annihilation. At the LHC, **this mechanism dominated by gluon fusion process at** $\sqrt{s}$ **= 13 TeV**.

- More data to be (being) collected at $\sqrt{s}$ **= 13-13.6 TeV - run III** and beyond;

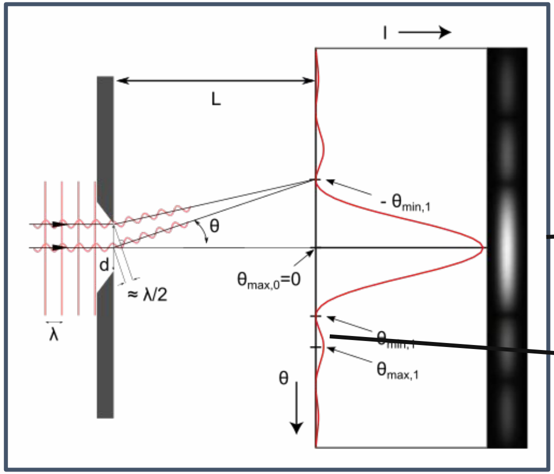
Diffractive Physics and top quark production



Diffractive Physics

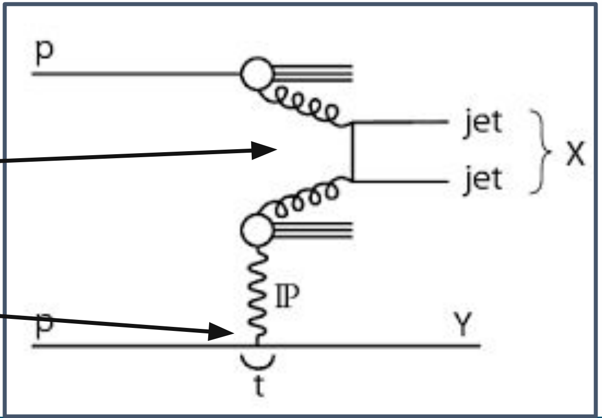
What is Diffraction in Optics?

- Diffraction occurs when waves encounter obstacles or slits.
- Creates interference patterns (e.g., light through a narrow slit).
- Wave nature of light becomes evident.



What is Diffraction in High-Energy Physics?

- Diffraction refers to interactions where one or both protons remain intact or dissociate slightly.
- Characterized by large rapidity gaps (regions without particles).
- Mediated by the exchange of a colorless object, such as the Pomeron.

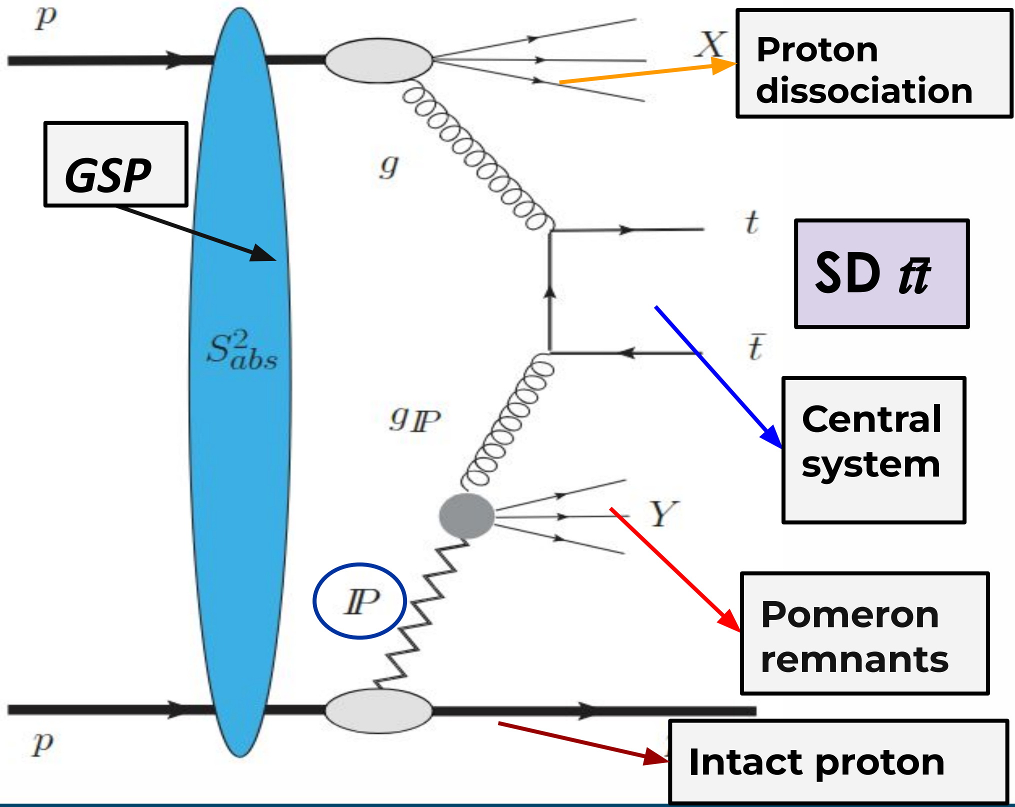


Summarizing…

Optics	High-Energy Physics
Light waves	Partonic (quark/gluon) waves
Slit/aperture	Colliding protons
Interference pattern	Rapidity gap / intact proton
Wave diffraction	Quantum coherence via Pomeron exchange

