THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
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Diffractive top pair production at LHC with forward detectors

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Outline

- Top physics - A brief discussion;
- Diffractive physics and event classification;
- Motivation to the study;
- Results;
- Summary;

And all the lighthouses
Their beams converge to guide me home…

Chemical wedding

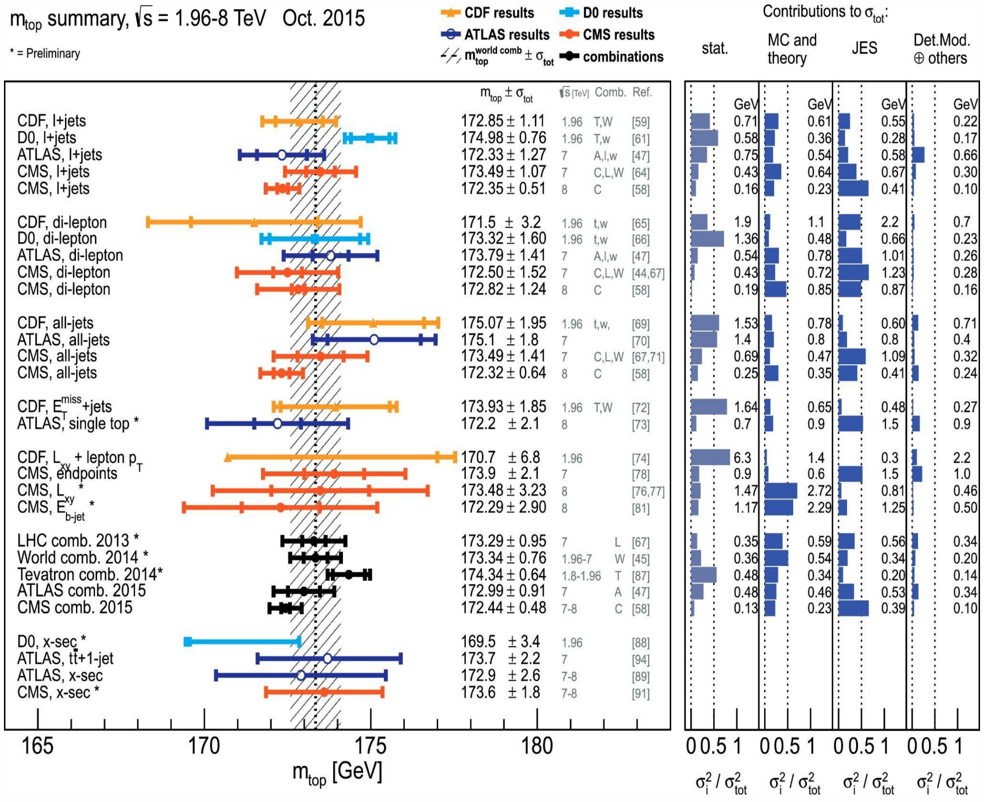
Top Physics: From Tevatron to LHC

- Top quark properties have already been performed at the Tevatron and at the LHC: **kinematical properties of top production, reco, measurement of the 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)**.

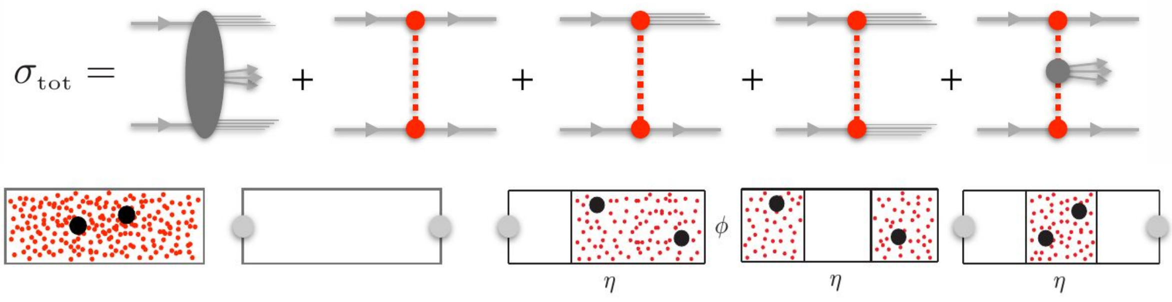
- More data to be (being) collected at $\sqrt{s}$ = 13-13.6 TeV - run III and beyond;

