Soft QCD, Diffraction and Exclusivity in high-energy collisions


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

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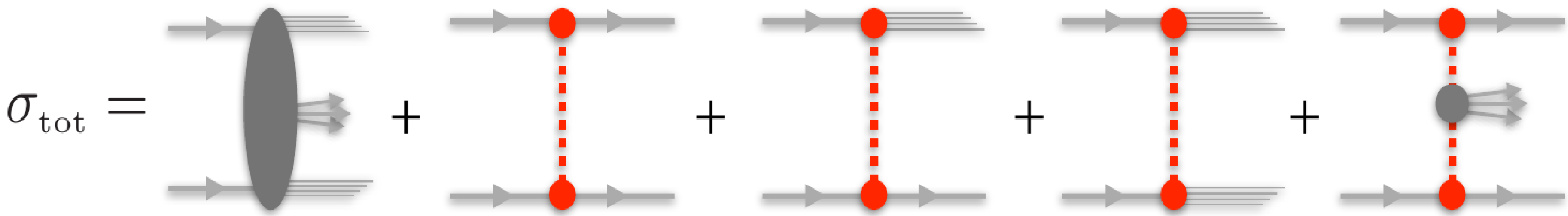
Proton-proton collisions

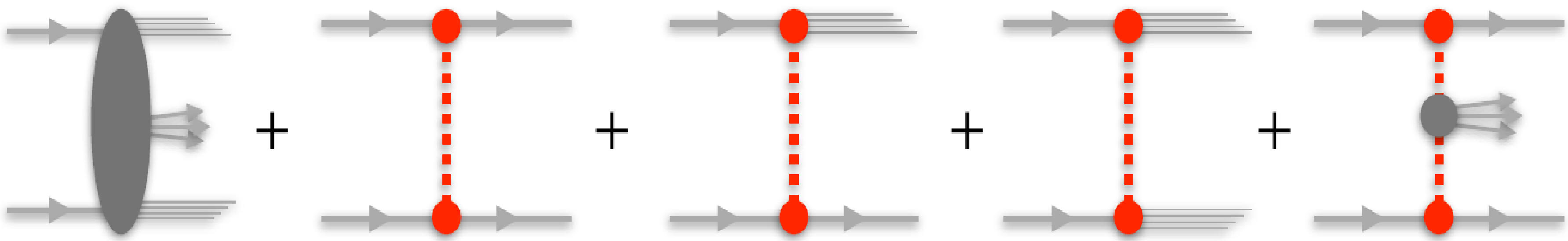
$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{ND}} + \sigma_{\mathrm{elastic}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{CD}}$$

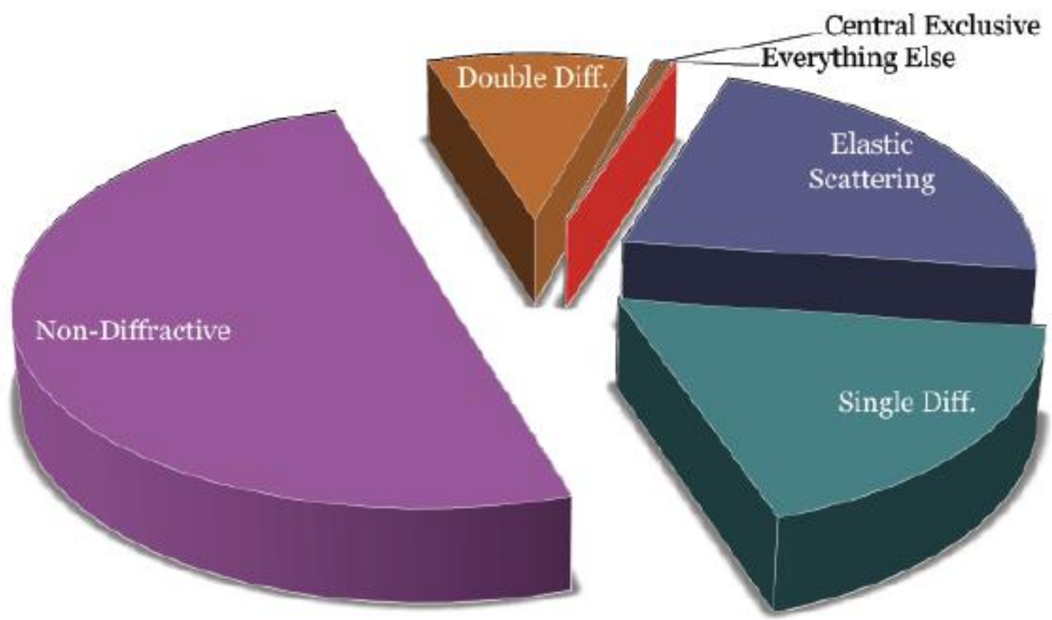


Proton-proton collisions

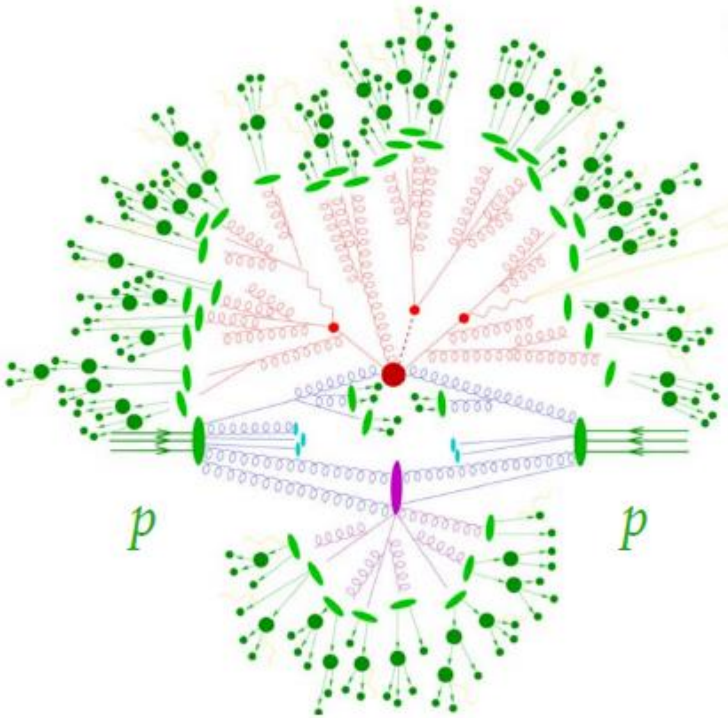
$$\sigma_{\rm tot} = \sigma_{\rm ND} + \sigma_{\rm elastic} + \sigma_{\rm SD} + \sigma_{\rm DD} + \sigma_{\rm CD}$$

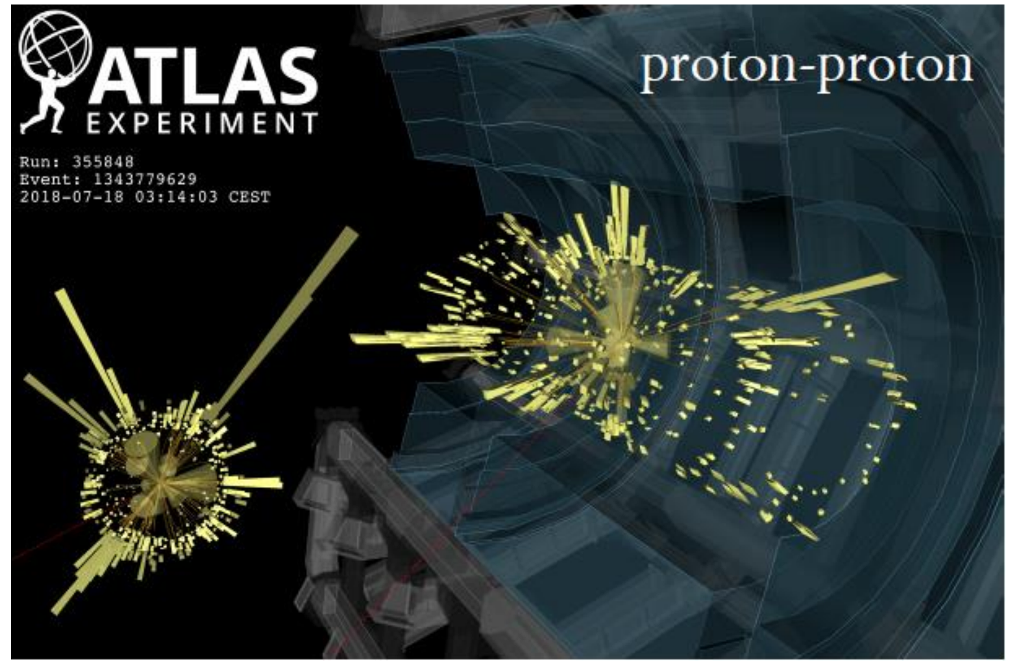
$\sigma_{\rm tot} =$





Typical proton-proton interaction





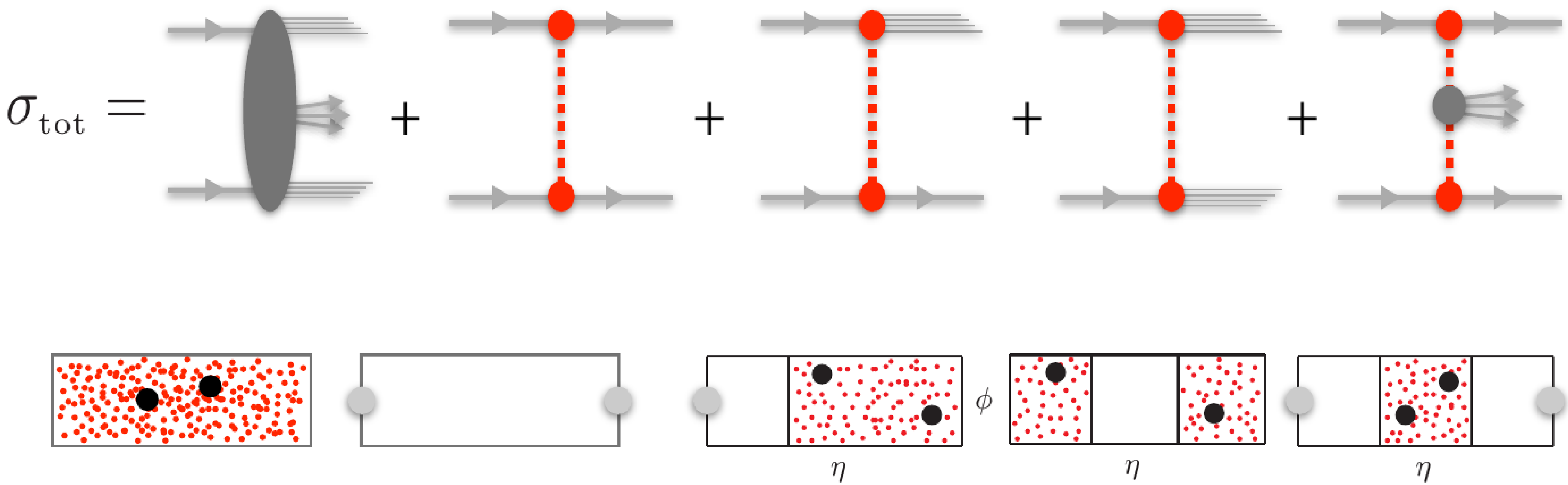
A lot of activity in the central detector:

- Hard scattering
- Multi-parton interactions
- Initial-state radiation
- Final-state radiation
- Hadronization + decays

Most of time at LHC: no (or small) rapidity gaps observed.
More precisely: Most of time the rapidity gap distribution is exponentially falling.

Diffractive interactions

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

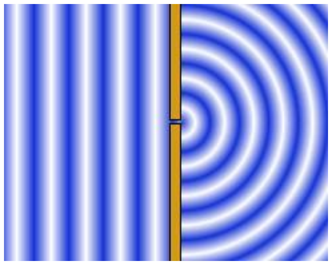


- Identified by the presence of an intact leading particle (measured in FPD = Forward
- Proton Detector) and/or a large rapidity gap (LRG)

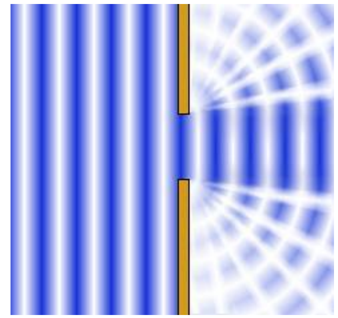
Diffraction

Diffraction in high-energy particle physics is analogy of diffraction in classical optics:

"bending of waves around the corners of an obstacle or through an aperture into the region of geometrical shadow of the obstacle/aperture"



Diffraction on a point slit



Diffraction on a slit of R~λ

Optics: intensity of diffracted light at small angles and large wave nr. k

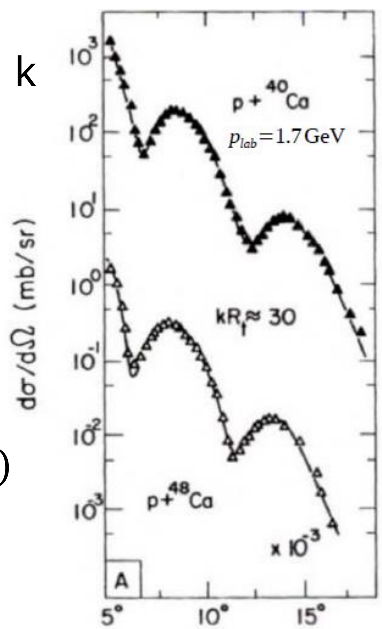
$I(\theta) = I(0)(1\text{-}Bk^2\theta^2)$