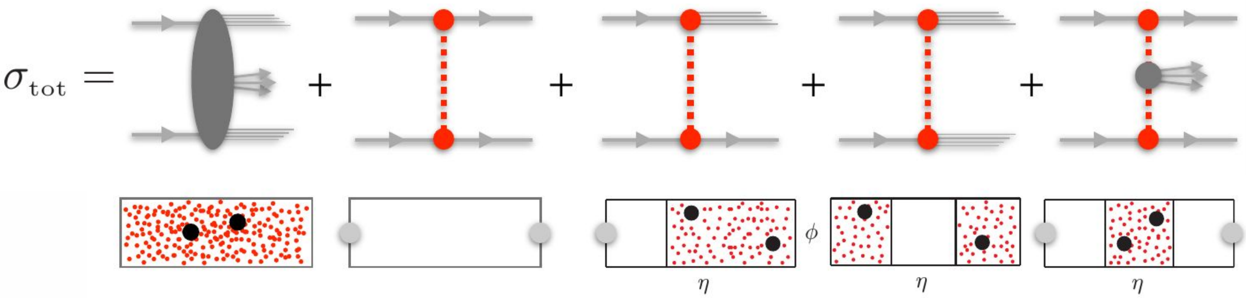
Diffractive Physics

- Involves interactions with **small momentum transfer** and **colorless exchange**(e.g.,**Pomeron**). Characterized by regions with **no particle activity**: **"rapidity gaps"**.
- **Elastic scattering**: protons remain intact.
- **Single diffraction (SD)**: one proton dissociates, the other remains intact.
- **Double diffraction (DD)**: both protons dissociate, gap in the center.
- **Central diffraction (CD/CEP)**: both protons survive, central system is produced via colorless exchange.



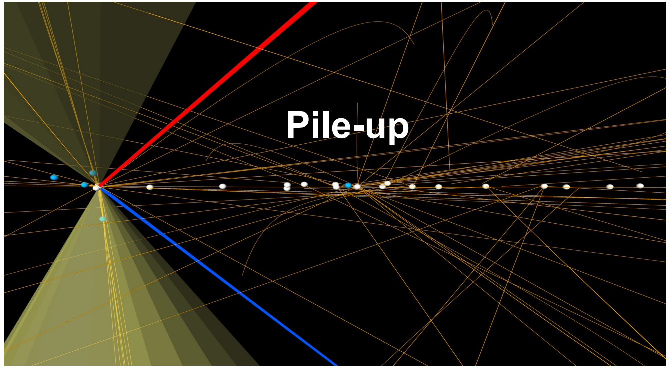
Diffractive physics

$$\sigma_{\text{tot}} = \sigma_{\text{ND}} + \sigma_{\text{elastic}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}}$$



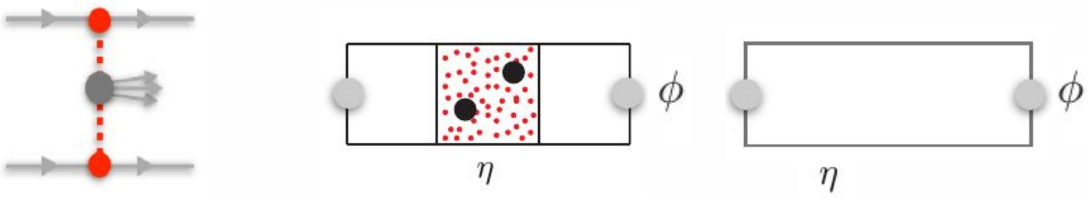
Diffraction:

- Vital aspect of QCD
- Place to look for New Physics;
- Favoured at low pile-up interactions;

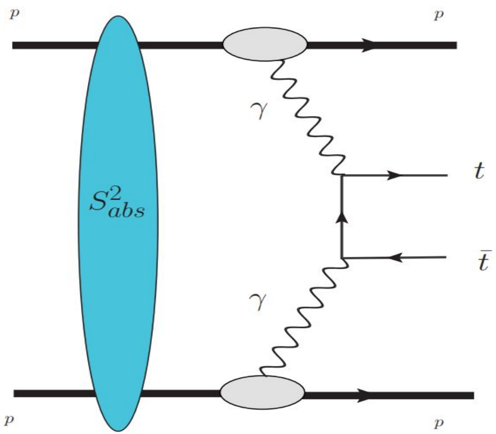


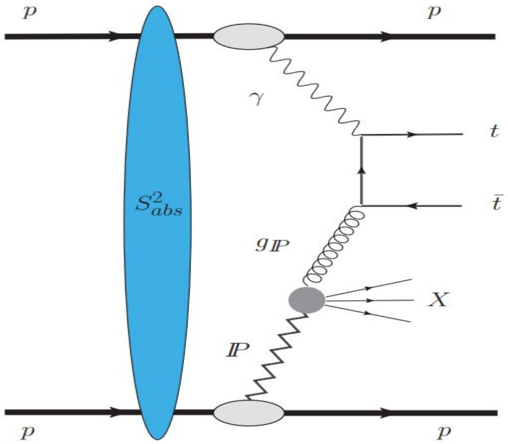
Typical *pp* events: Many tracks + high p_T particles

