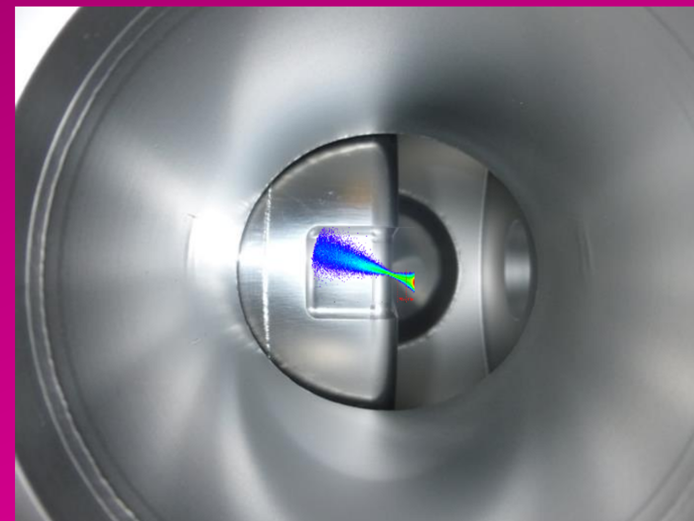
(Semi)exclusive production of top pair at LHC



Marek Taševský

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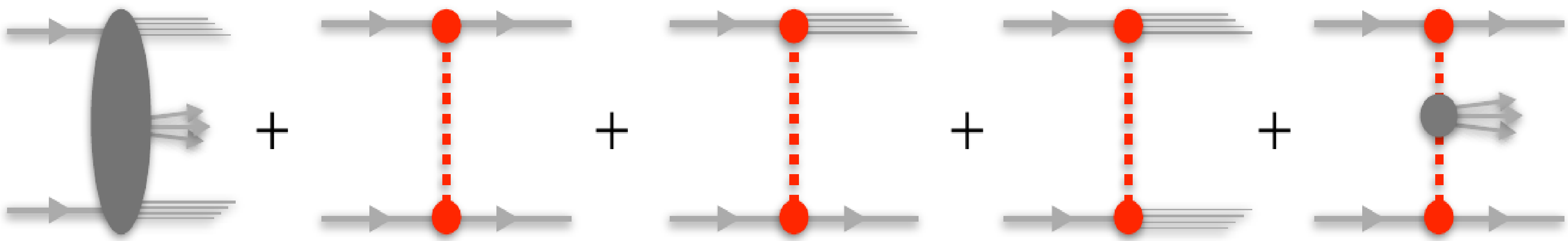
[based on PRD 102, 074014 (2020), arXiv:2007.04565[hep-ph]]

On behalf of Victor Goncalves, Daniel Martins and Murilo Rangel

Proton-proton collisions

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

$\sigma_{\mathrm{tot}} =$



Proton-proton collisions

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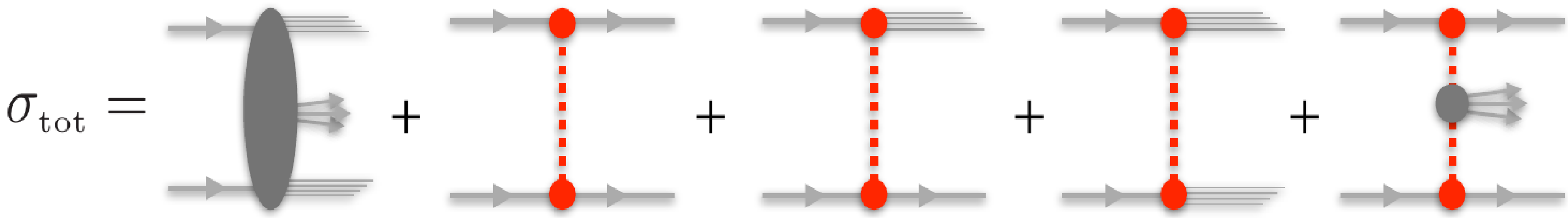

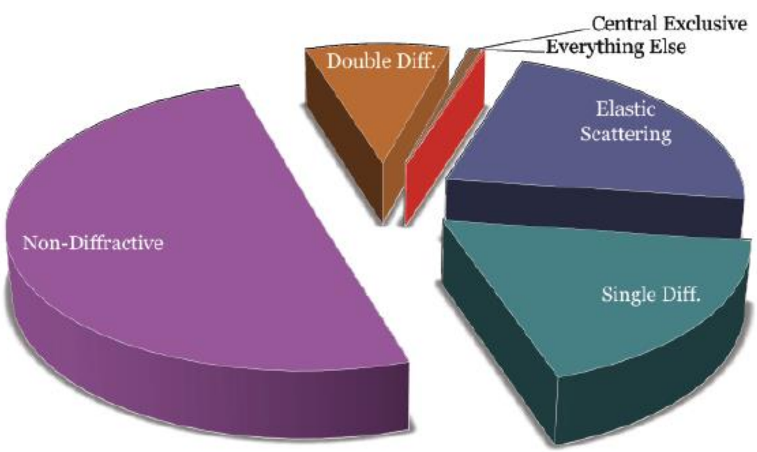

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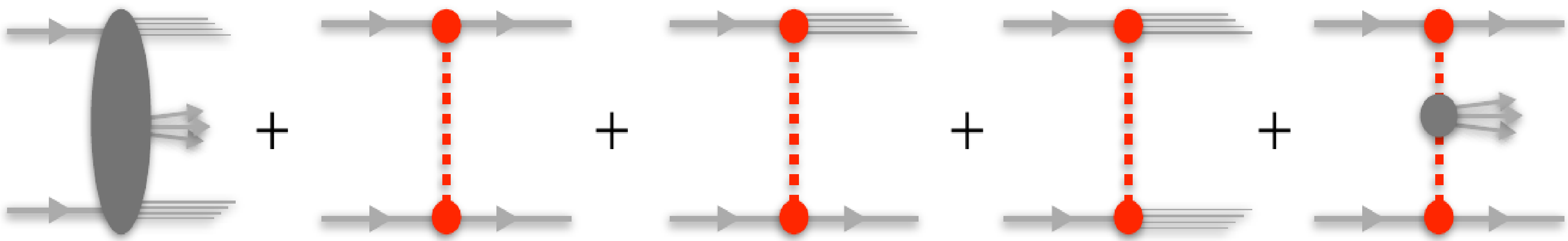
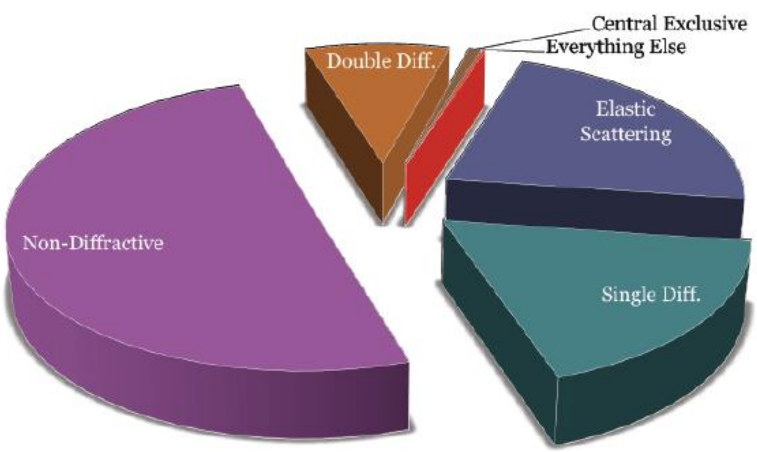
$\sigma_{\mathrm{tot}} =$ 