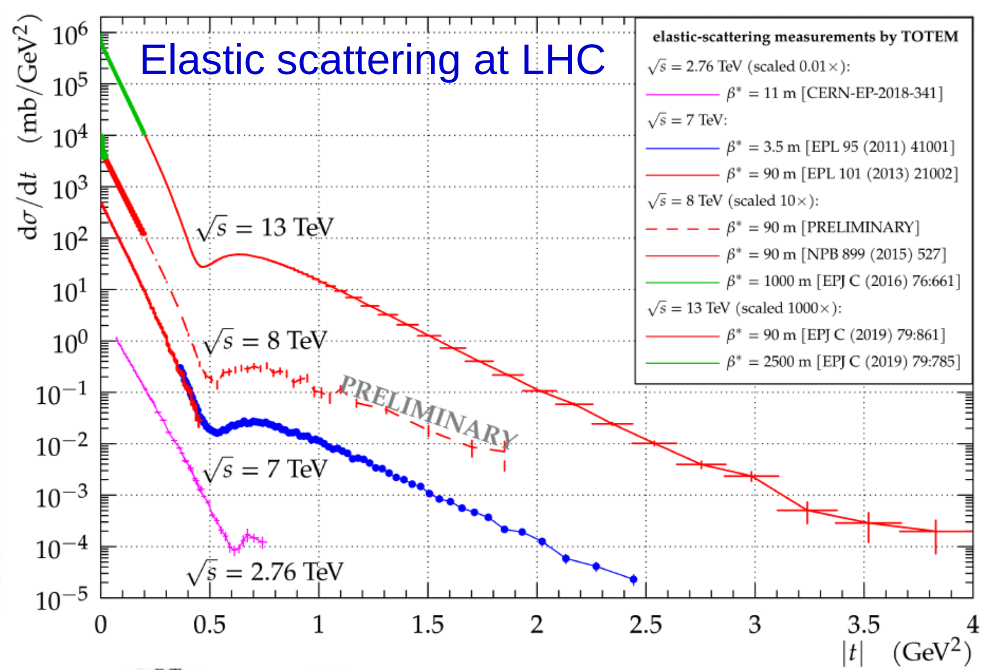
$B \sim R^2$(radius of obstacle)

Particle physics:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}(0)e^{-B|t|} \sim \frac{d\sigma}{dt}(0)(1\text{-}B|t|)$$

$|t| \sim \theta^2$ at high energies



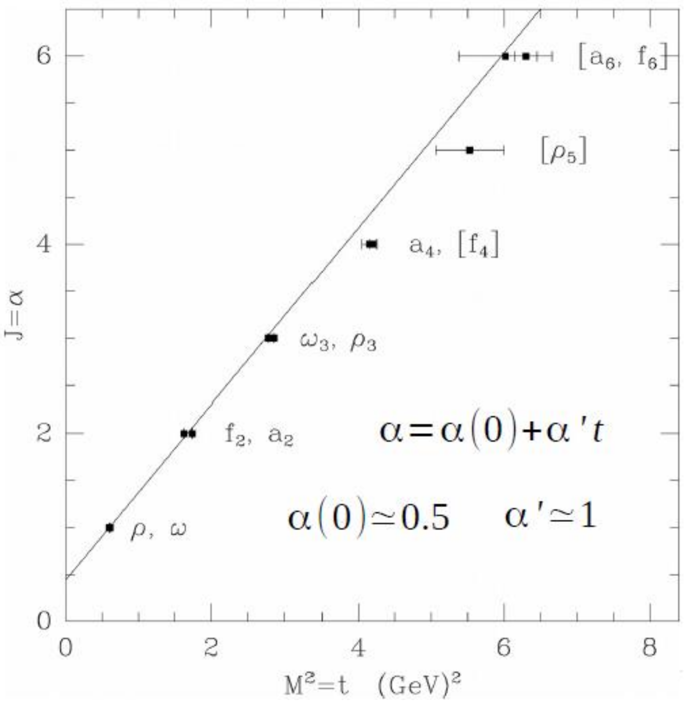


Definition of Diffraction in HEP

1) Interactions where no quantum numbers between colliding particles are exchanged

2) Presence of Large Rapidity Gap (non-exponentially suppressed) in the final state

Regge theory: describes soft (e.g. σ_{TOT}) and soft diffractive (e.g. Single Diffraction) phenomena using unitarity and analyticity of S-matrix & crossing symmetry and Regge trajectories



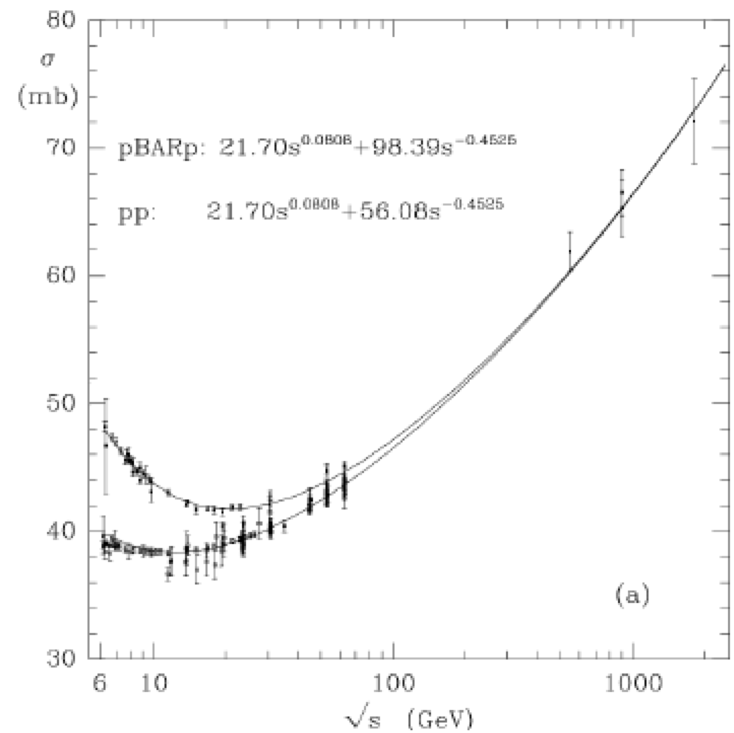
$f_2: P=+1, C=+1, G=+1, I=0$
$\rho: P=-1, C=-1, G=+1, I=1$
$\omega: P=-1, C=-1, G=-1, I=0$
$a_2: P=+1, C=+1, G=-1, I=1$

Asymptotic behavior of amplitude for t=fixed and s→∞ :

$A(s,t) \sim s^{\alpha(t)}$

$\sigma_{TOT} \sim s^{\alpha(0)-1}$

(from optical theorem $\sim 1/s \, \mathrm{Im}\, A_{el}(s,t=0)$)



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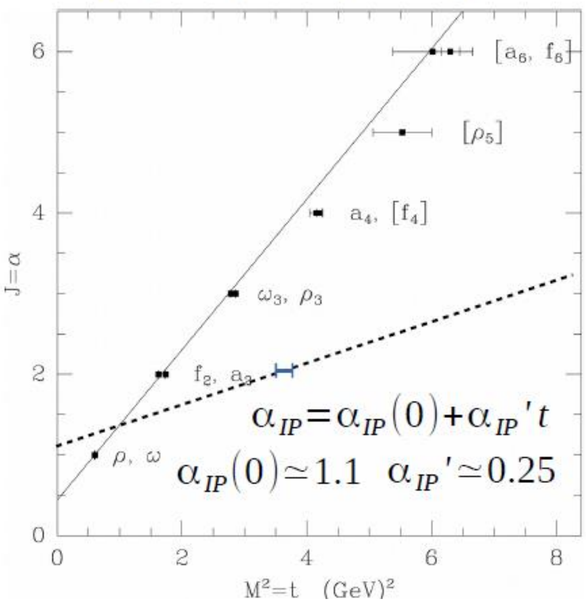
$IP: P=+1, C=+1, G=+1, I=0$



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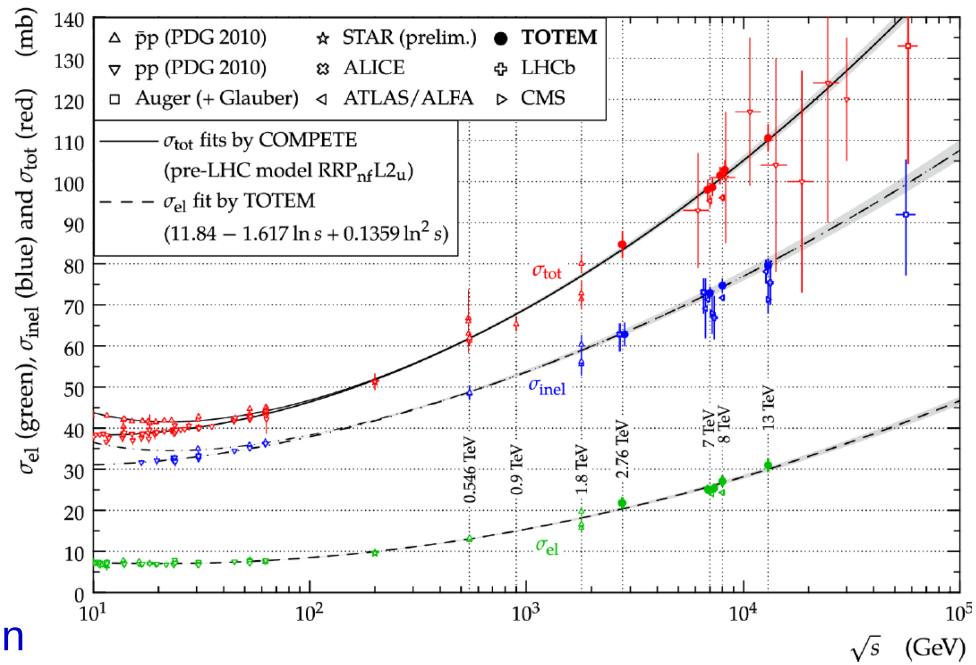
To describe the rise of σ_{TOT} with s, a new trajectory, Pomeron, was introduced. It has quantum numbers of vacuum.

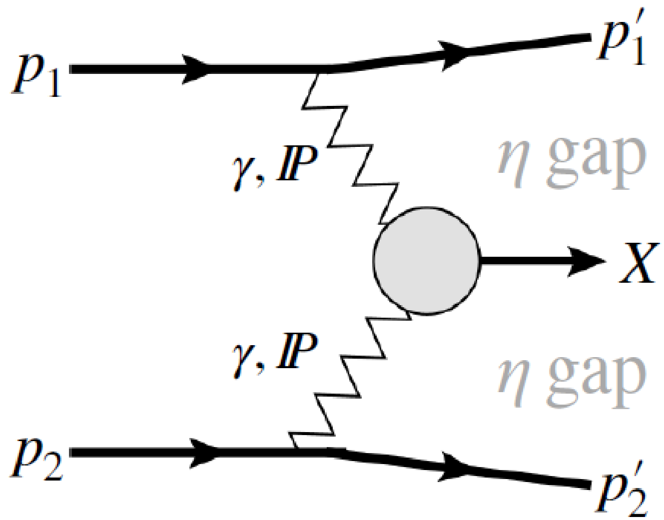
$$\sigma_{TOT} = As^{0.0808} + Bs^{-0.4525}$$

Pomeron ↗ Reggeon ↖



Special case: Exclusive production

$$p + p \rightarrow p \underset{\text{gap}}{\oplus} X \underset{\text{gap}}{\oplus} p$$



$$\xi_1 = \frac{\Delta p_1}{p}$$ **fractional momentum loss**

$$M_X = \sqrt{\xi_1 \xi_2 s} \quad y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$

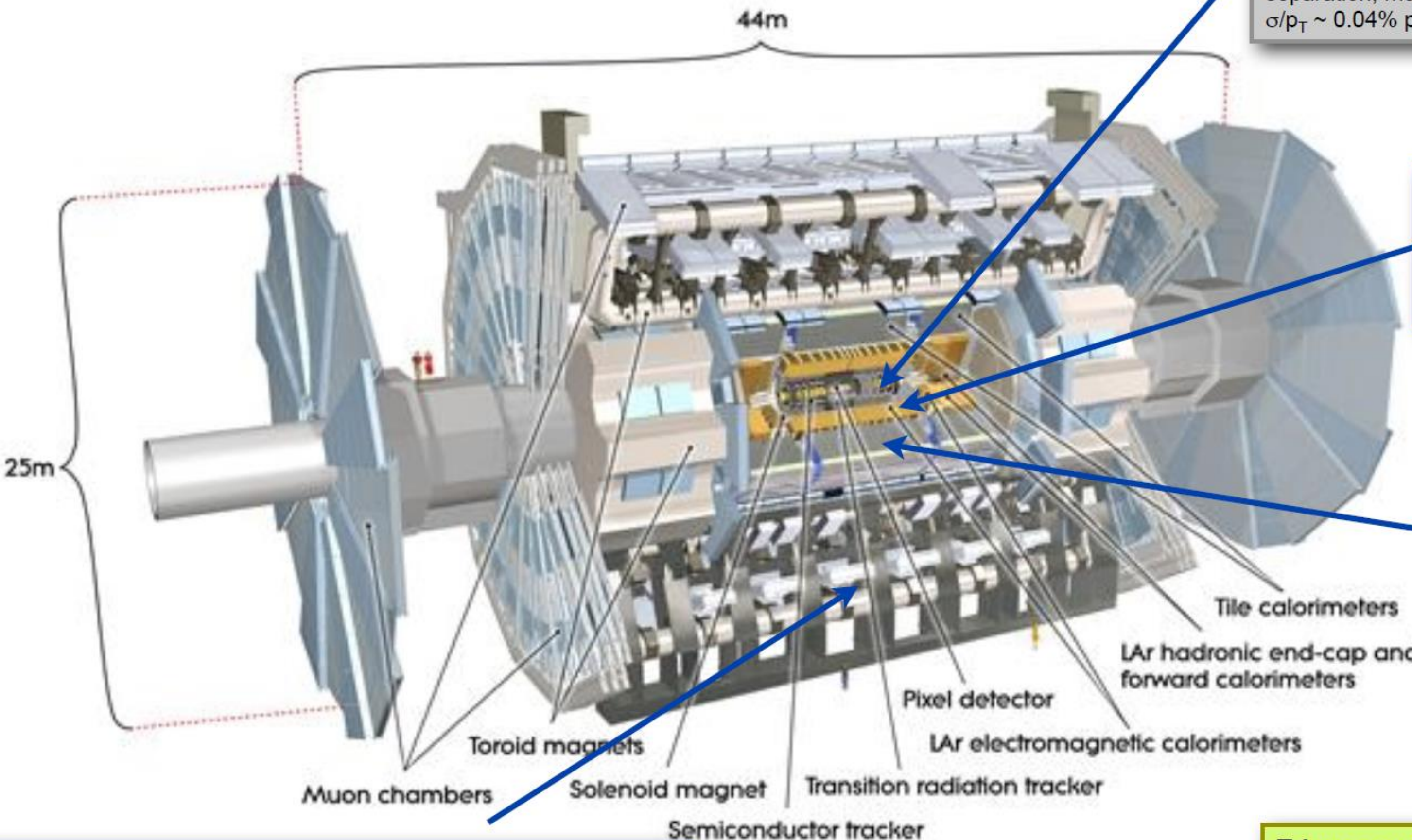
$$\xi_2 = \frac{\Delta p_2}{p}$$ **fractional momentum loss**