- Working with low and high mu interactions;



Diffractive physics

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

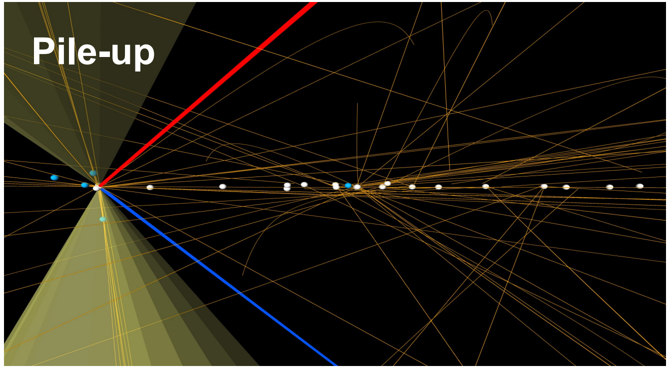


LHC:

- Discovery Machine
- QCD machine (always present!)

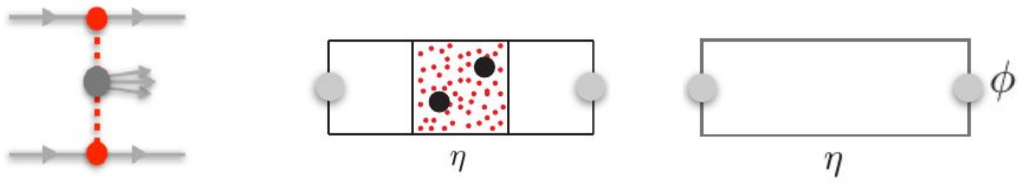
Diffraction:

- Vital aspect of QCD
- Place to look for New Physics;



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

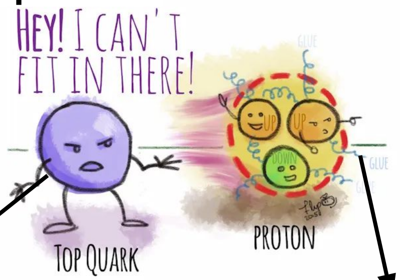
Exclusive events: Few tracks + low p_T particles



Top Physics: LHC as a top factory

- We can describe the proton constituents by a series of parton density functions (p.d.f): this distribution states the probability of interacting with a particular piece of proton.

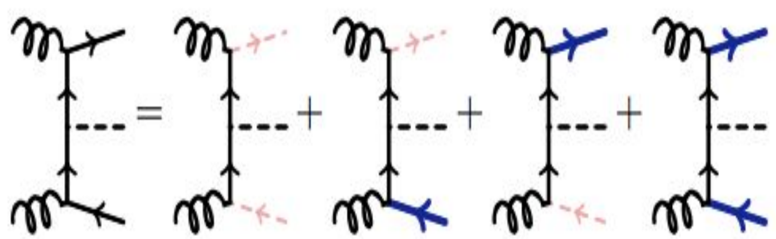
- These p.d.fs are energy-dependent: at high energies, it turns out that you're more likely to interact with a gluon than any of the "valence quarks" .



Can i come in?

No room for you!

- Keeping the expansion parameter small leads to an interpretation of this "high-energy gluon splitting into heavy quarks inside the proton" process as the proton having some intrinsic heavy quark. content.



- This is called perturbative QCD, the key equation known as DGLAP.

Top Physics @ LHC: Motivation

- When one of these is collinear (i.e. goes down the collider beamline), the expansion parameter blows up and the calculation misbehaves.

- To maintain a well behaved perturbation theory, DGLAP tells us to pretend that instead of a top/anti-top pair coming from a gluon splitting, one can treat these as a top that lives inside the high-energy proton.