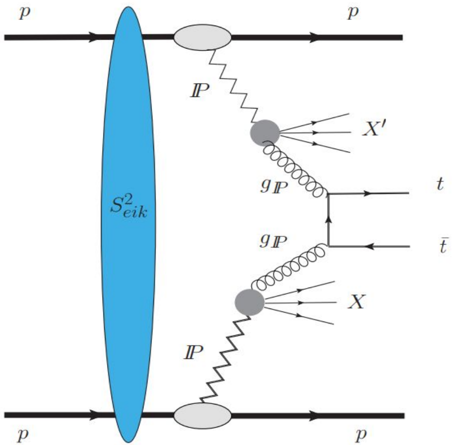
Exclusive events: Few tracks + low p_T particles



Diffractive/exclusive processes







Cross section:

$$\sigma(h_1 h_2 \to h_1 \otimes t\bar{t} \otimes h_2) = \int dx_1 \int dx_2 \gamma_1(x_1) \cdot \gamma_2(x_2) \cdot \hat{\sigma}(\gamma\gamma \to t\bar{t})$$

$$S^2_{abs} = 100\%$$

Photon flux:

$$\gamma(x) = -\frac{\alpha}{2\pi} \int_{-\infty}^{-\frac{m^2 x^2}{1-x}} \frac{dt}{t} \left\{ \left[2\left(\frac{1}{x} - 1\right) + \frac{2m^2 x}{t} \right] H_1(t) + x G_M^2(t) \right\},$$

Cross section:

$$\sigma(h_1 h_2 \to h_1 \otimes t\bar{t}X \otimes h_2) = \int dx_1 \int dx_2 [g_1^D(x_1, \mu^2) \cdot \gamma_2(x_2) + \gamma_1(x_1) \cdot g_2^D(x_2, \mu^2)] \cdot \hat{\sigma}(\gamma g \to t\bar{t})$$

Diffractive PDF:

$$g^D(x, \mu^2) = \int_x^1 \frac{dx_{\mathbb{P}}}{x_{\mathbb{P}}} f_{\mathbb{P}}(x_{\mathbb{P}}) g_{\mathbb{P}}\left(\frac{x}{x_{\mathbb{P}}}, \mu^2\right).$$

Cross section:

$$\sigma(h_1 h_2 \to h_1 \otimes X t\bar{t} X' \otimes h_2) = \int dx_1 \int dx_2 g_1^D(x_1, \mu^2) \cdot g_2^D(x_2, \mu^2) \cdot \hat{\sigma}(gg \to t\bar{t}).$$

$$S^2_{abs} = 3\%$$

Diffractive PDF is constrained by HERA data: H1-FiTA

Object identification

Why Leptons?

- Do not participate in strong interactions, i.e., **less background** from QCD.
- Leptons leave well-identified tracks and energy deposits:

+ **Electrons** → **energy clusters in the electromagnetic calorimeter** matched to **tracks** in the inner detector.
+ **Muons** → Reconstructed using tracks in the **muon spectrometer** matched to the **inner detector.**

- Useful for triggering and identifying **electroweak processes**: **W/Z bosons**, **top quark decays**, **Higgs**.

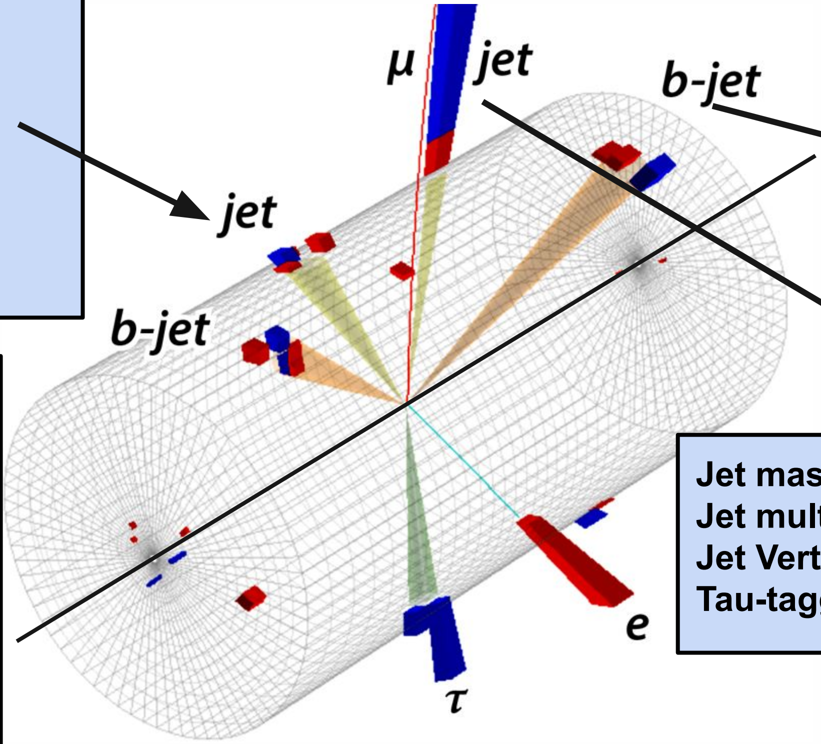
Why Jets?