LHC is a:

- Discovery Machine
- QCD machine (QCD is always present!)

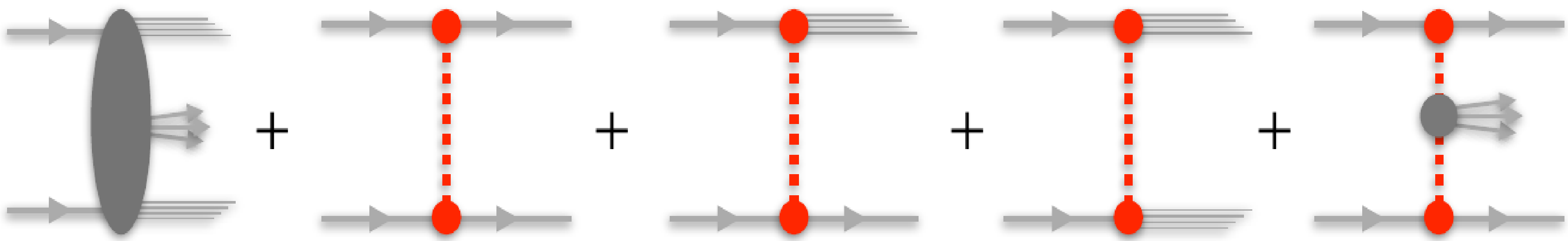
Diffraction is a:

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

Diffractive interactions

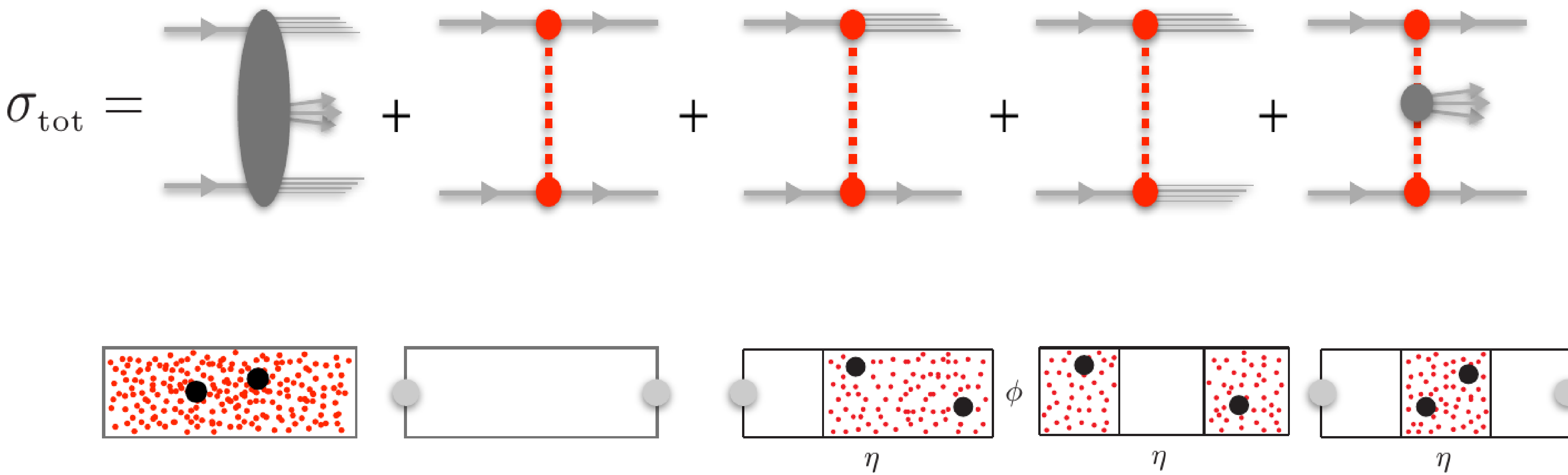
- Diffractive reactions at hadron colliders are defined as reactions in which a color singlet object (Pomeron or photon) is exchanged between colliding particles.

$$\sigma_{\text{tot}} =$$



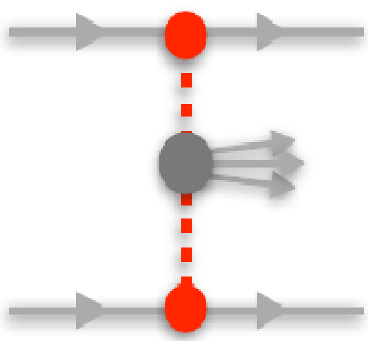
Diffractive interactions

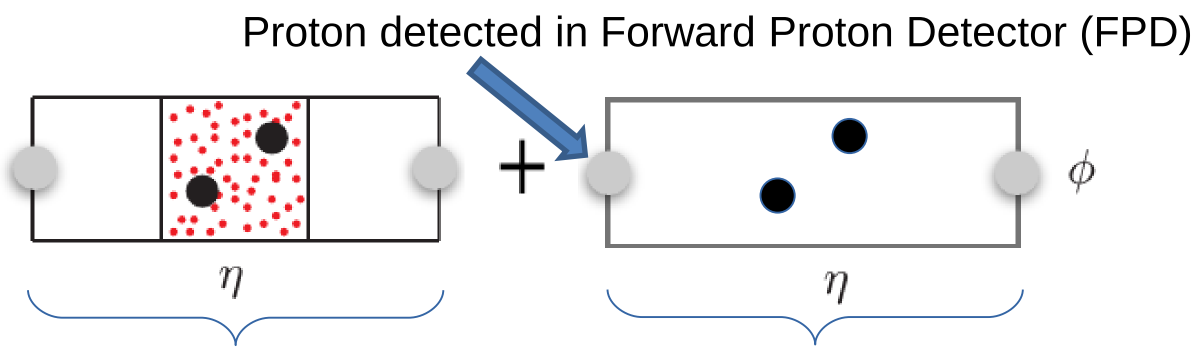
- Diffractive reactions at hadron colliders are defined as reactions in which a color singlet object (Pomeron or photon) is exchanged between colliding particles.