The ATLAS Detector @ LHC

L ~ 46 m, ∅ ~ 22 m, 7000 tons
~10^8 electronic channels

Inner Tracker ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Trans. Rad. Det.
Precise tracking and vertexing, e/π separation, momentum resolution:
$\sigma/p_T \sim 0.04\%\ p_T\,(\mathrm{GeV}) \oplus 1.5\%$

EM calorimeter:
Pb-LAr Accordion, e/γ trigger, id. and meas., energy res.: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$



HAD calorimetry ($|\eta|<5$): Fe/scintillator Tiles (cen), Cu/W-LAr (fwd). trigger and meas. of jets and $E_{T,miss}$, energy res.: $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

Muon Spectrometer: air-core toroids with gas-based muon chambers.
trigger and meas. with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Trigger system: 3-levels reducing the IA rate from 40 MHz to ~200 Hz

Rapidity gaps in ATLAS detector

- **Large Rapidity Gap (LRG) : $\Delta\eta \sim -\log \xi_X$** → small ξ_X (M_X) ~ big gap

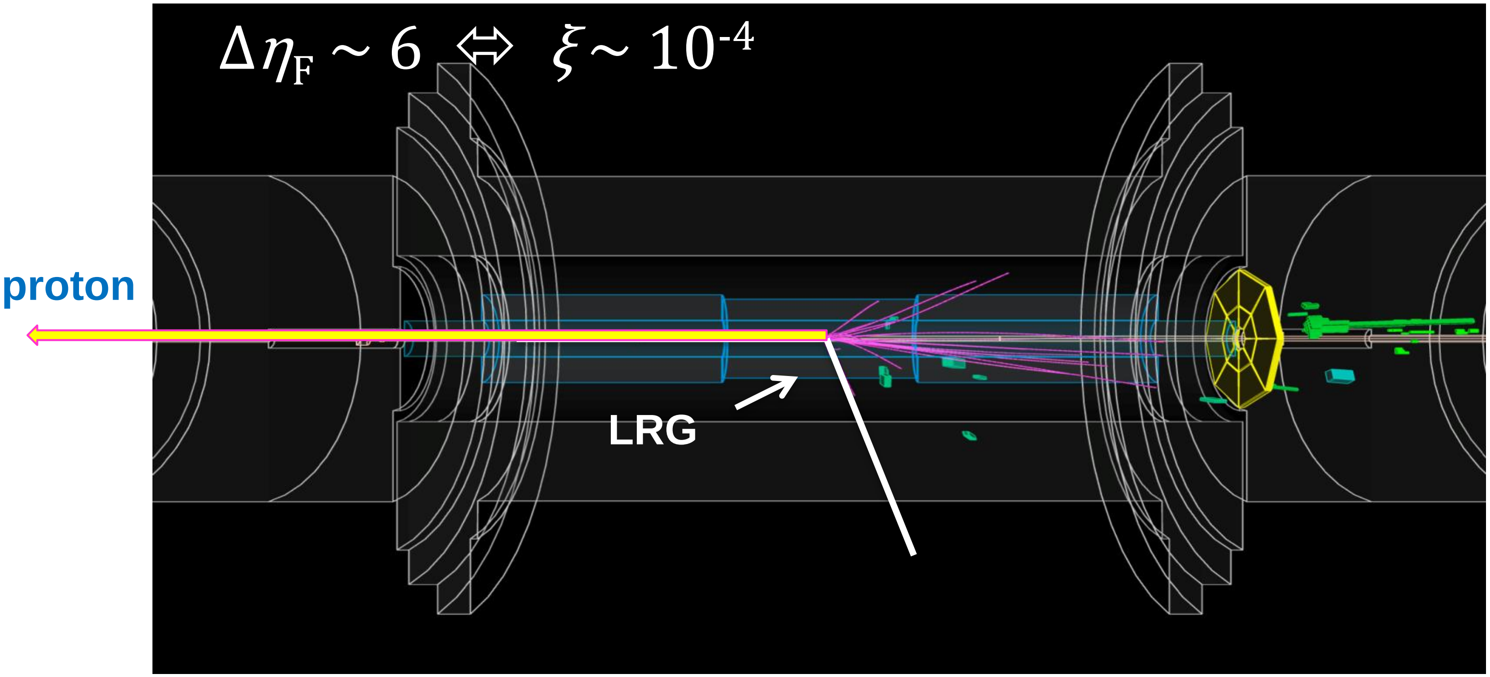
  Region in η devoid of hadronic activity due to the exchange of colorless object (Pomeron)

  $\xi_i = 1 - \frac{E_{p'_i}}{E_{p_i}}$ *(i=1,2)* measured precisely in FPD

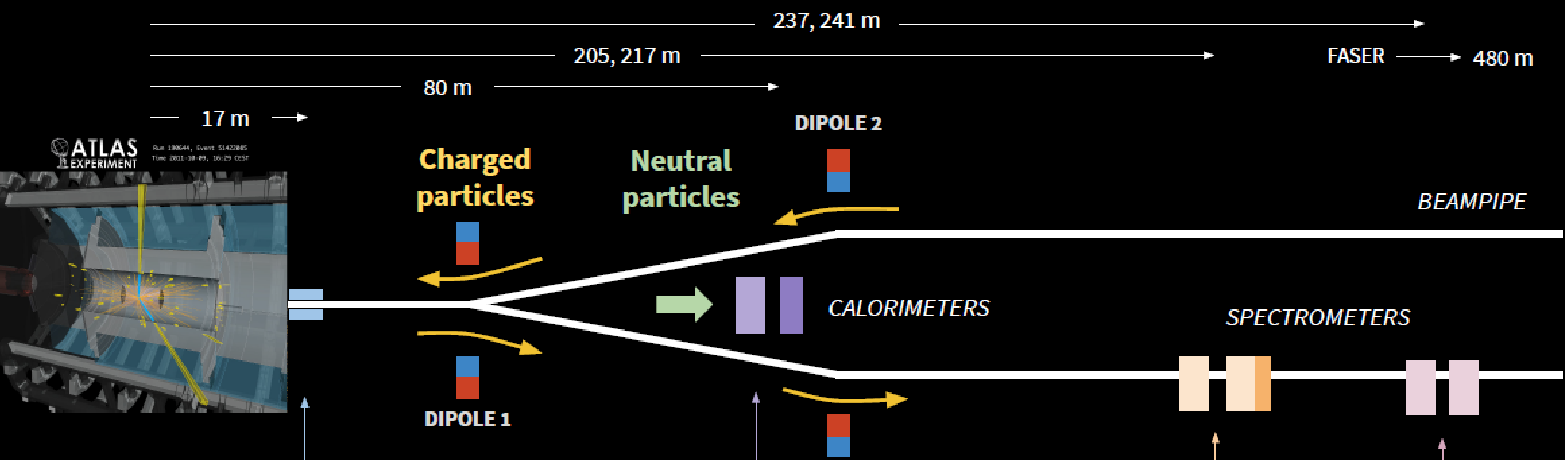
- **Detector-level LRG definition : $\Delta\eta^F$**

  Largest region in η (starting at the edge of the detector η = ±4.8) absent of clusters and tracks

- Non-pileup environment optimal since multiple soft *pp* interactions could fill the gap



LOOKING FORWARD



LUCID

Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

For luminosity measurement

LHCf

LHC Forward

ZDC

Zero Degree Calorimeter

Low-μ, $|\eta| > 8.0$

For cosmic-ray & heavy-ion physics

AFP

ATLAS Forward Proton

Low & high μ

$0.02 < \xi < 0.12$

ALFA

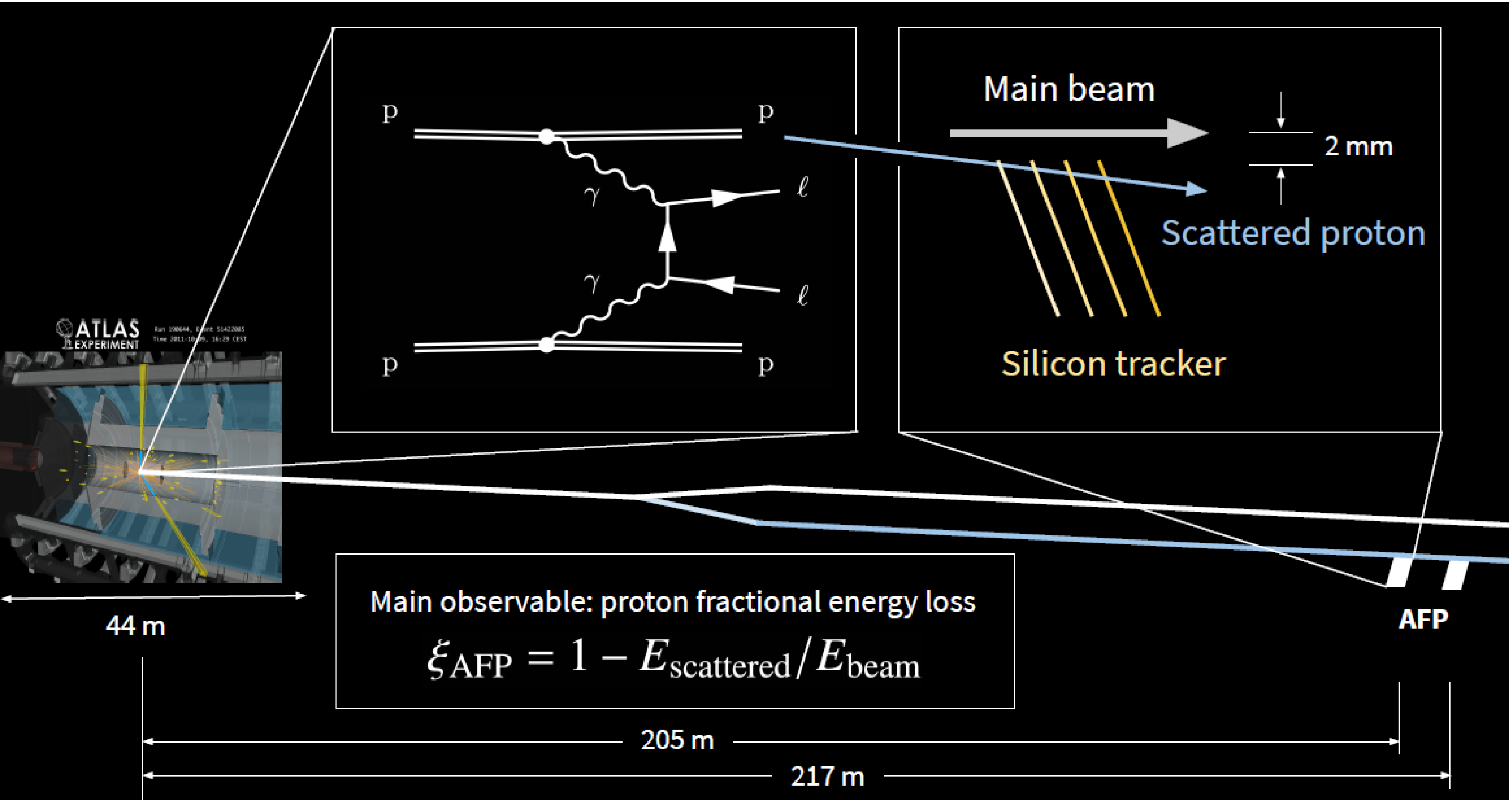
Absolute Luminosity For ATLAS

Low-μ, $0 < \xi < 0.2$

$10.6 < |\eta| < 13.5$

ARP (ATLAS Roman Pot)