Jets are traces of quarks and gluons

- **Collimated sprays of hadrons** resulting from quark or gluon fragmentation (hadronization);
- Provide access to **QCD dynamics** and hadronic decays: **Top quark hadronic decay**, **H → $b\bar{b}$**, **QCD backgrounds**.
- Allow for **full event reconstruction** and balance of momenta.
- **Challenges: Large uncertainties. Model dependent**;

Kinematic variables and attributes

jets: **hadronic calorimeter** and **tracking system**;
jets: **anti-kT** (dR = 0.4 or 0.6)
pT (transverse momentum): related to the initiating parton.
η (pseudorapidity): angular position in the detector.



b-jets: Experimentally categorized with Flavour ID algorithms at LHC framework

- **Leptons:** Clean, low-rate, but high-precision.
- **Key attributes:**
  - pT, η
  - **Isolation**
  - **Charge and flavor.**

Jet mass: for boosted object tagging.
Jet multiplicity;
Jet Vertex Tagger (JVT): veto pile-up jets.
Tau-tagging: ID hadronically decaying taus.

Top pair production: setup

Signal

photon – photon, photon – Pomeron and Pomeron – Pomeron interactions

Final state: $t\bar{t} \rightarrow jjbl\nu_l\bar{b}$ (Semileptonic decays)

Backgrounds

Irreducible: $\gamma\mathbb{P} \rightarrow Wt$ **and** $\gamma\gamma \rightarrow WW$

Reducible: $t\bar{t}$ **+ pileup**

Inclusion of pileup scenarios

$$< \mu >= 5, 10, 50$$

Event generation

Signal: Forward Physics MC (FPMC);

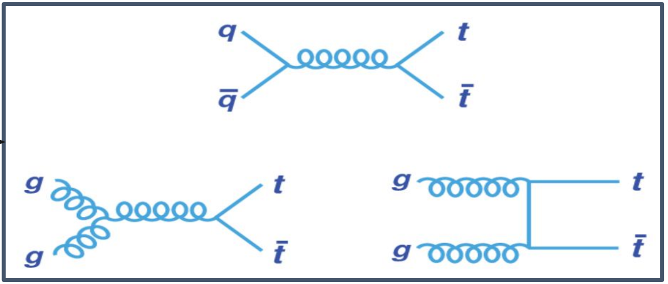
Background: FPMC, Madgraph5, Pythia8

Detector effects and pileup mixing:
DELPHES v3.4, v3.5;

Most dangerous combination
2x soft SD events + hard-scale top-pair event.

Backgrounds

Inclusive tt Background (Non-diffractive)



- **Dominant background**: **high cross section** via **gluon-gluon fusion (gg → tt)**.
- Topologies **identical** to signal in final state (e.g. dilepton + jets).
- **No rapidity gap**, but can mimic diffractive events due to:
  - **Pile-up fluctuations**,
  - **Proton mis-tagging** (e.g., accidental match with a forward proton) - Combinatorial.
  - **Fake gaps** from detector inefficiencies.

Irreducible Background: $\gamma p \to Wt$

- A **photoproduction** process:
  - Proton emits a **quasi-real photon**, which interacts with the other proton.
- Final state with **1 top + 1 W**, leading to **2 leptons + b-jets**, similar to dileptonic $t\bar{t}$.
- **Very similar topology** to SD $t\bar{t}$.
- Proton often remains intact → appears diffractive.

Top pair production: setup

Signal selection and background rejection cuts

Cut and count

Cut
$N_{\text{jet}} \geq 4(E_T > 25 \text{ GeV}, \lvert\eta\rvert < 2.5)$
$N_{e/\mu} \geq 1(E_T > 25 \text{ GeV}, \lvert\eta\rvert < 2.5)$
$\Delta R(\mathrm{e}/\mu, \text{jet}) > 0.2$
$N_{b\text{-jet}} \geq 2$
$0.015 < \xi_{1,2} < 0.15$
$N_{\text{trk}}(p_{\text{T}} > 0.2 \text{ GeV}, \lvert\eta\rvert < 2.5, \lvert\Delta z\rvert < 1 \text{ mm}) \leq X$

Usual **semileptonic cuts** used in inclusive ATLAS & CMS analyses:

- Reasonable S/B
- Reasonable purities
- Reasonable trigger efficiencies
- Remaining backgrounds < 10%

FPD acceptance (assuming 100%)

AFP-ATLAS and CT-PPS

Exclusivity cut:
Number of tracks close to the primary vertex and outside ttbar system must be low (not sufficient to remove the incl.ttbar+PU → use Time-of-Flight (ToF) in FPD)

Top pair production: pu scenario

Fake Double-Tag events in AFP and CT-PPS

Time-of-flight (ToF) detectors are necessary to suppress the PU background.