- Identified by the presence of an intact leading particle or a large rapidity gap (LRG)

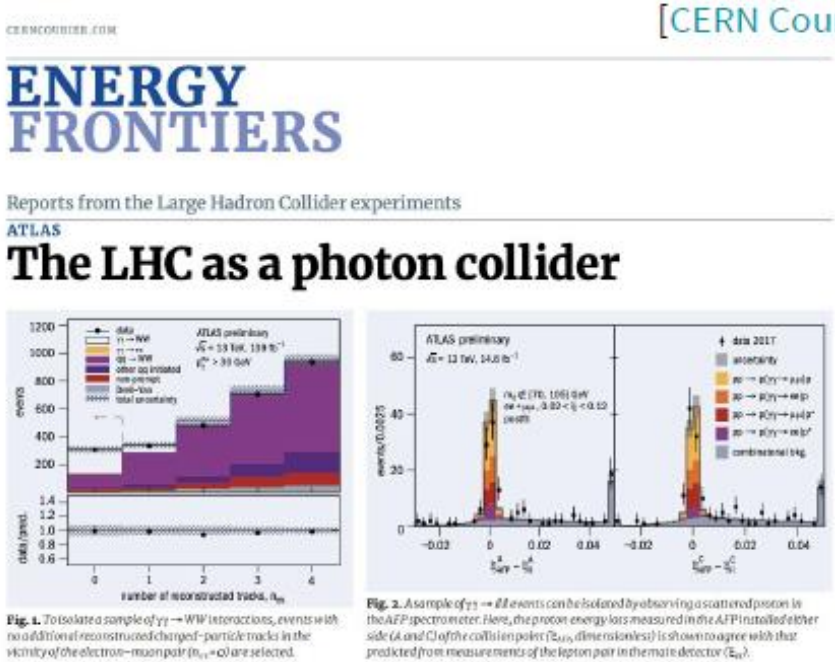
(Semi) exclusive processes





- Semiexclusive production
- Exclusive production

[CERN Courier]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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

The LHC as a photon collider

Fig. 1. *To isolate a sample of $\gamma\gamma \rightarrow WW$ interactions, events with no additional reconstructed charged-particle tracks in the vicinity of the electron–muon pair ($n_{trk}=0$) are selected.*

Fig. 2. *A sample of $\gamma\gamma \rightarrow \ell\ell$ events can be isolated by observing a scattered proton in the AFP spectrometer. Here, the proton energy loss measured in the AFP installed either side (A and C) of the collision point (ξ_{AFP}, dimensionless) is shown to agree with that predicted from measurements of the lepton pair in the main detector ($\xi_{\ell\ell}$).*

LHC can also serve as a photon collider

ATLAS, CMS, LHCb:
Good know-how about how to measure exclusive processes:

without FPDs: $\gamma\gamma \rightarrow \mu\mu/ee$, $\gamma\gamma \rightarrow WW$
with FPDs: $\gamma\gamma \rightarrow \mu\mu/ee$
(all in presence of pile-up, without timing detectors)

New Physics in exclusive processes

$\gamma\gamma \to WW/ZZ/\gamma\gamma$: anomalous quartic gauge couplings

$\gamma\gamma \to$ 2 sleptons/charginos $\to$ 2 neutralinos (DM candidates) + $\mu\mu$/ee

$\gamma\gamma \to a \to \gamma\gamma$: axion-like particle searches

$\gamma\gamma \to$ ttbar: anomalous γttbar coupling,

$\gamma\gamma \to \tau\tau$: anomalous magnetic moment of τ

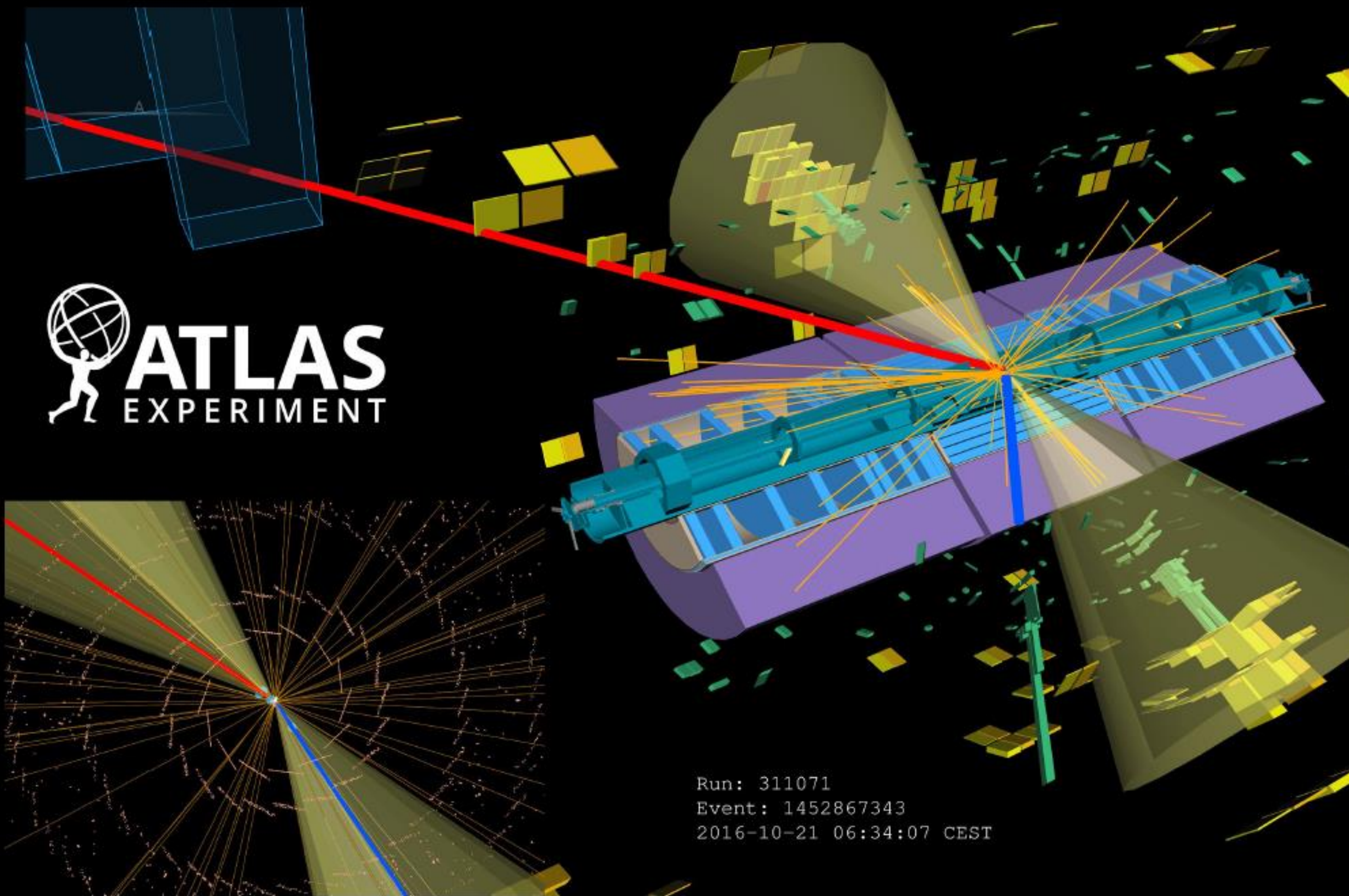
$\gamma p \to$ t: FCNC (see Jay's presentation)