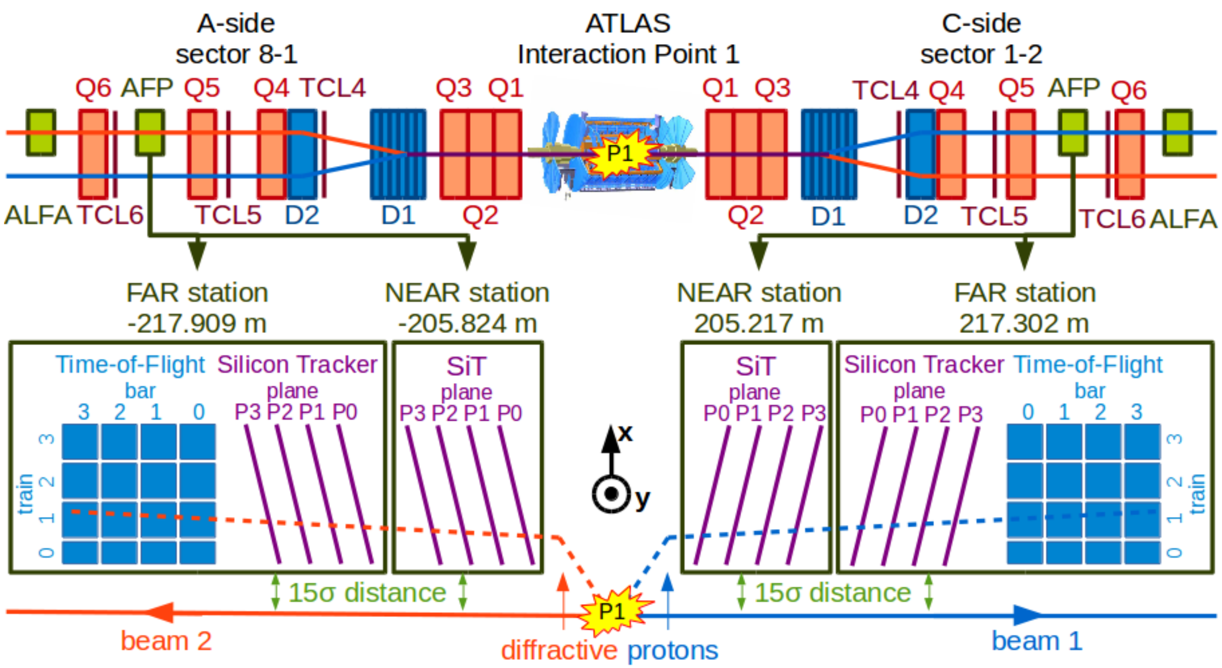
Forward Proton Detector: Principle



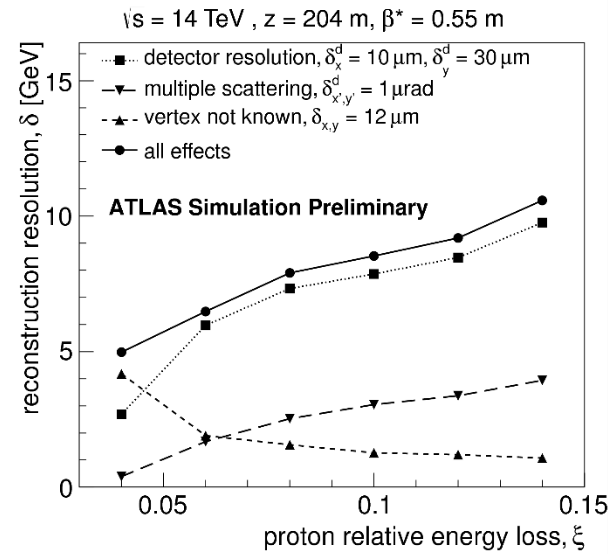
Main observable: proton fractional energy loss

$$\xi_{AFP} = 1 - E_{scattered}/E_{beam}$$

Forward Proton detectors (FPDs) at LHC



AFP

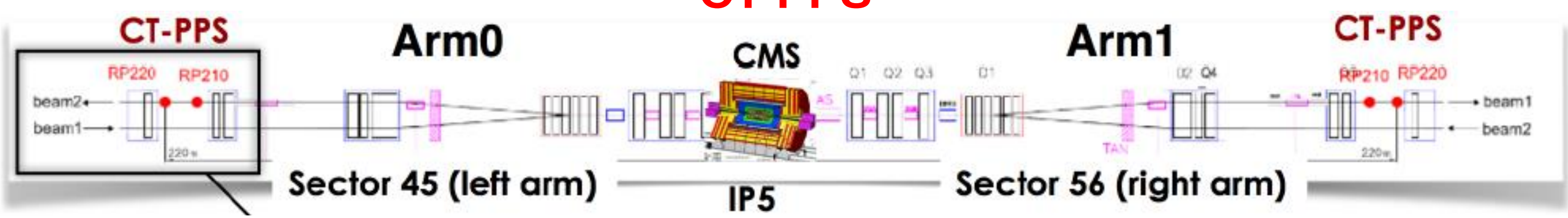


[AFP TDR, CERN-LHCC-2015-009]

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

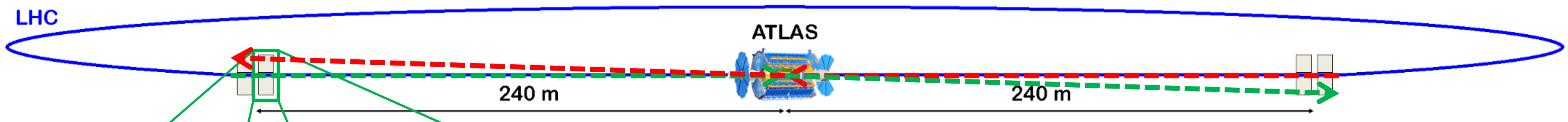
Excellent ξ (hence central system mass) resolution