Time resolution → **10 ps**

$<\mu>$	5	10	50
P_{Fake}	0.0031	0.014	0.246
ToF suppr.	18.3	17.3	10.8

ToF performance studies: arXiv: 2010.00237[hep-ph]

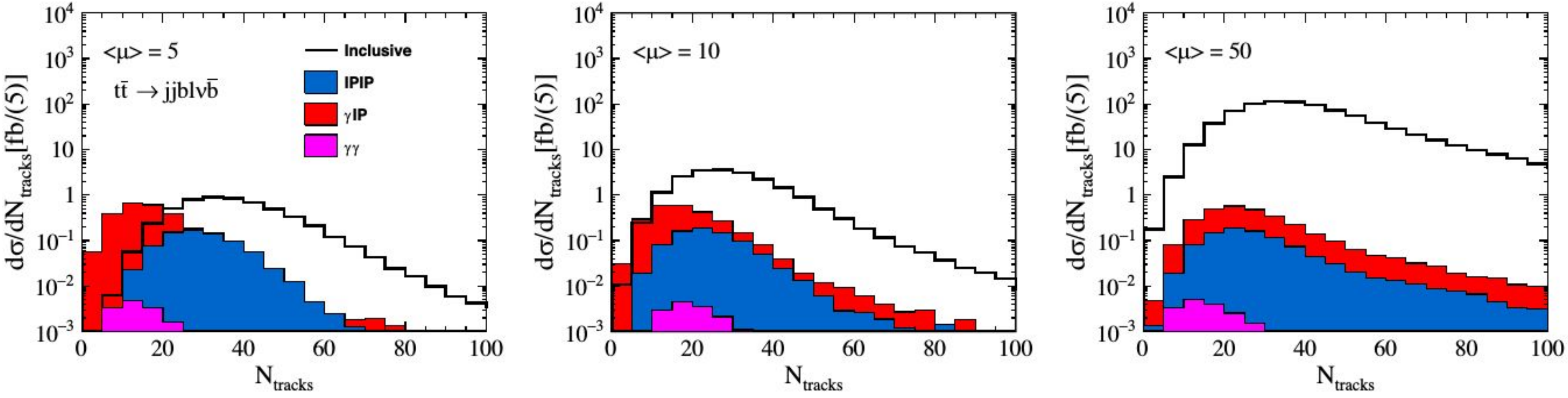
Process	$\gamma\mathbb{P}(\langle\mu\rangle = 5/10/50)$	$\mathbb{PP}(\langle\mu\rangle = 5/10/50)$	Incl. $t\bar{t}$ + PU$(\langle\mu\rangle = 5/10/50)$
Generated cross section (fb)	52.0	28.4	390000
$N_{e/\mu} \geq 1(E_T > 25$ GeV, $\lvert\eta\rvert < 2.5)$	14.1/14.2/13.4	7.4/7.3/6.7	90057/90042/82994
$N_{\text{jet}} \geq 4(E_T > 25$ GeV, $\lvert\eta\rvert < 2.5)$	4.2/4.4/5.4	2.1/2.2/2.6	38157/38928/42821
$\Delta R(e/\mu, \text{jet}) > 0.2$	4.2/4.4/5.4	2.1/2.2/2.6	38157/38928/42821
$N_{b\text{-jet}} \geq 2$	4.2/4.4/5.4	2.1/2.2/2.6	38157/38928/42821
$0.015 < \xi_{1,2} < 0.15$	2.4/2.6/3.2	0.8/0.8/1.0	118.2/423.3/10534
$m_{t\bar{t}} < 1000$ GeV, $m_X > 400$ GeV	2.4/2.6/3.1	0.8/0.8/1.0	97.6/349.6/9107
TOF suppression	2.4/2.6/2.4	0.8/0.8/0.8	5.3/20.2/843.2
$N_{\text{trk}} \leq 10$	0.45/0.44/0.14	0.002/0.02/0.02	0.006/0.35/2.7
$N_{\text{trk}} \leq 15$	1.12/1.12/0.60	0.10/0.10/0.10	0.12/1.39/15.4
$N_{\text{trk}} \leq 20$	1.73/1.76/1.20	0.11/0.26/0.25	0.29/3.94/52.8
$N_{\text{trk}} \leq 25$	2.11/2.16/1.80	0.30/0.45/0.44	0.81/7.49/123.9

P_{Fake}

ToF suppr.