Papers published:

- *V. Goncalves, D. Martins, M. Rangel, and M. Tasevsky, PRD 102, 074014 (2020).*
- *D. Martins, V. Goncalves and M. Tasevsky, PRD 105 (2022) 11, 114002.*

*"There in the middle of the circle he stands searching, seeking…
With just one touch of his trembling hand the answer will be found…"*

The temple of the king

Milestones

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

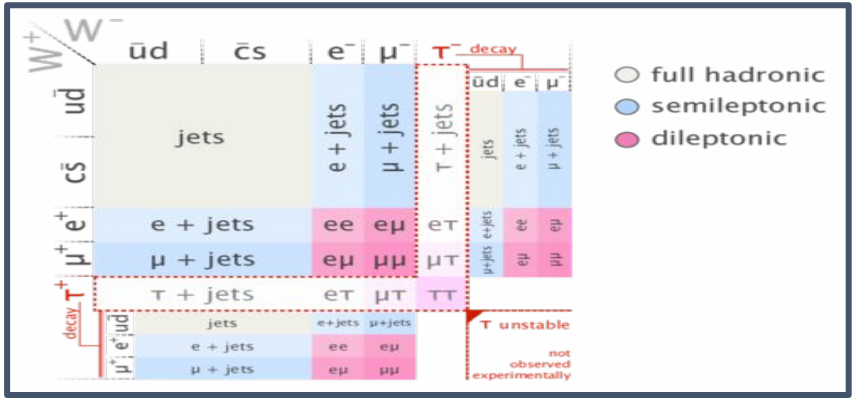
Studies conducted inside the ATLAS collaboration

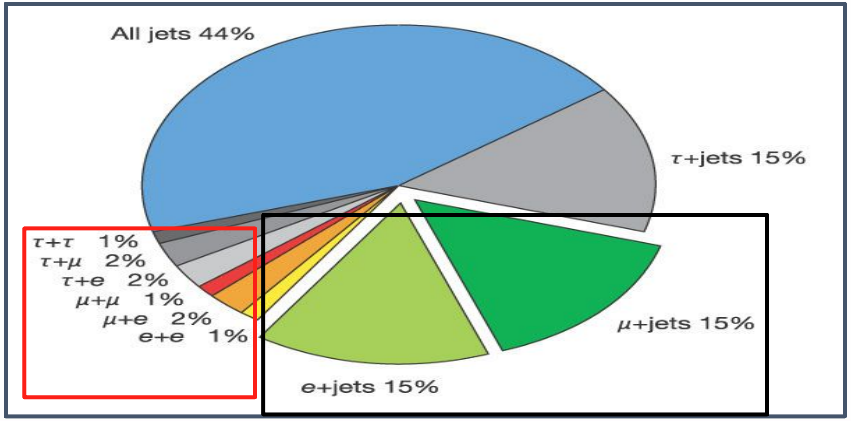
"Alea jacta est"

Top Physics@LHC:Decay channels

- Top quark is the **most massive of all observed elementary particles**. It derives its mass from its coupling to the Higgs Boson;

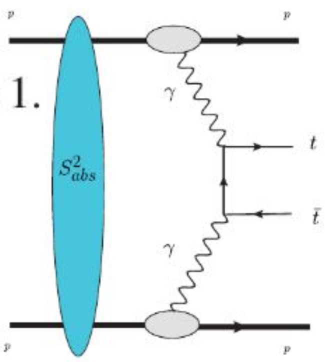
- Top decays through the **electroweak interaction into a W boson and (usually) a bottom quark**. The unique quark heavy enough to decay into a real (on-shell) W boson;

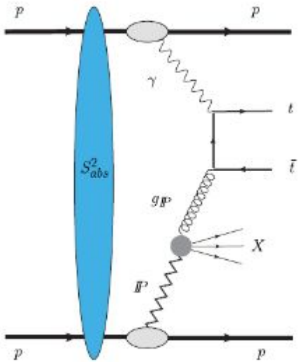


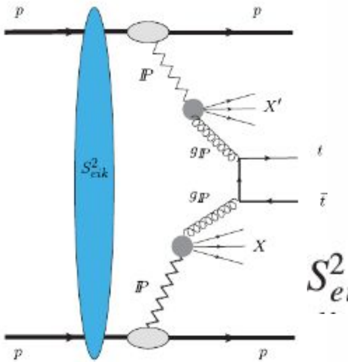


Diffractive and exclusive processes

$S^2_{abs} = 1.$







$S^2_{eik} = 0.03$

Cross section:

$$\sigma(h_1h_2 \to h_1 \otimes t\bar{t} \otimes h_2) = \int dx_1 \int dx_2 \gamma_1(x_1) \cdot \gamma_2(x_2) \cdot \hat{\sigma}(\gamma\gamma \to t\bar{t})$$