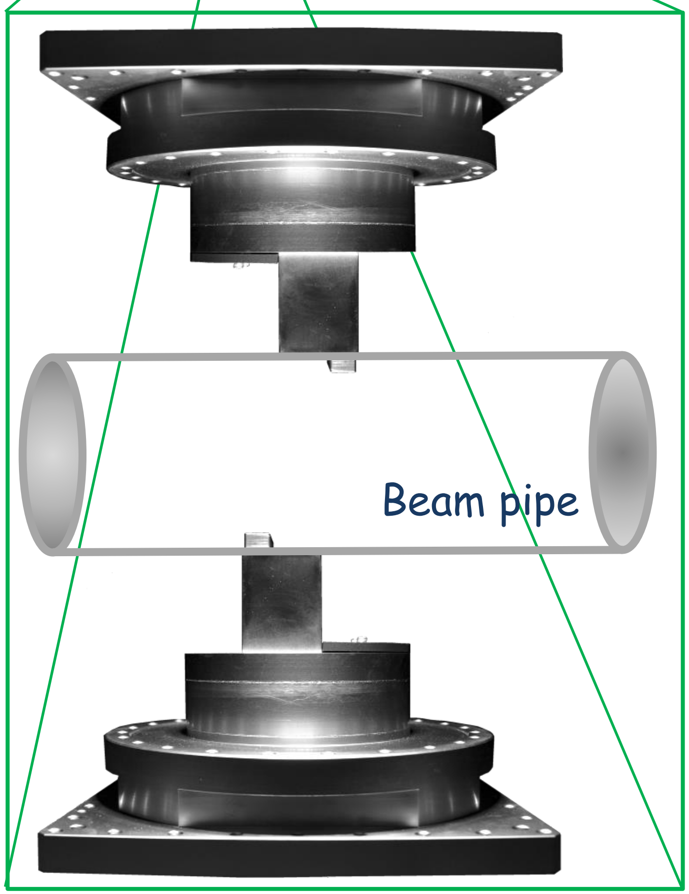
CT-PPS



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

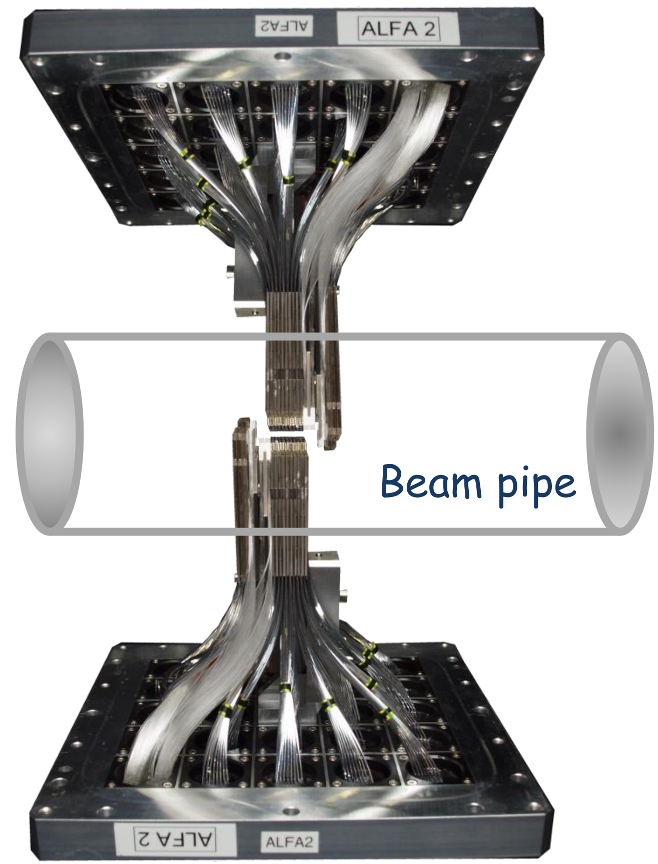
Absolute Luminosity For ATLAS - ALFA



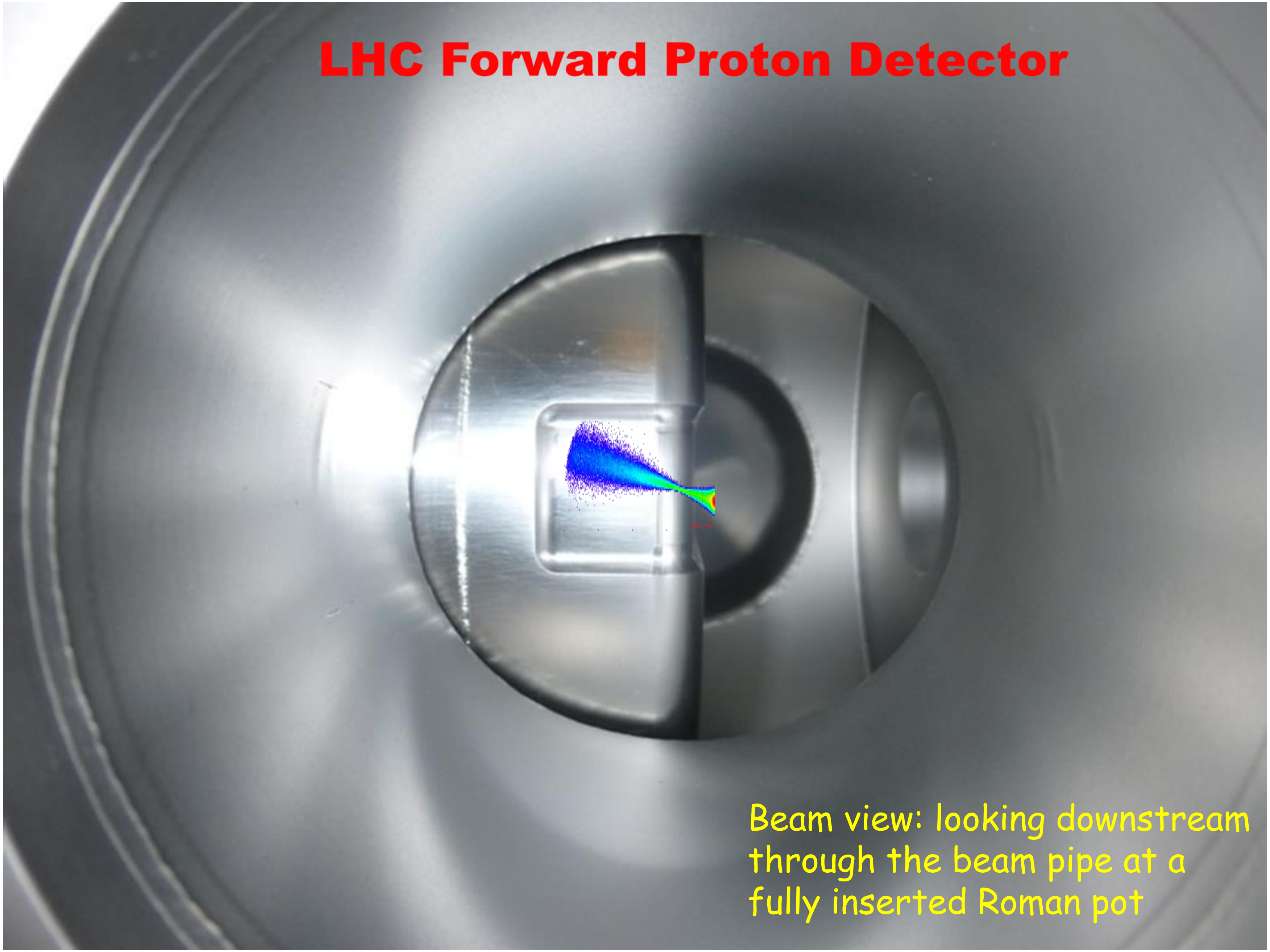


Approach the beam to few mm with Roman Pot

Only used in dedicated high β* runs

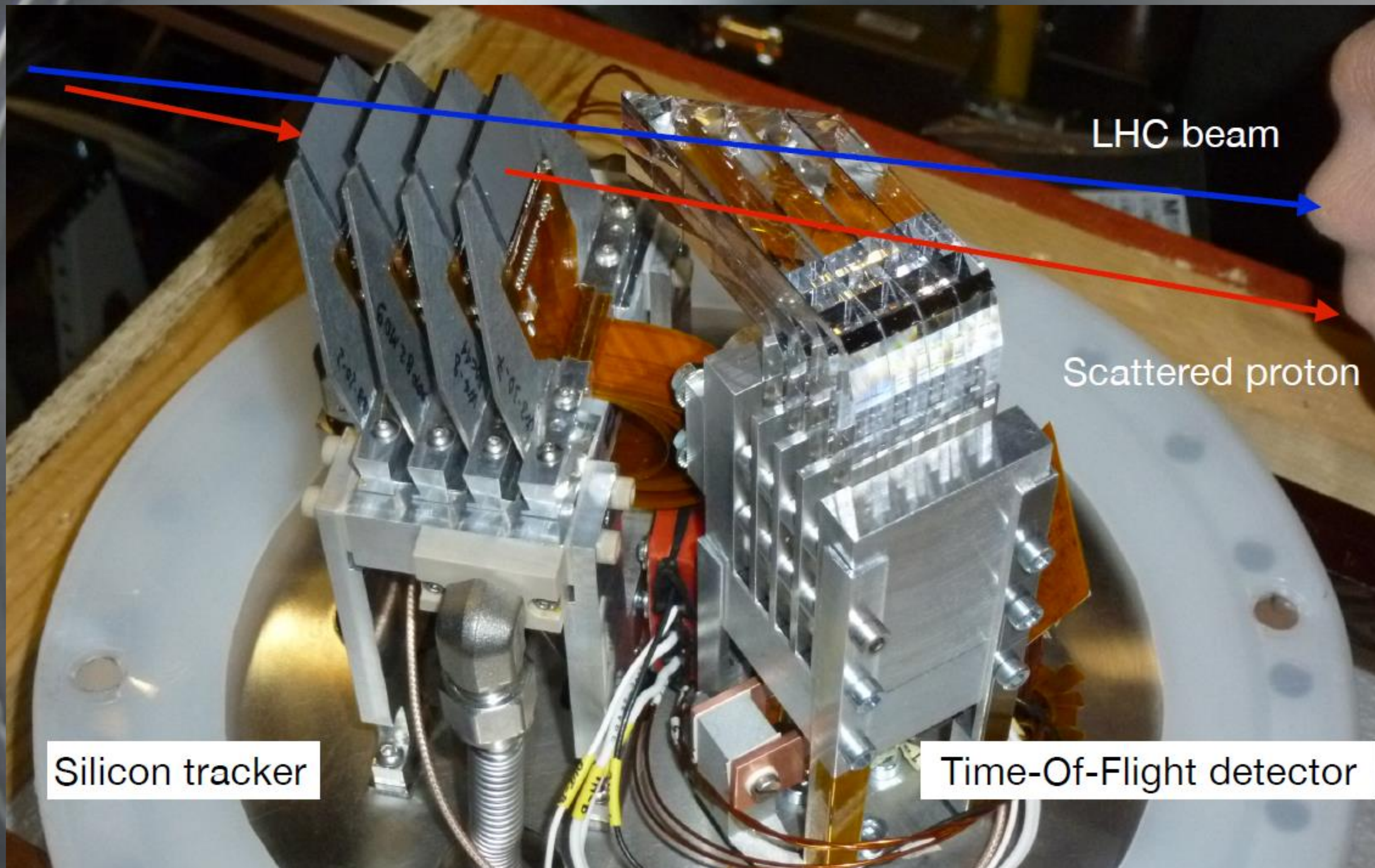


LHC Forward Proton Detector

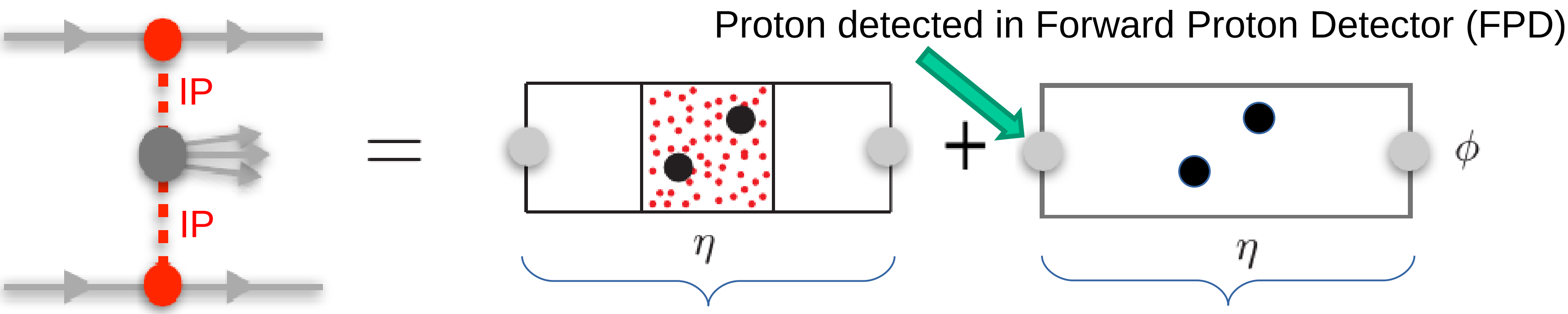


Beam view: looking downstream through the beam pipe at a fully inserted Roman pot

LHC Forward Proton Detector



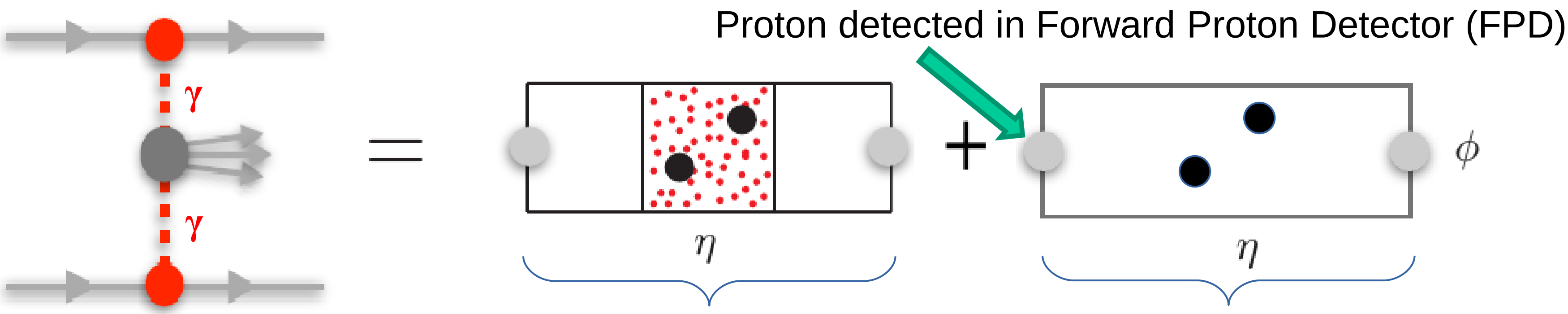
(Semi) exclusive processes



- Semiexclusive production

- Exclusive
- production

(Semi) exclusive processes



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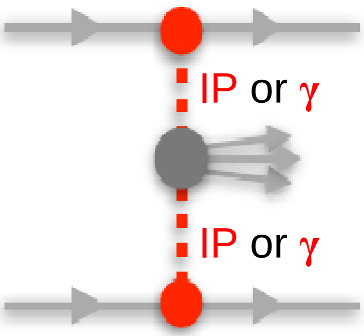

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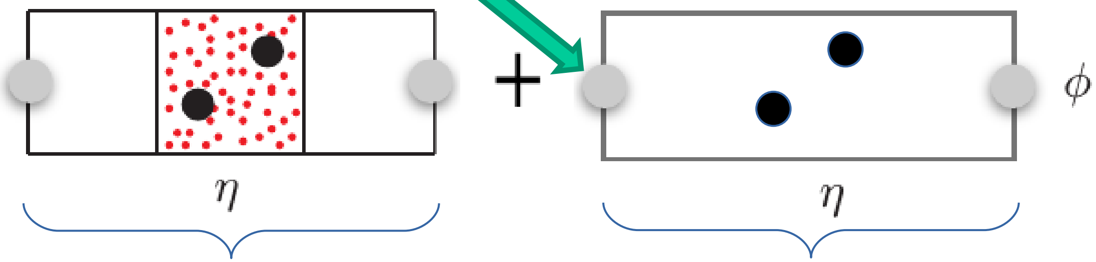
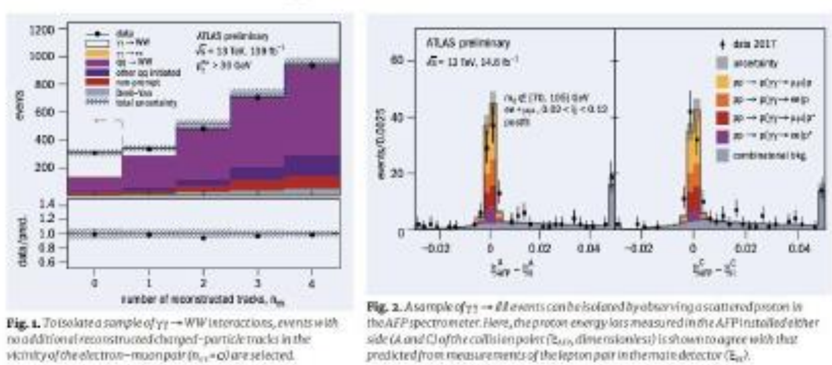


- Semiexclusive production
- Exclusive production

[CERN Courier]



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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

The LHC as a photon collider

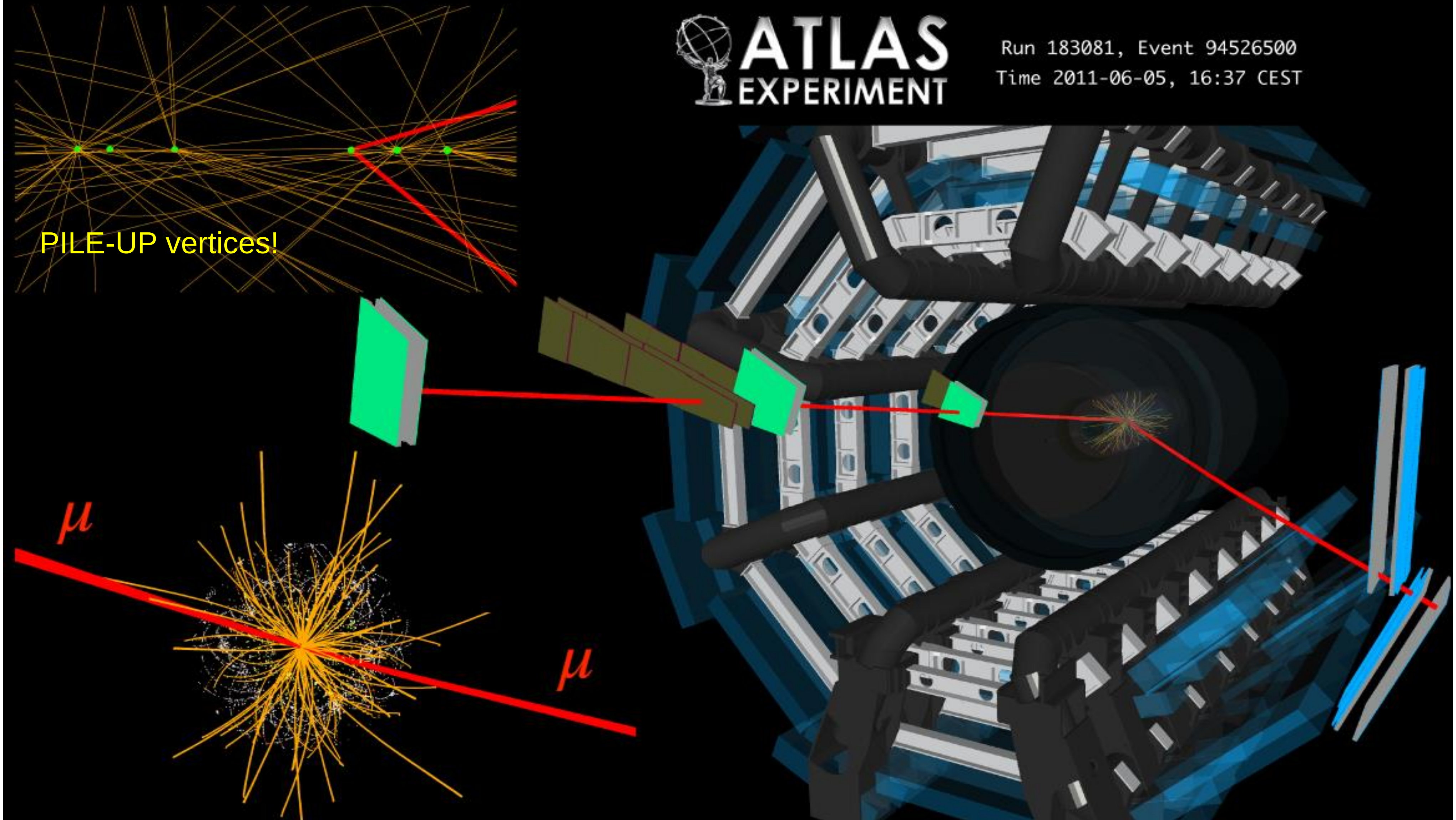
LHC can also serve as a photon collider !