All cuts + ToF suppression

- **Ntracks: number of charged tracks with p_T > 0.2 GeV, |η| < 2.5 and $|z_{trk} - z_{vtx}|$ < 1 mm;**
- **Outside jets: ΔR(trk,jet)>0.4 ; Leptons: ΔR(trk,lepton)>0.2;**
- **For each lumi scenario, cut Ntracks can be tuned to get optimal S/B;**



Distribution of the number of tracks with $p_T > 0.2$ GeV and $|\eta| < 2.5$ outside all four jets and one lepton for three amounts of pileup events per interaction, $\langle \mu \rangle$, of 5, 10, and 50, all at detector level and after applying cuts in Table I, except for the N_{trk} cut. Predictions for three (semi)exclusive signal processes are obtained with FPMC, while the inclusive $t\bar{t}$ background was generated with MadGraph5+PYTHIA8.

Top pair production: pu scenario

- Each lumi scenario prefers different *Ntrk* cut;
- Low values of <μ> seem to be preferred;

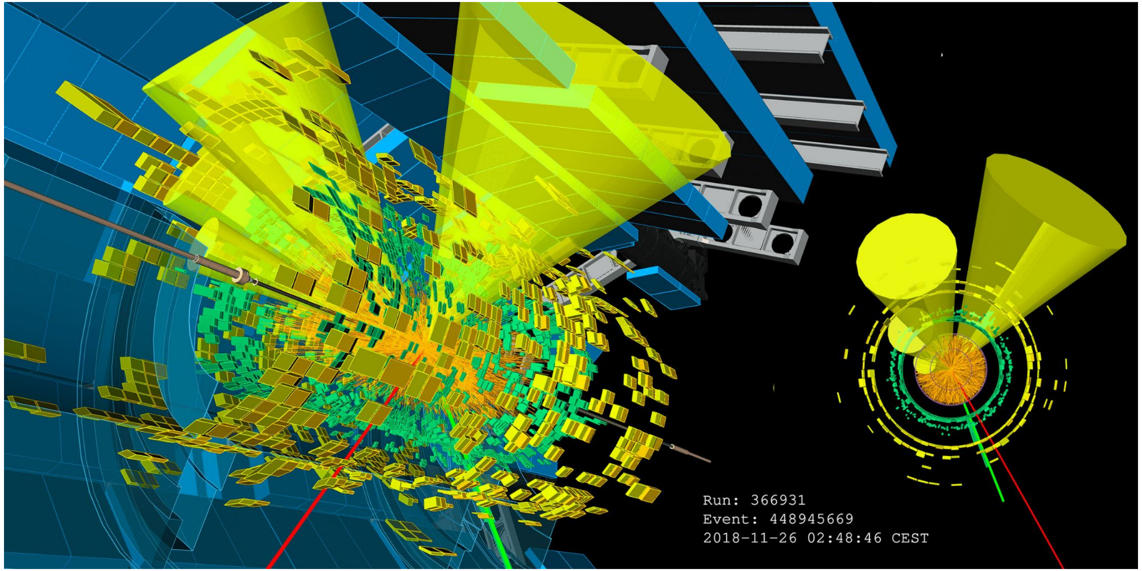
photon-pomeron

Sig/Bkg

Stat. Significance

$(\langle\mu\rangle, \mathcal{L}[\mathrm{fb}^{-1}])$	(5, 10)	(10, 30)	(50, 300)
$N_{\mathrm{trk}} \leq 10$	4.52/0.06, 18.5	13.8/10.5, 4.3	48.3/810.0, 1.7
$N_{\mathrm{trk}} \leq 15$	12.2/1.2, 11.1	36.6/41.7, 5.7	195/4616, 2.9
$N_{\mathrm{trk}} \leq 20$	18.3/2.9, 10.7	60.6/118.2, 5.6	429/15827, 3.4
$N_{\mathrm{trk}} \leq 25$	23.6/8.1, 8.3	78.3/224.7, 5.2	672/37195, 3.5

Top-quark physics highlights from ATLAS



Observation of $t\bar{t}$ production in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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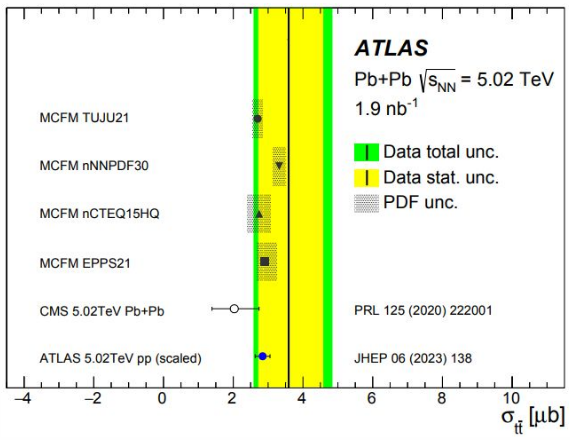
- ***Data Sample***: **lead-lead - 1.9 nb^{-1} (2015 and 2018);**
- Investigate the **presence of all quark flavors** in the **pre-equilibrium stage of the QGP**;
- **Event selection**: =1 electron and =1 muon with m($e\mu$)> 30 GeV; >= 2 jets with pT ≥ 35 GeV;
- Centrality intervals using a Glauber model, focusing on the 0–80% (prevent photon-induced processes);