Photon flux:

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

Cross section:

$$\sigma(h_1h_2 \to h_1 \otimes t\bar{t}X \otimes h_2) = \int dx_1 \int dx_2 [g_1^D(x_1, \mu^2) \cdot \gamma_2(x_2) + \gamma_1(x_1) \cdot g_2^D(x_2, \mu^2)] \cdot \hat{\sigma}(\gamma g \to t\bar{t})$$

Diffractive PDF:

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

Cross section:

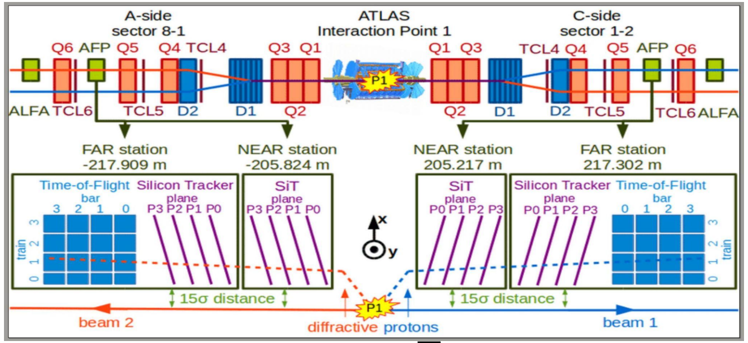
$$\sigma(h_1h_2 \to h_1 \otimes Xt\bar{t}X' \otimes h_2) = \int dx_1 \int dx_2 g_1^D(x_1, \mu^2) \cdot g_2^D(x_2, \mu^2) \cdot \hat{\sigma}(gg \to t\bar{t}).$$

Diffractive PDF is constrained by HERA data - H1- FiT A generated by FPMC

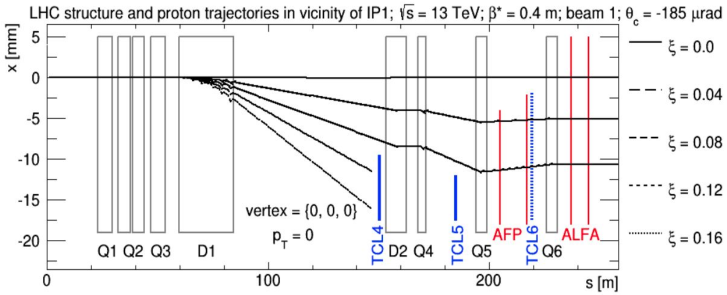
Atlas Forward Detector

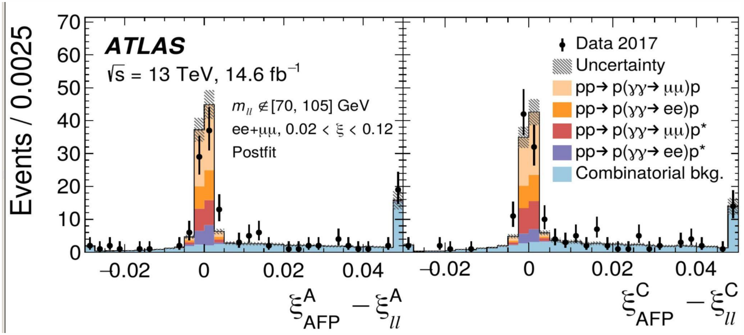
- Two Roman pot vacuum-sealed stations on either side of the interaction point;
- Far stations additionally house ToF detectors: pile-up suppression via the vertex location from relative timing of protons on A- and C-sides;

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



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





Top pair production: Analysis setup

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: Inclusive top pair production + pileup

Inclusion of H.L scenario with pileup

$$\mu = 5, 10, 50 \text{ and } 200$$

Event generation

Signal: **Forward Physics MC (FPMC)**

Background: **FPMC, Madgraph5, Pythia8**

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

Event selection

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

Signal selection and Background rejection cuts

TABLE I. Cuts used in this analysis.