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

without FPDs: γγ→μμ/ee; γγ→WW; γγ→γγ
with FPDs: γγ→μμ/ee; γγ→γγ
(all in presence of pile-up, without timing detectors)

Photon collision

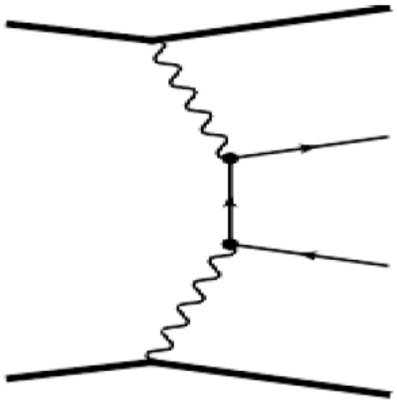
$\gamma\gamma \rightarrow \mu\mu$



LHC is world's highest energy photon collider

Exclusive processes in proton-proton collisions

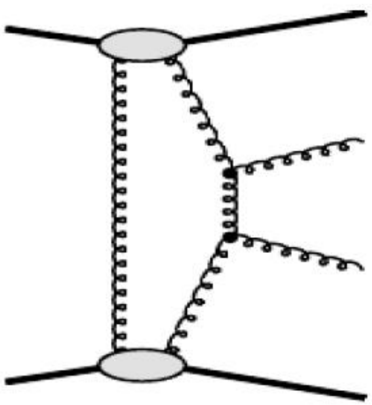
Photon-induced (QED)



1. Photon flux derived from EM form factors (measured precisely)
2. QED Matrix element
3. Soft survival probability (S^2 ~ 1.0 since p-p impact parameter large)

- Both outgoing protons stay intact (can be detected in FPD)
- No color flow between incoming protons in S^2 fraction of events
- Final state particles and nothing else in central detector
- Important constraints on the kinematics of final state

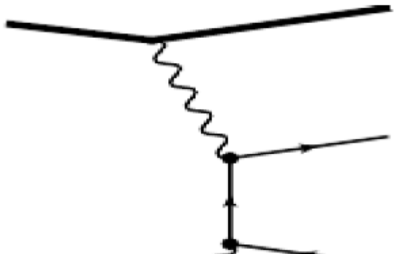
Pomeron-induced (QCD)



1. Gluon un-integrated PDF (2 couplings to each proton)
2. Sudakov suppression (prob of no extra g radiation from incoming g)
3. QCD Matrix element (perturbative QCD thanks to large energy scale)
4. Soft survival probability (S^2 << 1 since p-p impact parameter small)

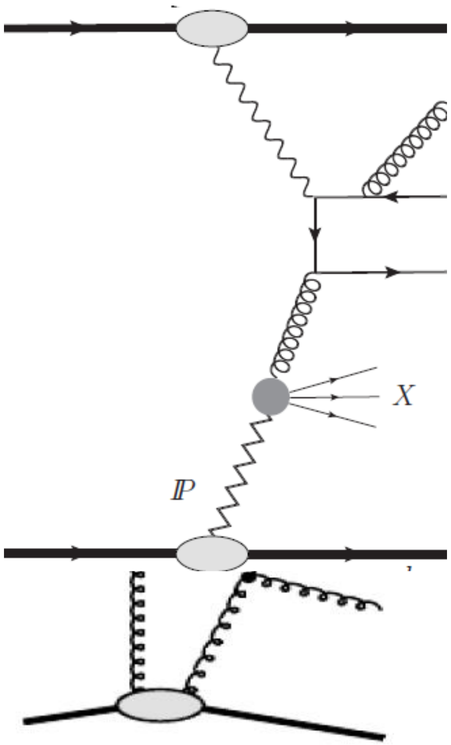
Exclusive processes in proton-proton collisions

Photon-induced (QED)



1. Photon flux derived from EM form factors (measured precisely)
2. QED Matrix element
3. Soft survival probability ($S^2 \sim 1.0$ since p-p impact parameter large)

Photon+Pomeron-induced



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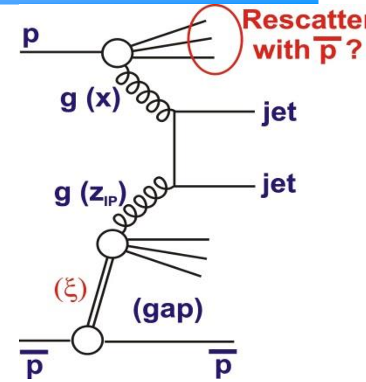
Soft survival probability S²

- Exclusive final state in central detector. But protons may interact in addition. S^2 = probability of no additional inelastic p-p interactions (no so called Underlying Event)



- Historically S^2 introduced to explain Tevatron measurements:

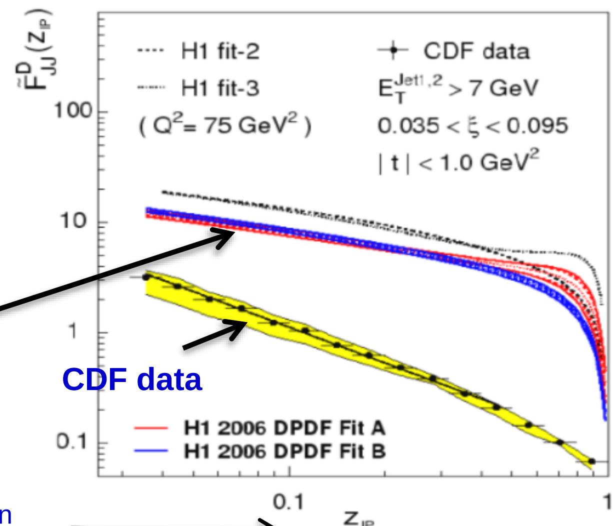
1) HERA (ep collisions): precise measurements of diffractive PDFs (PDFs under condition that proton remains intact) → such dPDFs are universal for ep interactions.

2) However: Tevatron ($p\bar{p}$ collisions) measured <u>10x smaller</u> dPDFs than HERA-based dPDFs predictions for Tevatron conditions. Explanation: rescattering of proton with anti-proton.

- $S^2 << 1.0$ typical for hadron-hadron collisions.

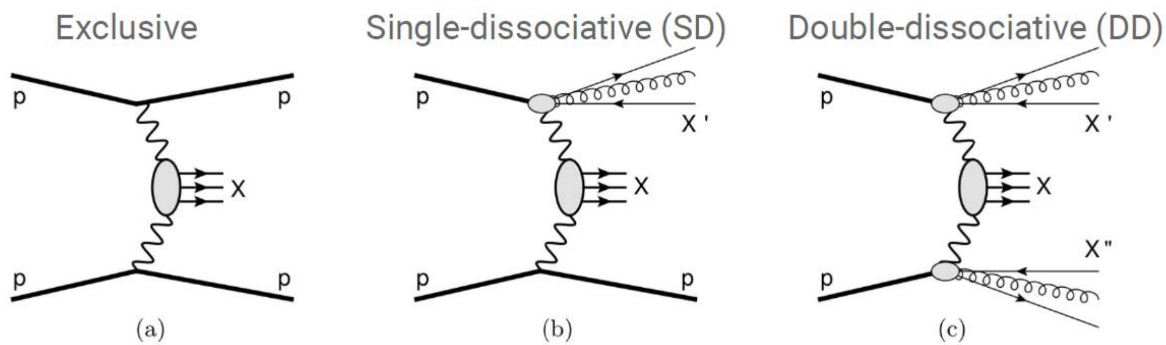
- $S^2 \sim 0.1$ measured for dijets at LHC
ATLAS: *Phys.Lett.B 754 (2016) 214*
CMS: *Phys. Rev. D 87 (2013) 012006*

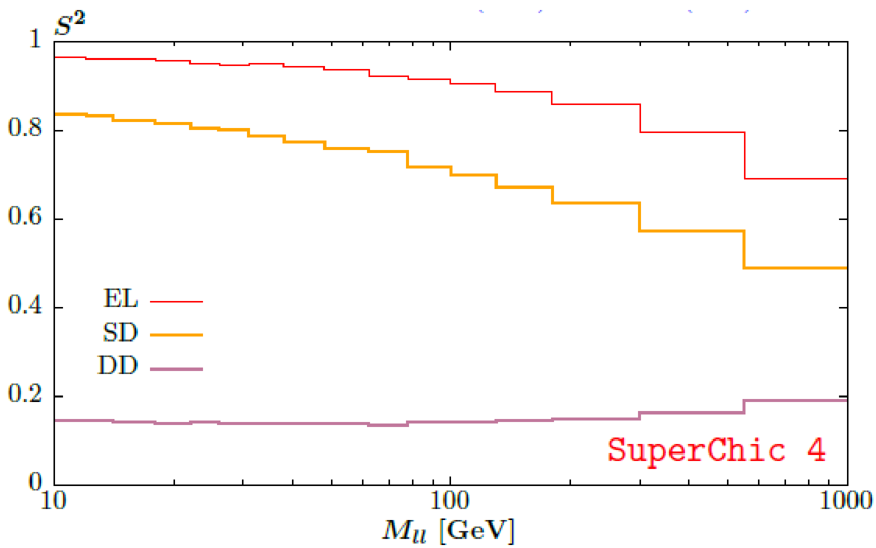
- *S^2 is process and kinematics dependent, see next slide*

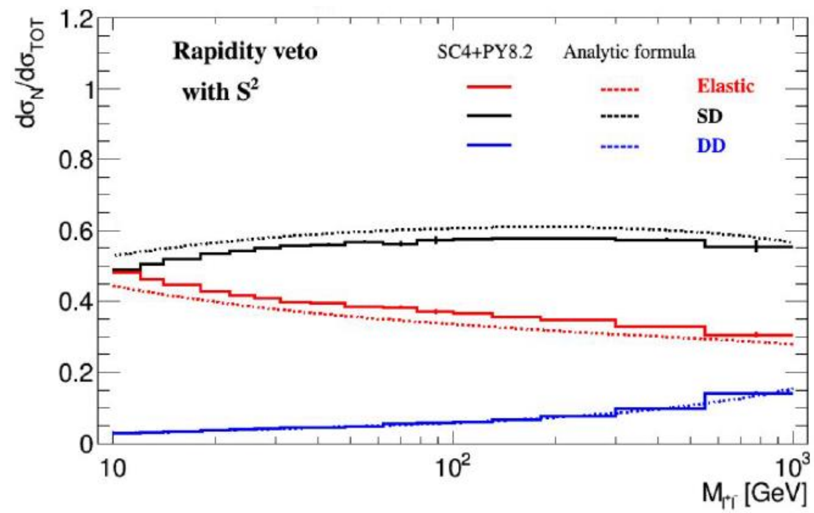


S^2: for example $\gamma\gamma \to ll$

EPJC 80 (2020) 925







$S^2(EL) > S^2(SD) > S^2(DD)$: expected, since
$b_\perp(EL) > b_\perp(SD) > b_\perp(DD)$.

$Q^2 \sim 0 \to b_\perp(EL)$ large $\to S^2 \sim 1$

Experimental evidence of (semi) exclusive processes

❑ TEVATRON:

- **Exclusive di-jets: $gg \rightarrow jj$:**

CDF *(PRD77 (2008) 052004)*
D0 *(PLB705 (2011) 193)*

❑ LHC:

- **Exclusive di-leptons $\gamma\gamma \rightarrow \mu\mu/ee$:**

without FPDs: ATLAS *(PLB **749** (2015) 242)*
ATLAS *(PLB **777** (2018) 303)*
with FPDs: ATLAS *(PRL **125** (2020) 261801)*
CMS, TOTEM *(JHEP **07** (2018) 153)*

Exclusive top: $\gamma\gamma \rightarrow tt$:
with FPDs: CMS *(JHEP 06 (2024) 187)*

- **Exclusive di-bosons: $\gamma\gamma \rightarrow WW/ZZ$:**

without FPDs: ATLAS *(PLB **816** (2021) 136190)*
with FPD: CMS *(JHEP **07** (2023) 229),* CMS *(EPJC 83 (2023) 827)*

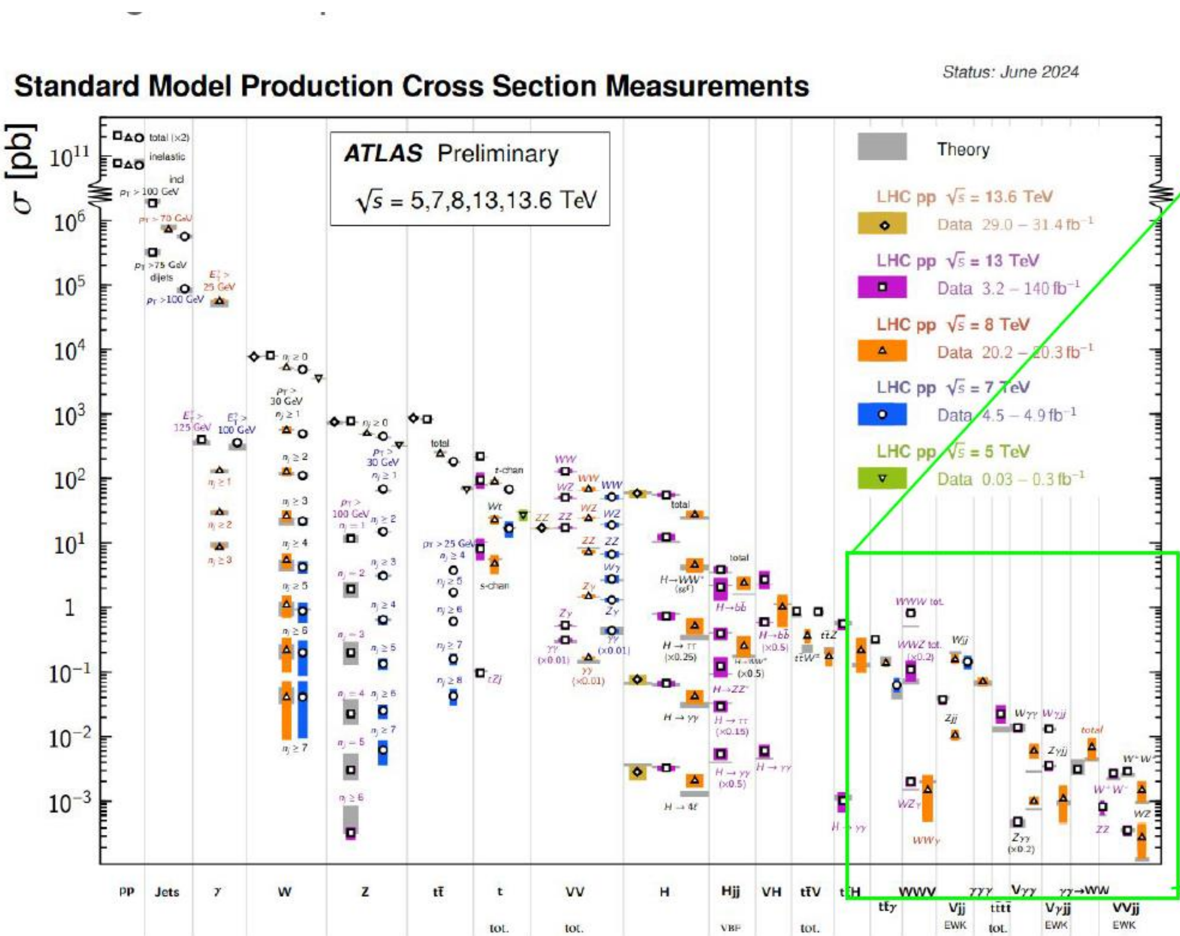
- **Exclusive di-photons: $PbPb \rightarrow \gamma\gamma \rightarrow \gamma\gamma$:**