Production cross section

$$\sigma_{t\bar{t}} = 3.6^{+1.0}_{-0.9}\,(\text{stat.})\,^{+0.8}_{-0.5}\,(\text{syst.})\,\mu b$$

- Observed (expected) significance: 5.0 (4.1);

Phys. Rev. Lett. 134, (2025) 142301



- **Total relative uncertainty**: 31%, primarily stat. unc.-limited data sample size;
- **Statistical**: 26%;
- **Systematic**: 18%;

Summary

- **Unique final states in Diffractive and exclusive processes;**

- **The study of exclusive processes in photon and pomeron induced interactions at LHC can be useful to probe the top pair production if we have a good forward proton detector working properly;**

- **Good prospects for observing the exclusive signal over a mixture of inclusive and combinatorial background are achieved for all luminosity scenarios, although a good separation between the two is observed for rather low amounts of pileup;**

Outlook

- **Window to New Physics and crucial to the Higgs Sector and can be a probe of quantum entanglement;**

- **Evidence for top quark production in heavy-ion collisions is growing: ATLAS and CMS are working on heavy ion top production. Probe initial conditions in flavour Interactions in Quark–Gluon Plasma (QGP);**

Dziękuję bardzo!

Thank you!

Muito obrigado!

Vielen Dank!

Grazie mille!

Merci!

BACKUP

Observation of quantum entanglement with $t\bar{t}$ events @ √s = 13 TeV

Nature 633 (2024) 542

- ***Data Sample***: **proton-proton - 140 fb^{-1}**;
- **Spin correlation between the top-antitop quark**: probe the effects of quantum entanglement;
- If two particles are entangled, the **quantum state of one particle cannot be described independently**;
- **Quantum entanglement** is a key test of the SM and probe for BSM physics;
- **Event selection**:

- **2 leptons: e±μ±,e±e±,μ±μ±;**
- **2 b-jets;**
- **High missing transverse energy;**

Two-qubit system whose spin quantum state is described by the spin density matrix ρ

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+\sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij}\sigma^i \otimes \sigma^j\right]$$

Angular direction of each of these leptons is correlated with the direction of the spin

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

Entanglement marker - Experimental approach

$$D = -3 \cdot \langle \cos\varphi \rangle$$

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Measurement of Entanglement Observable (D)

- Angle between charged leptons in the rest frames of their parent top and antitop quarks.

For 340 < $m(t\bar{t})$ < 380 GeV

$$D = -0.537 \pm 0.002\,[\text{stat.}] \pm 0.019\,[\text{syst.}]$$ **Obs**

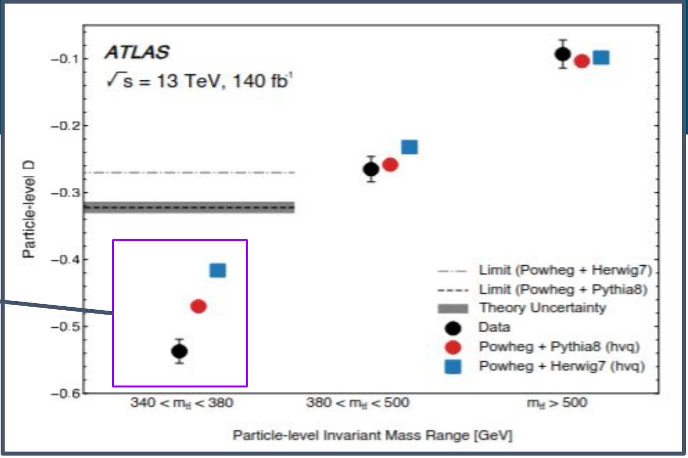
$$D = -0.470 \pm 0.002\,[\text{stat.}] \pm 0.017\,[\text{syst.}]$$ **Exp**

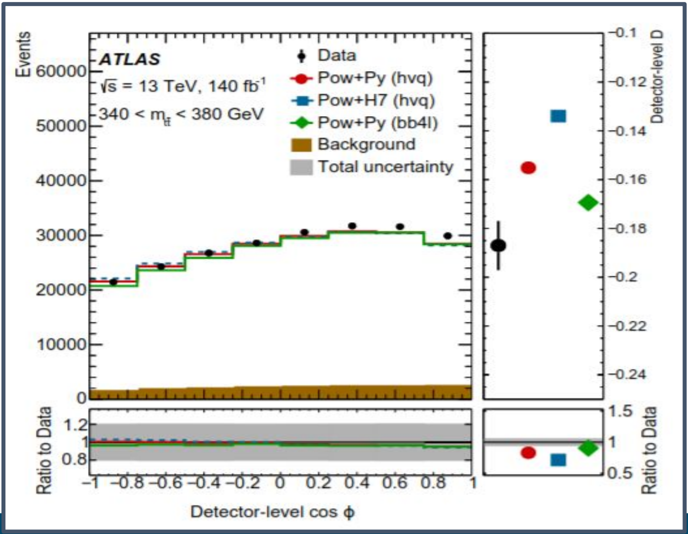
Validation regions: **380 < $m(t\bar{t})$ < 500 GeV, $m(t\bar{t})$ > 500 GeV**