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

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

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

FPD acceptance (assuming 100%)

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: Non - Zero pu scenario

Fake Double-Tag events in FPD

Most dangerous combination

2x soft SD events + hard-scale top-pair event.
Time-of-flight (ToF) detectors 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
$\Delta R(\text{e}/\mu, \text{jet}) > 0.2$	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	[illegible]2/1.39/15.4
$N_{\text{trk}} \leq 20$	1.73/1.76/1.20	0.11/0.26/0.25	[illegible]9/3.94/52.8
$N_{\text{trk}} \leq 25$	2.11/2.16/1.80	0.30/0.45/0.44	[illegible]1/7.49/123.9

After applying 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: ∆R(trk,jet)>0.4 ; Leptons: ∆R(trk,lepton)>0.2**
- **For each lumi scenario, cut Ntracks can be tuned to get optimal S/B**

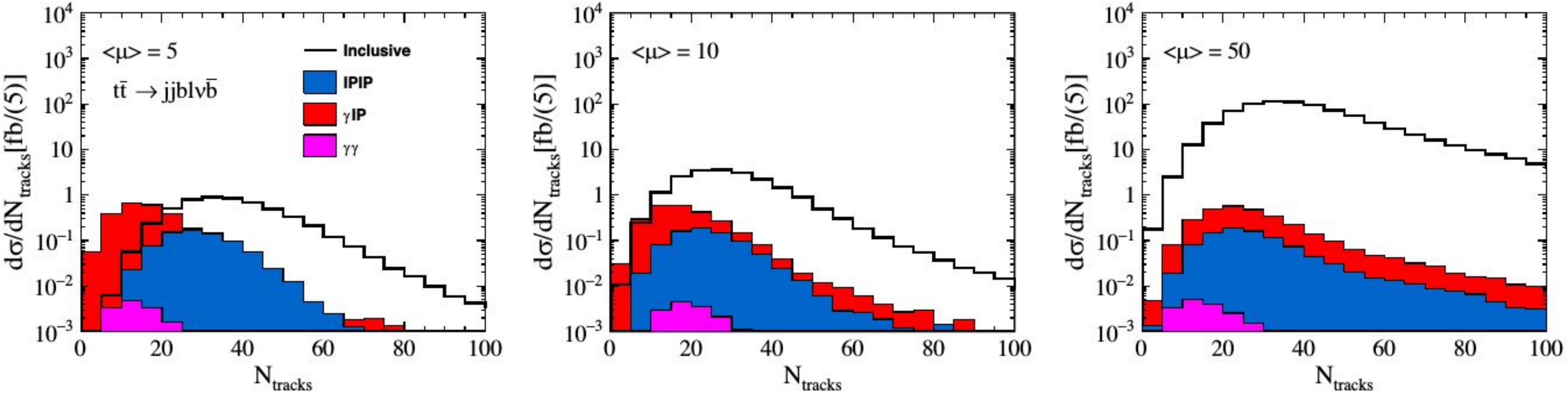


FIG. 4. Distribution of the number of tracks with $p_T > 0.2$ GeV and $|\eta| < 2.5$ outside all four jets and one lepton for three amounts of pileup events per interaction, $\langle\mu\rangle$, of 5, 10, and 50, all at detector level and after applying cuts in Table I, except for the $N_{\rm trk}$ cut. 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: Non - Zero pu scenario

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

S/B — stat. significance

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

Summary

- **The LHC is the world's most powerful collider not only for protons but also for photon – photon and photon – hadron collisions;**

- **The study of exclusive processes in photon and pomeron induced interactions at LHC can be useful to probe the top pair production as well to search for signals of BSM physics in this final state;**

- **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, typically lower than <μ> of 50;**

- **In the follow up more stringent cuts with new kinematical variables were applied for when considering a new version of Delphes and its different configurations;**

FCC race - Warming up

Muito obrigado!

Dziękuję bardzo!

Thank you!