pp $\to$ pHp: H$\to$bbbar, Hbb Yukawa coupling

…

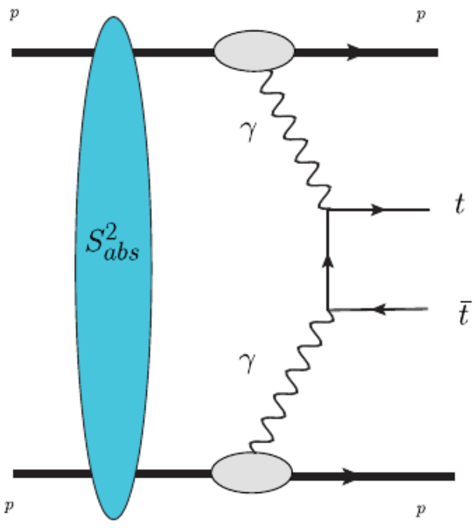
…

TOP QUARKS + AFP

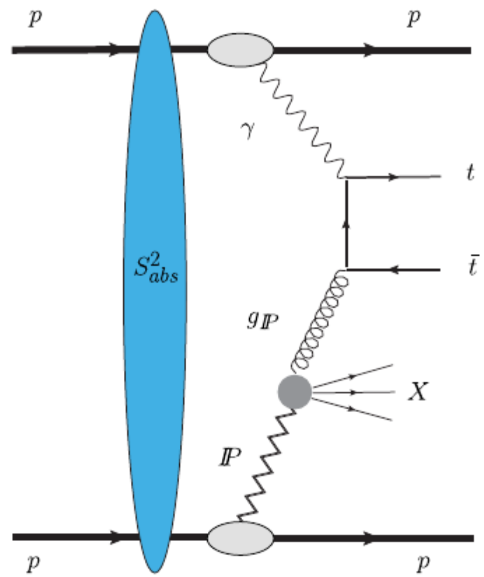


Top-pair production in (semi)exclusive processes

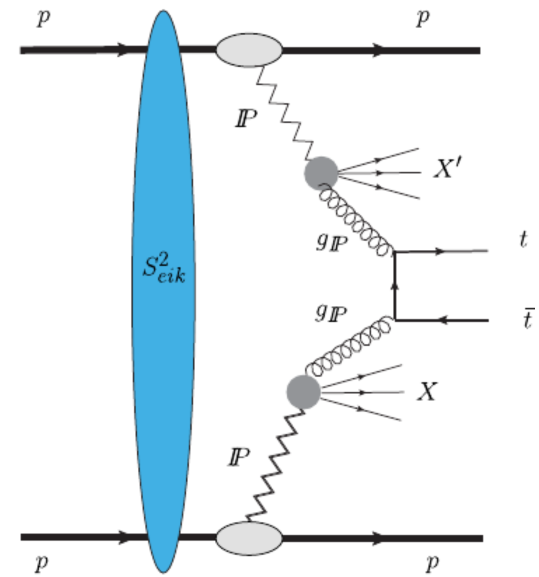
Photon – photon



Photon – Pomeron



Pomeron – Pomeron



Cross section:

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

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

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

Photon flux:

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

Diffractive PDFs:

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

(constrained by HERA data)

Survival factor:

$S^2_{abs} = 1.$ $S^2_{abs} = 1.$ $S^2_{eik} = 0.03$

Experimental procedure

- **Signal:**

top-pair produced in photon-photon, photon-Pomeron and Pomeron-Pomeron interactions

Forward Proton MC (FPMC)

- **Final state:** Two tagged protons in FPDs + semi-leptonic decays in central det.

$$t\bar{t} \rightarrow jjbl\nu_l\bar{b}$$

- Gives best efficiency and reasonable purity, huge know-how in ATLAS and CMS

- **Backgrounds:**

- Irreducible: $\gamma p \rightarrow Wt$ (MadGraph 5) $\gamma\gamma \rightarrow WW$ (FPMC)

- Reducible: Inclusive top-pair + Pile-up (Pythia 8.2 + Delphes)

- Delphes used for fast simulation and pile-up event mixing for all signal processes and reducible background

Signal selection and Background rejection cuts

TABLE I. Cuts used in this analysis.