Uncertainties:

- **Signal modelling: 3.2 (3.2)%;**
- **Backgrounds: 0.9 (1.1)%**
- **total: 3.5 (3.6)%;**

- This result deviates from the **non-entanglement scenario by more than five sigmas;**





Observation of $t\bar{t}$ production in p+Pb collisions in lepton+jets and dilepton channels at $\sqrt{s_{NN}}$ = 8.16 TeV

- *Data Sample*: **proton-lead - 165 nb^{-1} (2016);**
- Measurement of the nuclear modification factor for $t\bar{t}$ pair production in p+Pb collisions;
- Event selection: **Single leptonic:** =1 lepton (electron or muon) with pT > 15 GeV and >= 4 jets (>= 1 b-tagged jet);
  Dileptonic: =2 opposite-charge leptons with additional Invariant mass cuts and >= 2 jets;
- Top-quark pair cross section: observed with a significance higher than 5 sigma in both channels with a total uncertainty of 9%;

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\text{stat.})\ ^{+4.8}_{-4.4}\ (\text{syst.})\ \text{nb}$$

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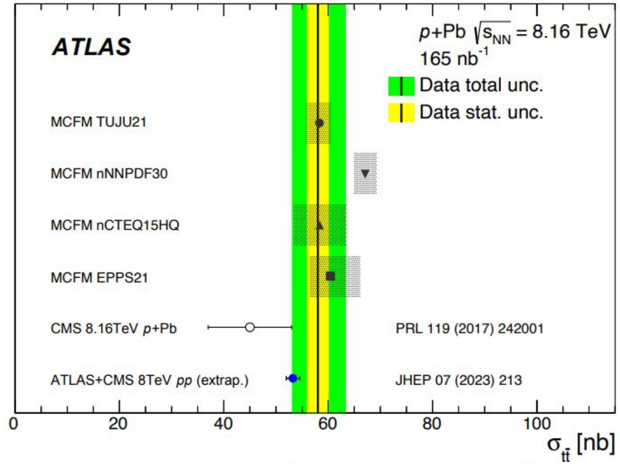
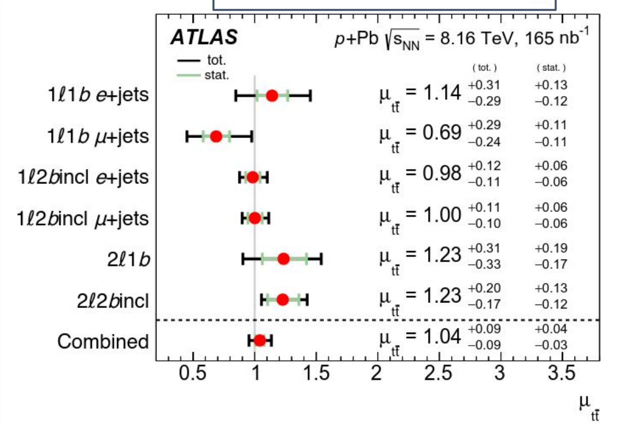


Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6

$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\text{Pb}} \cdot \sigma^{\text{th}}_{t\bar{t}}$$

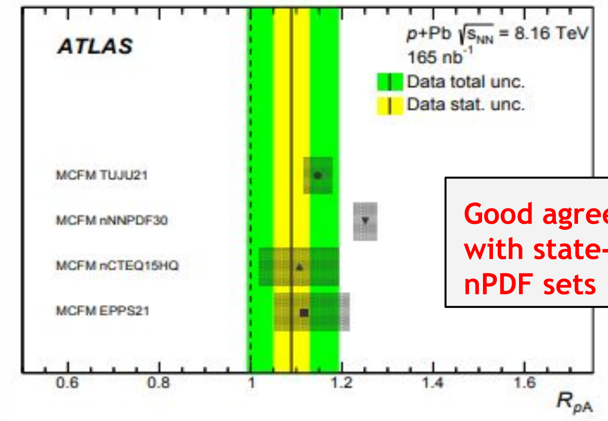


- $\mu_{t\bar{t}}$ are consistent with the SM predictions. Confirms the observation of $t\bar{t}$ production in p+Pb collisions for the first time at the LHC;

$$R_{pA} = \frac{\sigma^{p+\text{Pb}}_{t\bar{t}}}{A_{\text{Pb}} \cdot \sigma^{pp}_{t\bar{t}}}$$

→ **Nuclear modification factor**

$$R_{pA} = 1.090 \pm 0.039\ (\text{stat.})\ ^{+0.094}_{-0.087}\ (\text{syst.})$$



Good agreement with state-of-art nPDF sets

- The measured value is found to be consistent with unity within the uncertainty.
- New way to constrain nPDFs in the high Bjorken-x;
- Input for upcoming measurements involving the extraction of QGP properties in Pb+Pb collisions;