Vielen Dank

Back up Slides

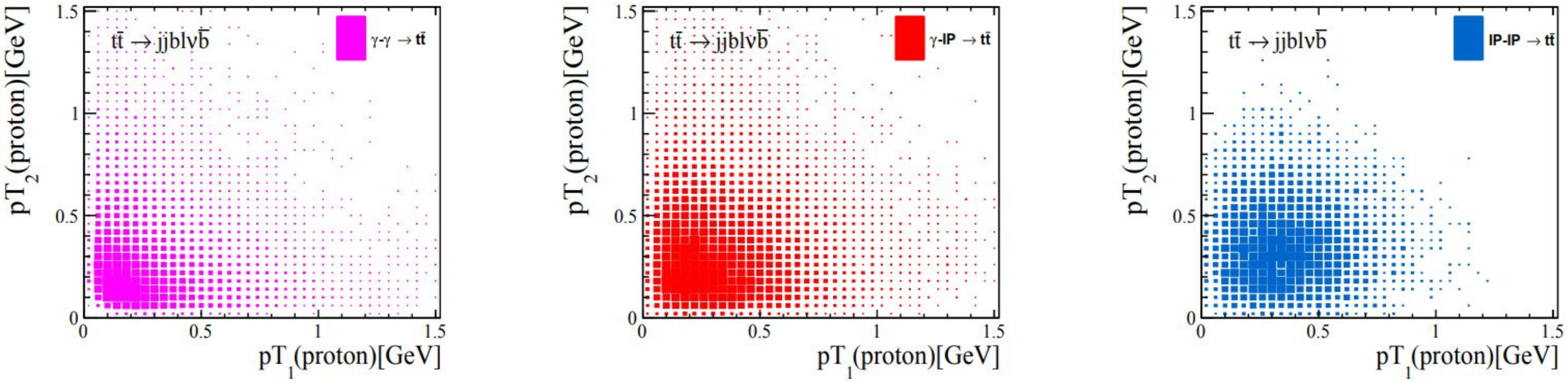


FIG. 2: 2-dimensional distribution of the transverse momentum of proton on one side from the interaction
versus that on the opposite side, after applying cuts in Table I up to the row corresponding to the ξ accep
inclusively and without considering pile-up effects. Predictions for the signal processes ($\gamma\gamma$ on the left, $\gamma\mathbb{P}$ i
middle and $\mathbb{PP}$ on the right) are obtained with FPMC and are scaled by effective cross sections correspon
to the set of applied cuts.

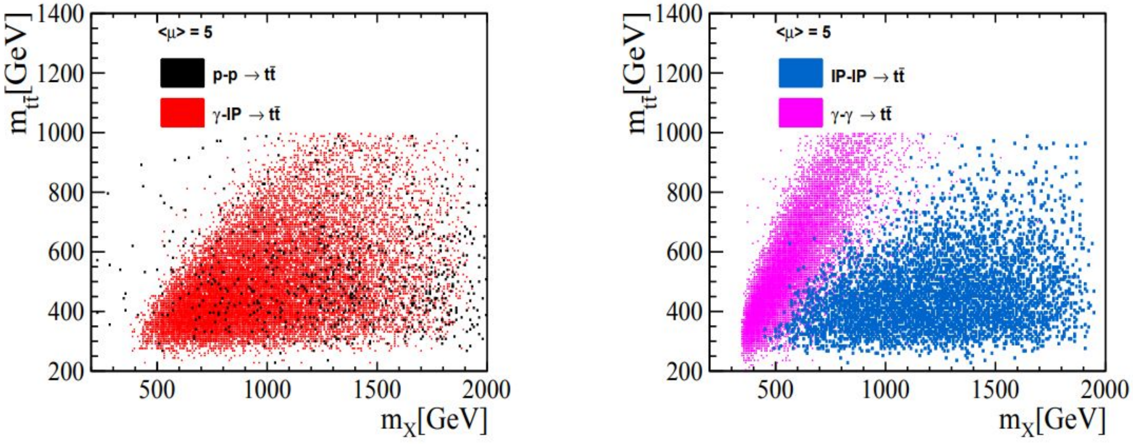


FIG. 3: 2-dimensional distribution of the central $t\bar{t}$ system mass measured by forward proton detectors (m_X) versus that measured by central detector ($m_{t\bar{t}}$) after applying all cuts in Table I up to the row corresponding to the ξ acceptance inclusively. Predictions, scaled by effective cross sections corresponding to the set of applied cuts, are obtained with FPMC for processes $\gamma\gamma$, $\gamma\mathbb{P}$ and $\mathbb{P}\mathbb{P}$, while MadGraph 5+PYTHIA 8 is used for the inclusive $t\bar{t}$ production. All processes are mixed with pile-up with $\langle\mu\rangle = 5$.