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

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

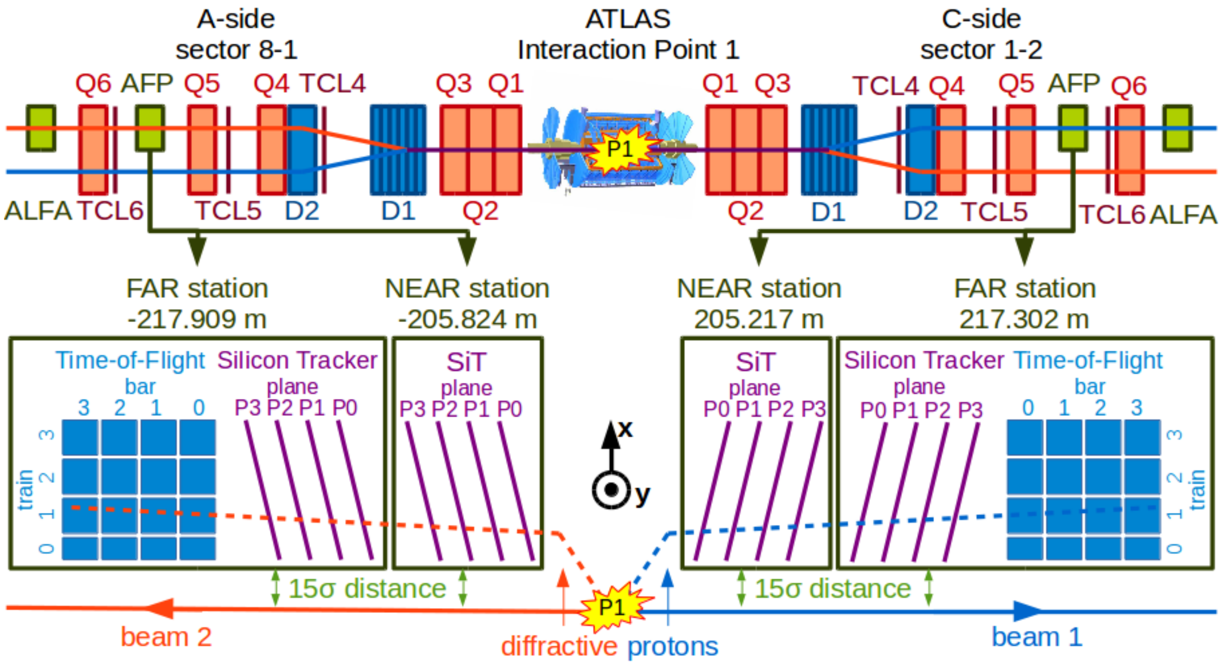
- Reasonable S/B
- Reasonable purities
- Reasonable trigger efficiencies
- Remaining backgrounds < 10%

FPD acceptance (assuming 100%)

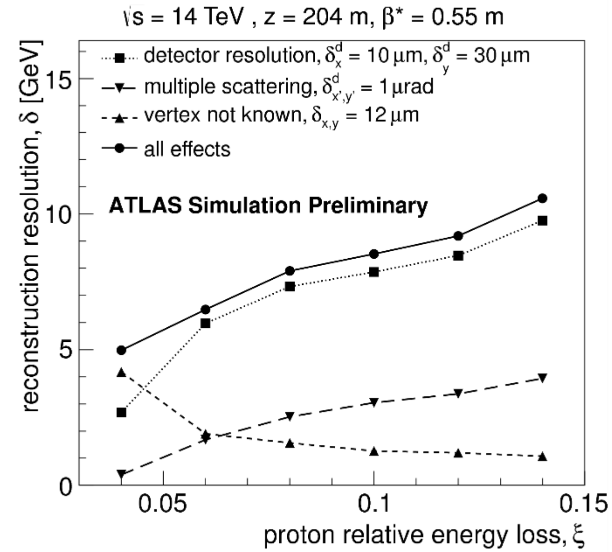
Exclusivity cut:
Number of tracks close to the primary vertex and outside ttbar system must be low (not sufficient to remove the incl.ttbar+PU → use Time-of-Flight (ToF) in FPD)

✓ Delphes with proper input cards takes care of applying central detector acceptances, efficiencies, b-tagging, pile-up mixing…

Forward Proton detectors (FPDs) at LHC



AFP

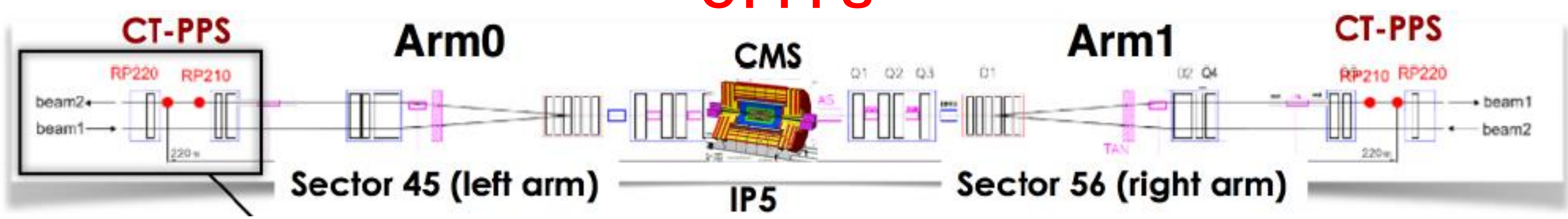


[AFP TDR, CERN-LHCC-2015-009]