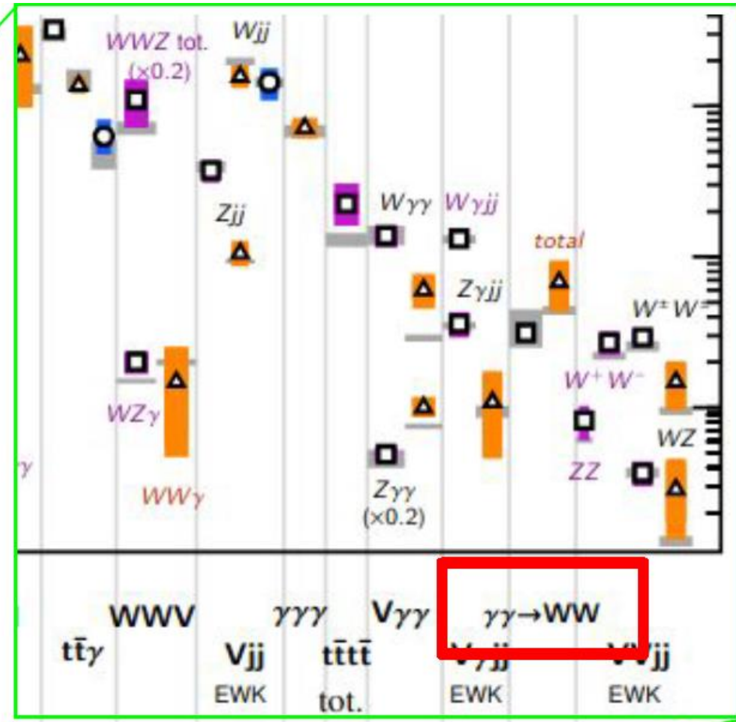
CMS *(PLB **797** (2019) 134826)*
ATLAS *(PRL **123** (2019) 052001)*
ATLAS *(JHEP **03** (2021) 243)*

$pp \rightarrow \gamma\gamma \rightarrow \gamma\gamma$:
with FPDs: ATLAS *(JHEP 07 (2023) 234)*
with FPDs: CMS *(PRL 129 (2022) 011801)*
with FPDs: CMS *(PRD 110 (2024) 012010)*

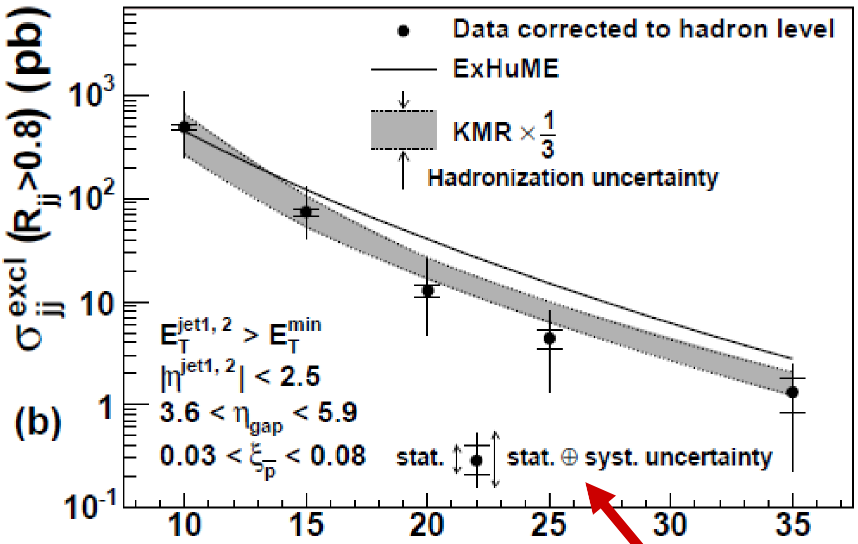
Cross sections of exclusive processes

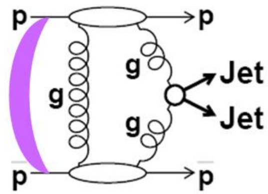
Did I mention that exclusive processes are rare??

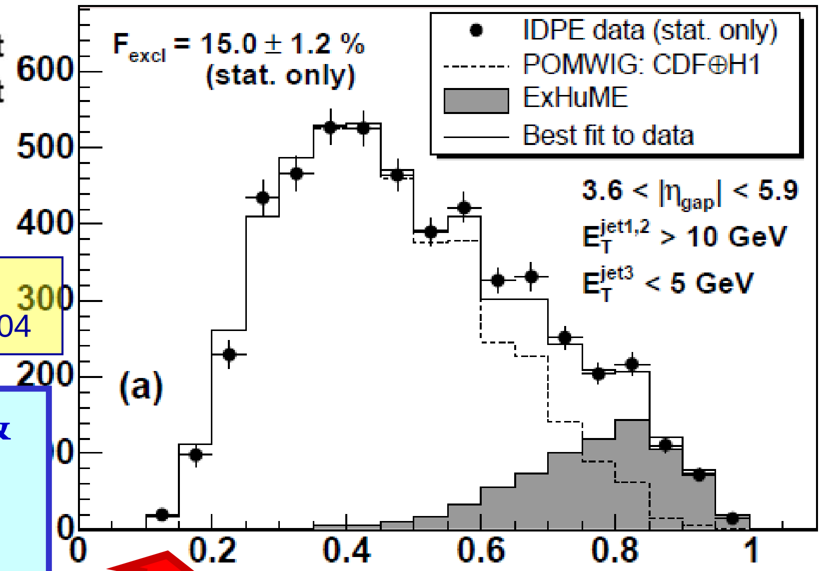




Evidence of exclusive dijets at Tevatron





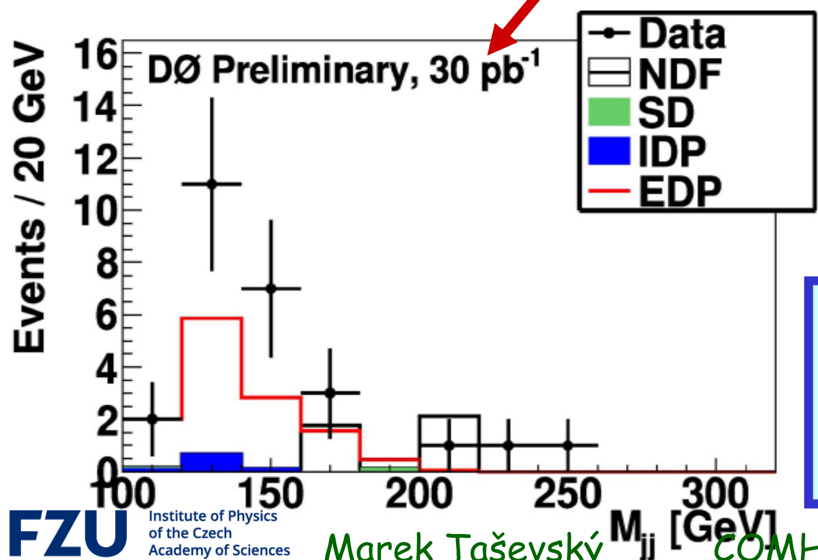


CDF Collaboration
PR D77 (2008) 052004

E_{Tjet} > 10 GeV & R_{JJ} >0.8:
CED with significance of 6σ

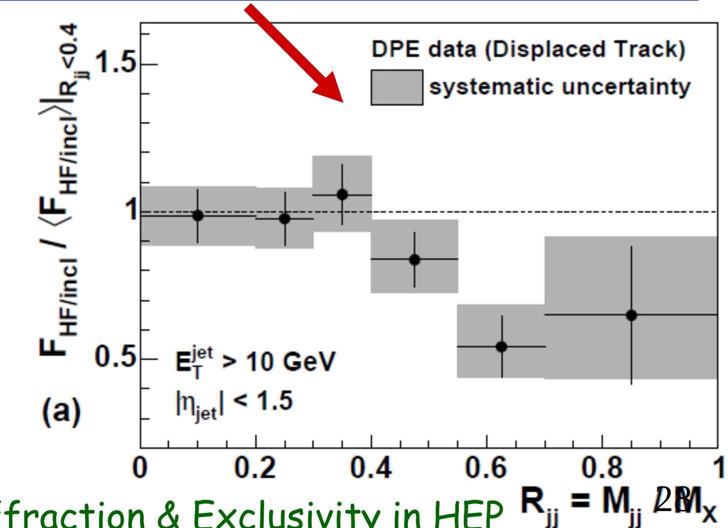
Data consistent with KMR predictions

Suppression of $b\bar{b}$ production as expected



D0 collaboration
PL B705 (2011) 193

M_{JJ} > 100 GeV! &
exp(-ΣE_T) > 0.85:
CED with significance of 4.1σ



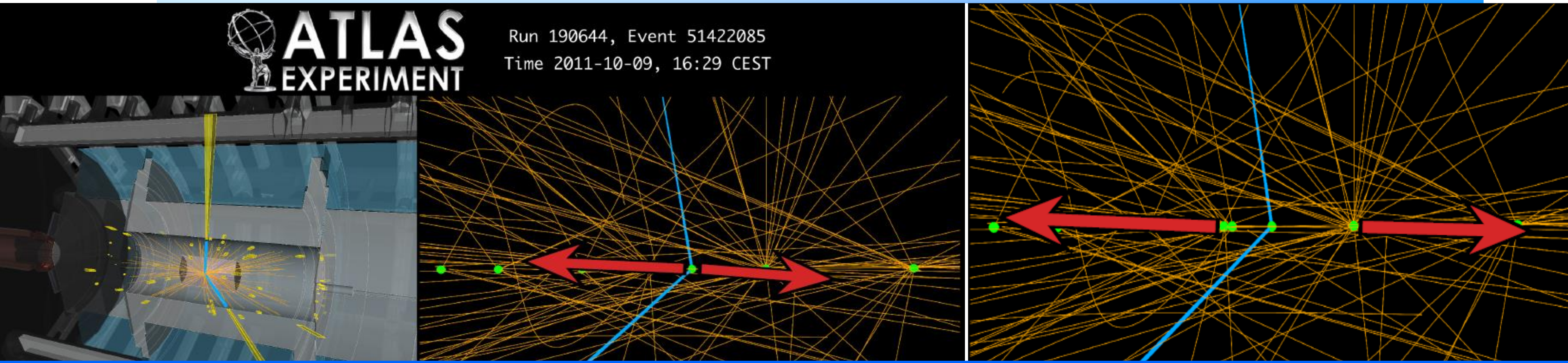
PILE-UP

Did I mention pile-up?

Lots of soft particles produced in numerous vertices!

How can you even think of exclusivity in such an environment??

PILE-UP effects



Pile-up = soft independent interactions in the same bunch crossing whose number rises with increasing instantaneous luminosity → **very dangerous for diffractive and exclusive events by**

1) Producing soft particles in Central detector (CD), influencing efficiencies of various finding algorithms (primary vertex, triggers, tracks, jets, leptons, W-bosons, etc.)

2) Producing forward protons which can end up in the acceptance of Forward proton detectors (FPD) (due to large cross section of soft Single-Diffraction process)

PU proton from Event 1 detected in FPD + PU proton from Event 2 detected in FPD+ hard-scale activity in central det. from Event 3 = COMBINATORIAL BACKGROUND.