1) Single-Tag probability to find a PU proton in FPD acceptance: 1.4%(PY8.2)

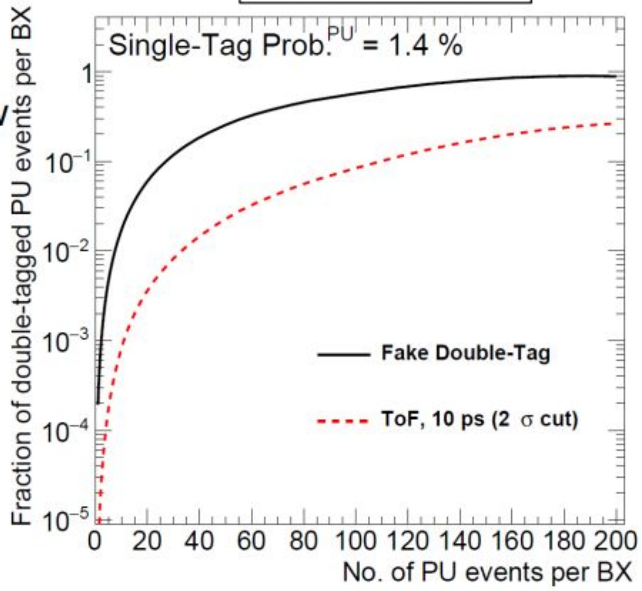
Minimum Bias events, MPI on

2) Rate of fake Double-Tagged events, assuming

- bunch longitudinal size: 7.5 cm
- time resolution: σ_t = 10 ps
- time window: $2\sigma_t$

Requiring arrival times difference to be zero within time window

$<\mu>$	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]

These factors only applied for inclusive top-pair background

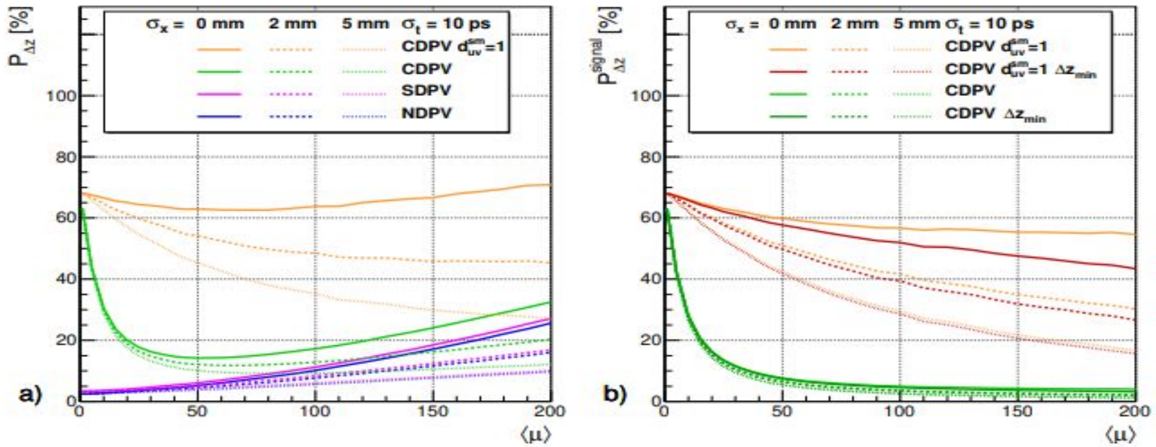


Figure 6: $P_{\Delta z}$ and $P_{\Delta z}^{\text{signal}}$ probabilities as a function of $\langle\mu\rangle$ for $\sigma_t = 10$ ps and three σ_x values of 0, 1 and 2 mm shown by solid, dashed and dotted lines. a) $P_{\Delta z}$ of the CDPV sample using the $d_{\text{uv}}^{\text{smear}} = 1$ selection are shown by the orange lines, the unconstrained case $P_{\Delta z}$ is shown in green. The NDPV and SDPV values are shown by blue and magenta lines. b) $P_{\Delta z}^{\text{signal}}$ results corresponding to the $d_{\text{uv}}^{\text{smear}} = 1$ selection using all measured Δz values are shown by the orange lines. The results for Δz_{min} method is shown by the dark red lines. $P_{\Delta z}^{\text{signal}}$ of the unconstrained case is shown by the green and dark green lines.