$\xi_{1,2} = 1 - E_{proton1,2}/E_{beam}$, $M = \sqrt{\xi_1 \xi_2 s}$

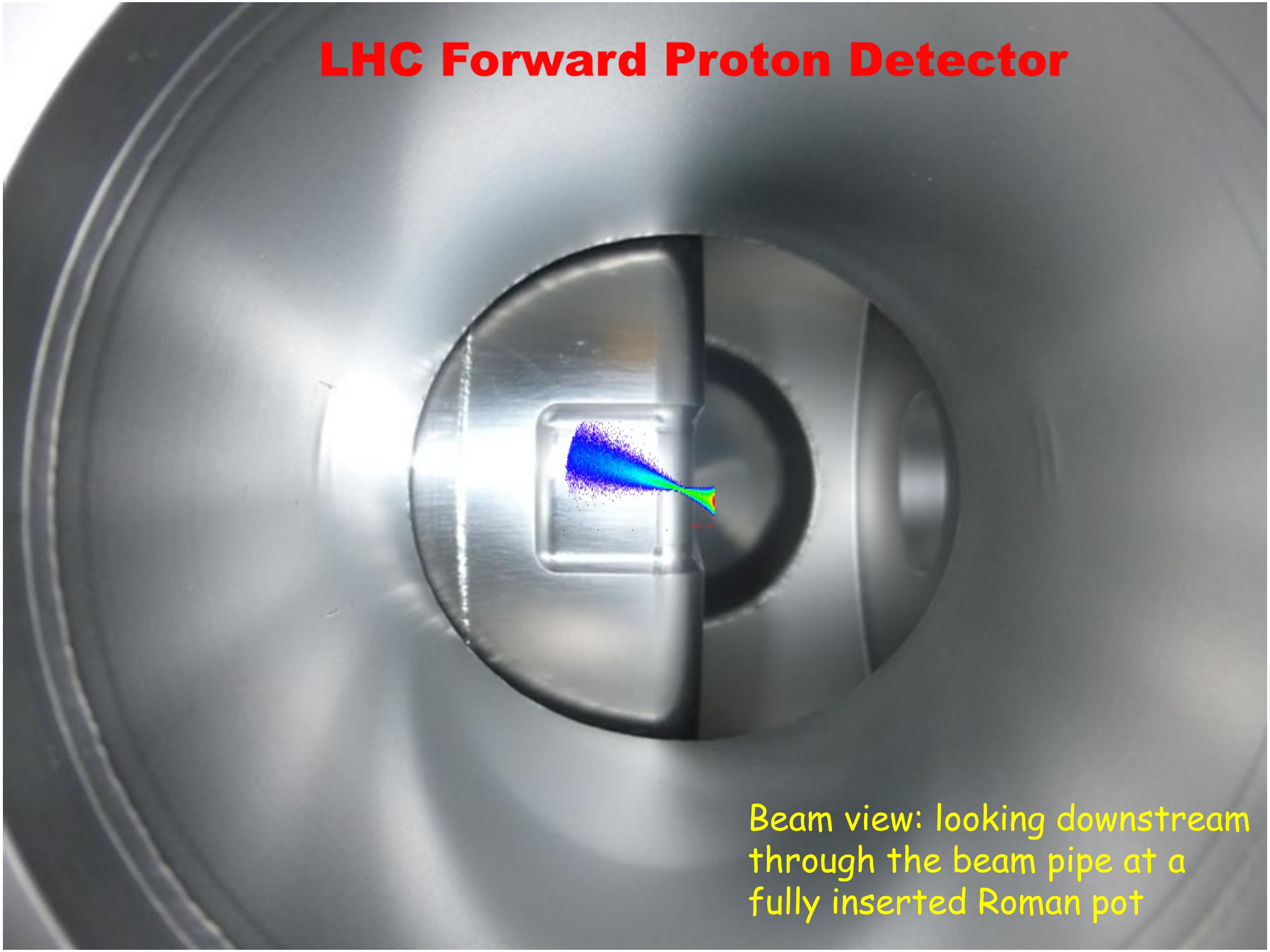
Excellent ξ (central system mass) resolution

CT-PPS



[CT-PPS TDR, CERN-LHCC-2014-021]

LHC Forward Proton Detector



LHC Forward Proton Detector

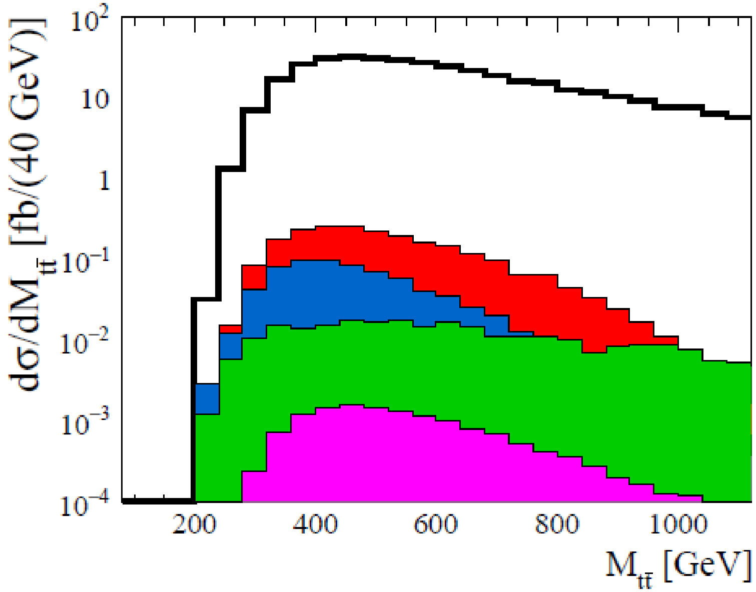
Beam view: looking downstream through the beam pipe at a fully inserted Roman pot

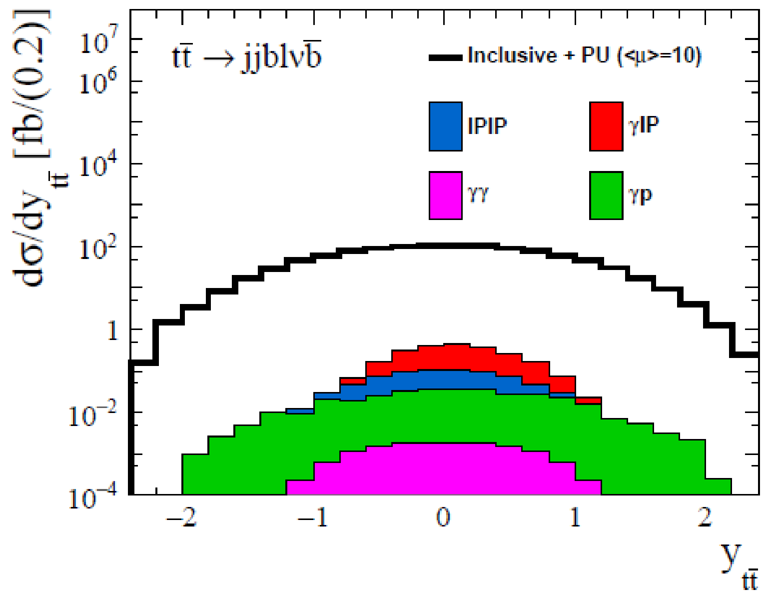
Zero Pile-up

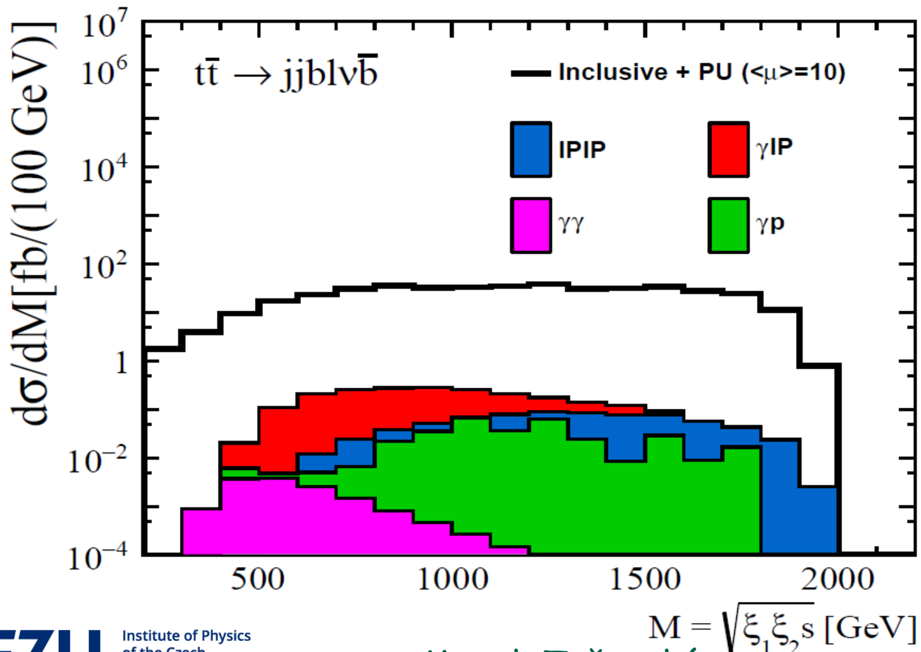
Process	$\gamma\gamma$	$\gamma\mathbb{P}$	$\mathbb{PP}$	Incl.$t\bar{t}$+PU	$\gamma\gamma \to WW$	$\gamma\mathbb{P} \to Wt$
Generated cross section [fb]	0.34	52.0	28.4	390000	75.6	12.0
$N_{e/\mu} \geq 1$ ($E_T > 25$ GeV, $\lvert\eta\rvert < 2.5$)	0.09	14.1	7.4	89991	0.06	2.0
$N_{\rm jet} \geq 4$ ($E_T > 25$ GeV, $\lvert\eta\rvert < 2.5$)	0.02	3.9	2.0	36412	4.7	0.4
$\Delta R(\mathrm{e}/\mu, \mathrm{jet}) > 0.2$	0.02	3.9	2.0	36412	0.003	0.4
$N_{\rm b-jet} \geq 2$	0.02	3.9	2.0	36412	10^{-4}	0.4
$0.015 < \xi_{1,2} < 0.15$	0.014	2.3	0.74	~ 0	~ 0	0.1

- All backgrounds vanish but the signal event yields are too low → go to higher instantaneous luminosities (higher pile-up).
- Photon-photon yield too low → drop it

Non-zero Pile-up







- All cuts but exclusivity cut applied
- Inclusive ttbar + already <μ>=10 overwhelms all signal processes → apply exclusivity cuts and make use of ToF
- Study 3 lumi scenarios (<μ>, L[fb-1]):

(5,10); (10,30); (50,300)

Fake Double-Tag events in FPD

- What is the rate of fake double-tagged events with protons coming from PU in the acceptance 0.015 < ξ <0.15?

Most dangerous combination: 2x soft SD events + hard-scale top-pair event.
Time-of-flight (ToF) detectors necessary to suppress the PU background.

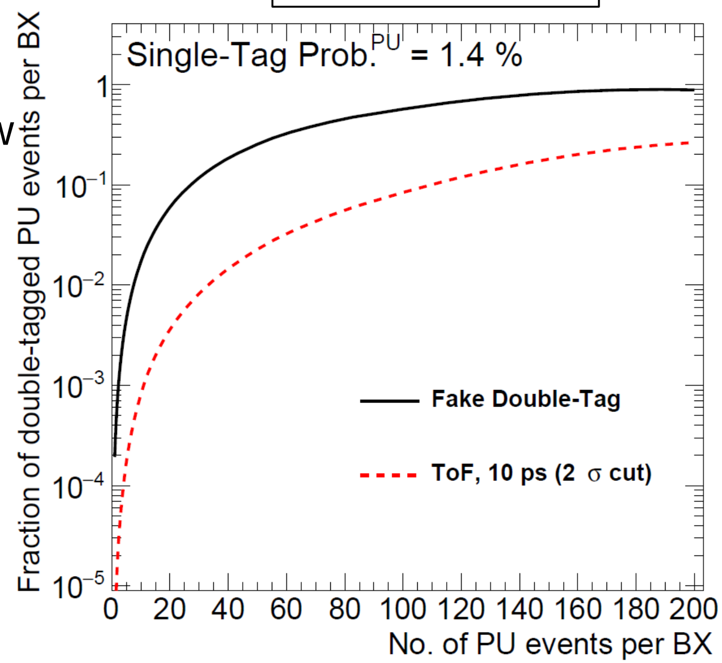
1) Single-Tag probability to find a PU proton in FPD acceptance: 1.4%(PY8.2)

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

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

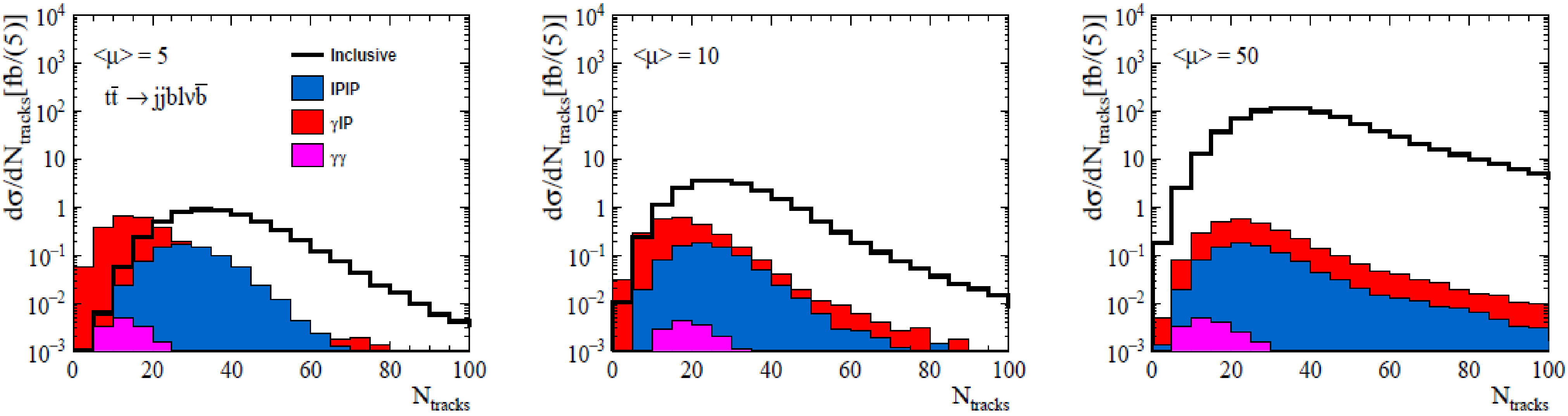


ToF performance studies: arXiv: 2010.00237[hep-ph]

These factors only applied for inclusive top-pair background

Exclusivity cut study

After applying all cuts including ToF suppression



- Ntracks: number of charged tracks with
p_T > 0.2 GeV, |η| < 2.5 and $|z_{trk}$ - $z_{vtx}|$ < 1 mm
and outside jets: ΔR(trk,jet)>0.4 and leptons: ΔR(trk,lepton)>0.2

- For each lumi scenario, cut Ntracks can be tuned to get optimal S/B

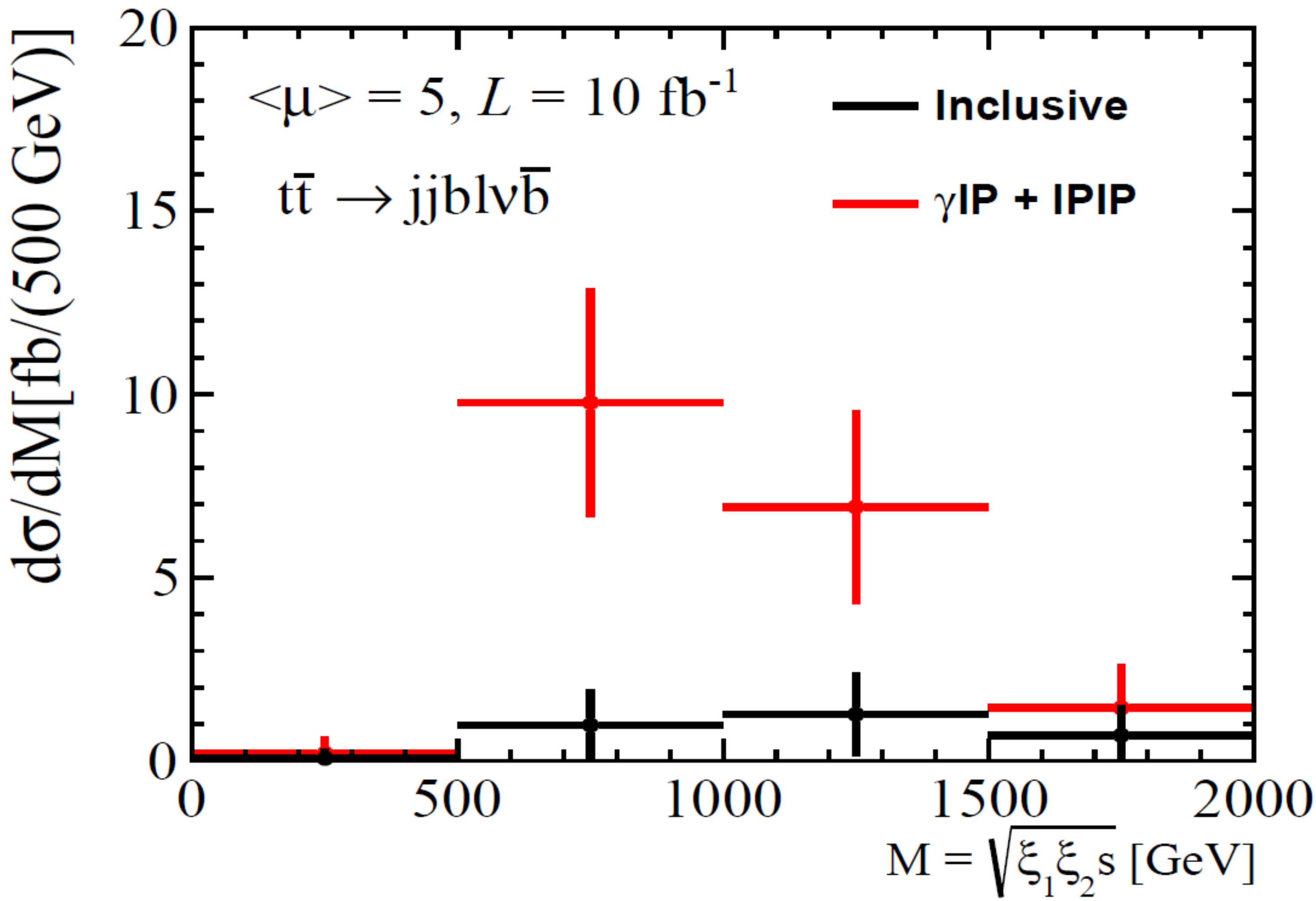
Non-zero Pile-up

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

- Each lumi scenario prefers different N_{trk} cut
- Low values of μ seem to be preferred.

Simulation of experimental output



For $N_{tracks} < 20$ and lumi scenario (5,10): good separation of signal from combinatorial background → observation of the semi-exclusive signal possible

SUMMARY

- ❑ LHC can act as a photon collider
- ❑ In exclusive and semi-exclusive interactions, New Physics can be searched for
- ❑ Forward Proton Detectors measure precisely mass of central system
- ❑ Good prospects for measuring semi-exclusive top-pair production for pile-up amounts smaller than $<\mu> \sim 50$

BACKUP SLIDES

Non-zero Pile-up

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, $\|\eta\| < 2.5$)	14.1/14.2/13.4	7.4/7.3/6.7	90057/90042/82994
$N_{\mathrm{jet}} \geq 4$ ($E_T > 25$ GeV, $\|\eta\| < 2.5$)	4.2/4.4/5.4	2.1/2.2/2.6	38157/38928/42821
$\Delta R(\mathrm{e}/\mu, \mathrm{jet}) > 0.2$	4.2/4.4/5.4	2.1/2.2/2.6	38157/38928/42821
$N_{\mathrm{b-jet}} \geq 2$	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
$N_{\mathrm{trk}} \leq 10$	0.45/0.44/0.14	0.002/0.02/0.02	0.006/0.35/2.7
$N_{\mathrm{trk}} \leq 15$	1.12/1.12/0.60	0.10/0.10/0.10	0.12/1.39/15.4
$N_{\mathrm{trk}} \leq 20$	1.73/1.76/1.20	0.11/0.26/0.25	0.29/3.94/52.8
$N_{\mathrm{trk}} \leq 25$	2.11/2.16/1.80	0.30/0.45/0.44	0.81/7.49/123.9