It can be suppressed by:

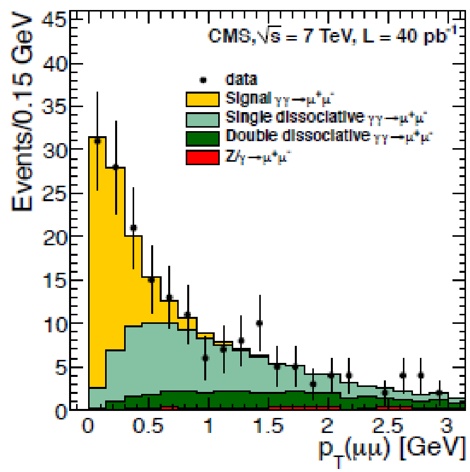
1) Kinematics matching: quantity measured in CD should match that measured in FPD within resolution
2) Primary vertex matching: z_{vtx} found by Time-of-Flight detector should match primary z_{vtx} found in CD
3) Track veto: no additional tracks and vertices in a narrow region (e.g. +-1mm) around primary vertex
4) Properly modelling it using mixed events (or shifted events)

Exclusive $\gamma\gamma \rightarrow ll$ (without FPDs)

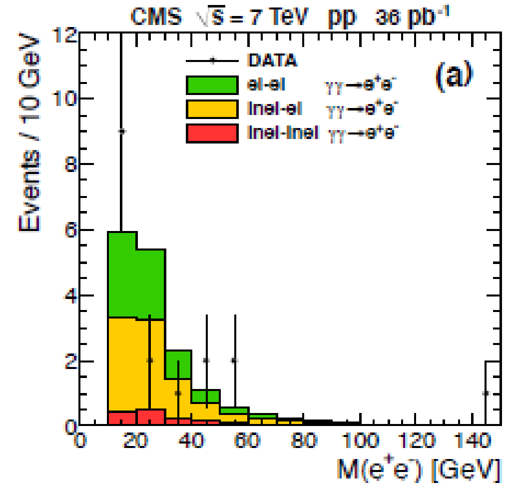
Run 1:

- Veto on additional activity in the whole detector
- Low pile-up

JHEP 01 (2012) 052

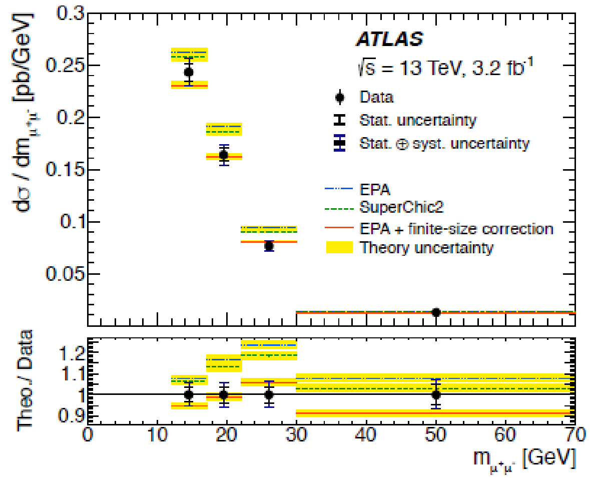


JHEP 11 (2012) 080



Run 2:

- z-vertex veto: no additional tracks and vertices in a +-1mm region around primary vertex
- Standard pile-up

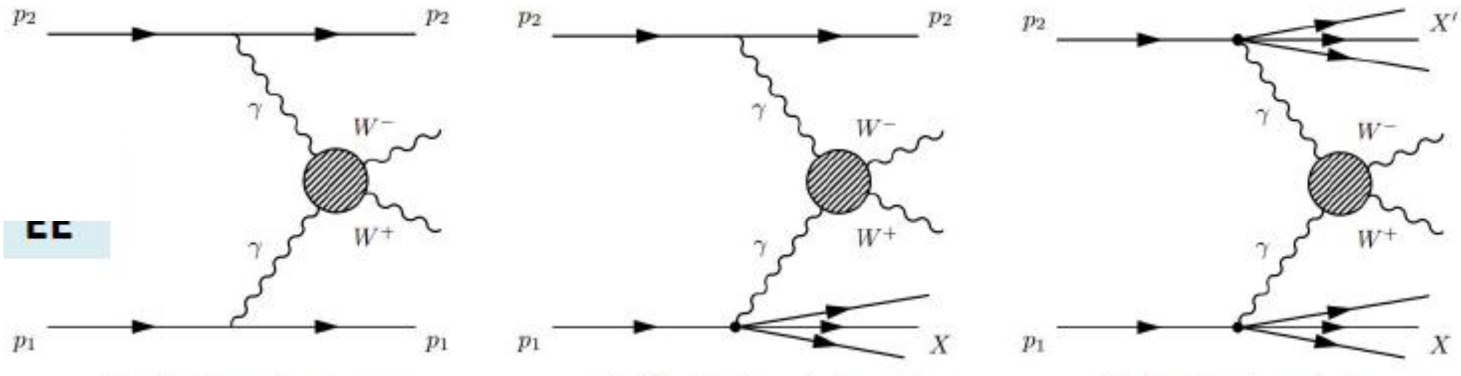


PLB 777 (2018) 303

PLB 749 (2015) 242

Exclusive $\gamma\gamma \rightarrow WW$ (without FPDs)

PLB 816 (2021) 136190

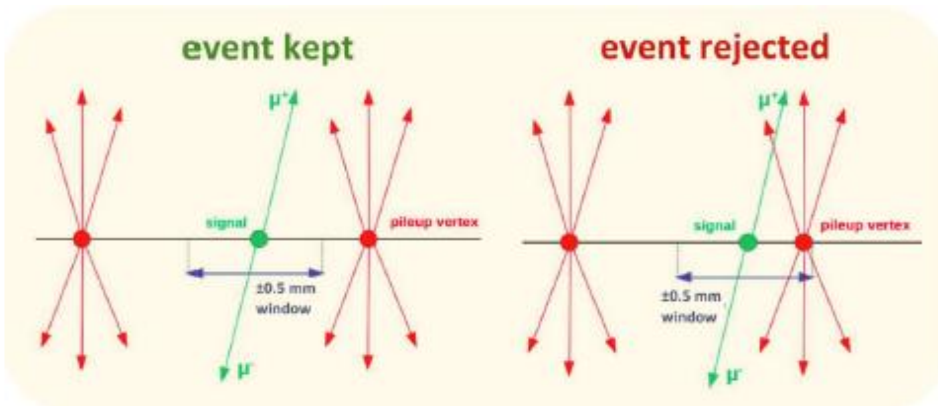


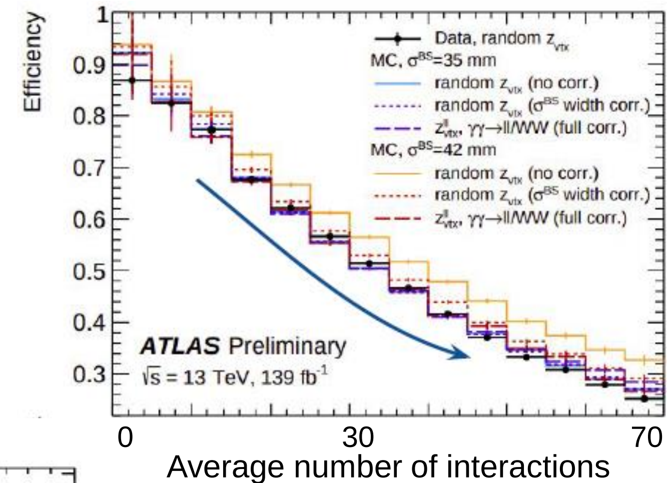
(a) Elastic production (EE) (b) Single-dissociation (SD) (c) Double-dissociation (DD)

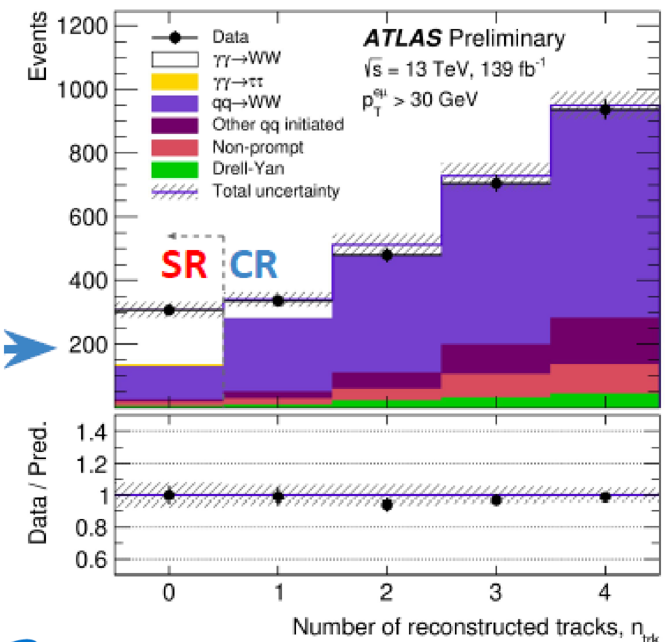
- Process can only proceed via EW gauge boson couplings at LO → ideal probe for anomalous couplings
- Signal: opposite sign, opposite flavor dilepton: $e^{\pm}\mu^{\mp}$
- p_T^{lep} > 27, 20 GeV; p_T(eμ) > 30 GeV, $m_{e\mu}$ > 20 GeV
- Exclusivity cuts only using Central detector: e.g. track veto (no additional tracks with p_T > 0. 5 GeV in the region +-1mm around primary vtx)
- Dominant background: inclusive qq → WW

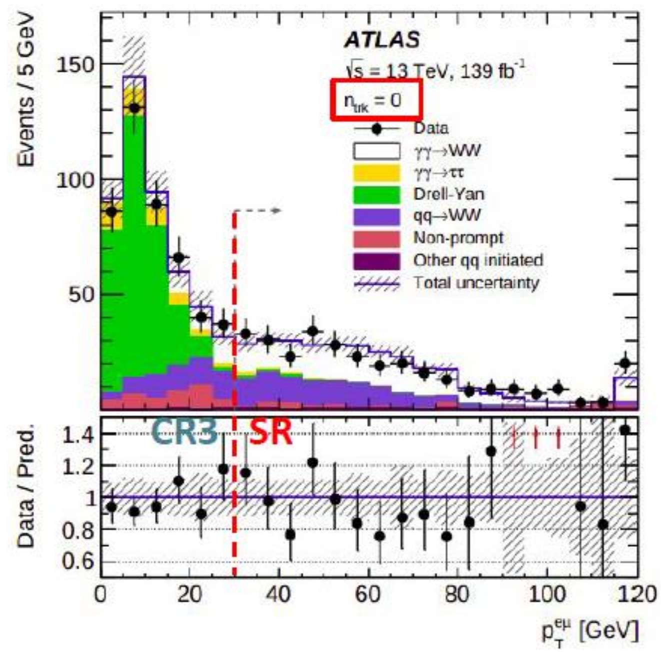
Exclusive $\gamma\gamma \to WW$: Track veto

Track veto = no additional tracks (p_T>0.5 GeV) in the region +-1mm around primary vertex.
It suppresses inclusive background (and also pile-up effects). Efficiency drops with incr. pile-up.









- Background hypothesis rejected with significance of 8.4σ
- Rare process: measured cross section: 3.13 ± 31(stat) ± 28(syst) fb

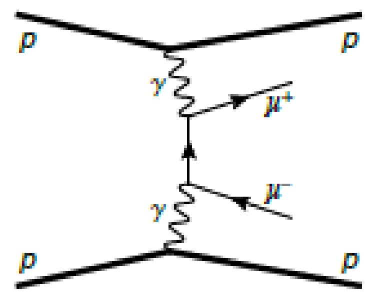
Exclusive $\gamma\gamma \to ll$ (with FPDs)

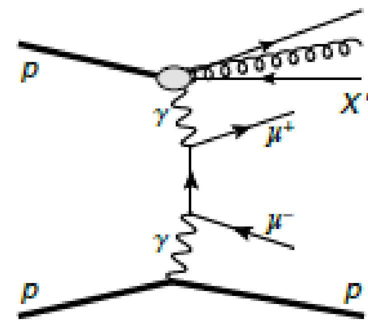
PRL 125 (2020) 26, 261801

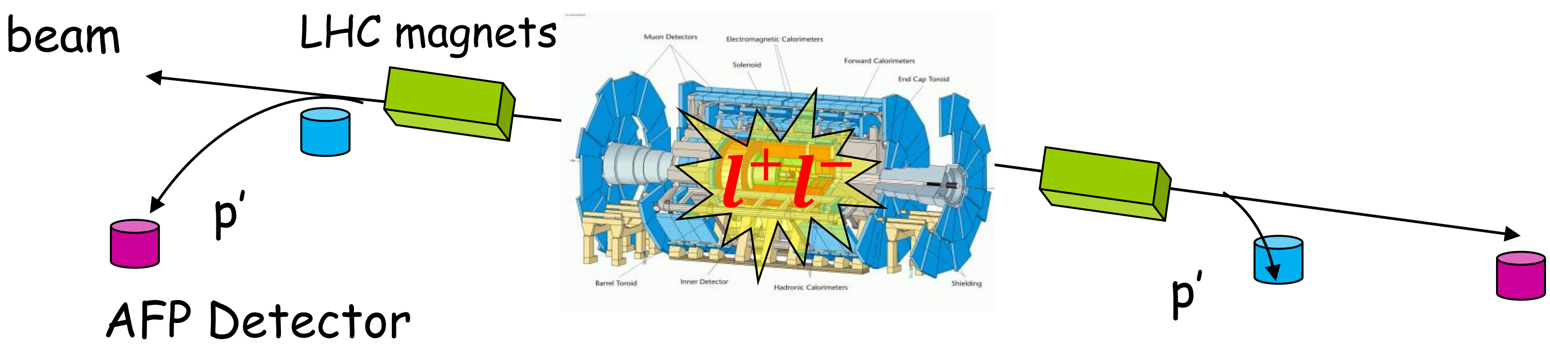
- At least 1 proton tagged required → signal is a sum of pure exclusive and Single-Dissociation

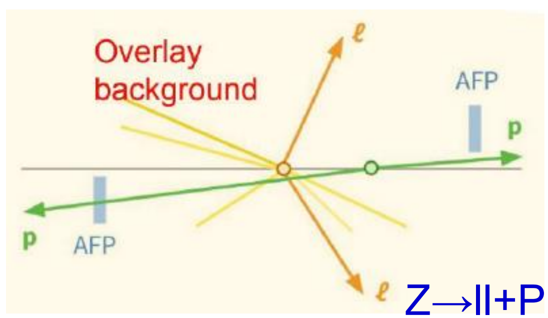
Large rapidity gap

$$pp \to p\gamma\gamma p \to p \,\square\, l^+ l^- \,\square\, p$$

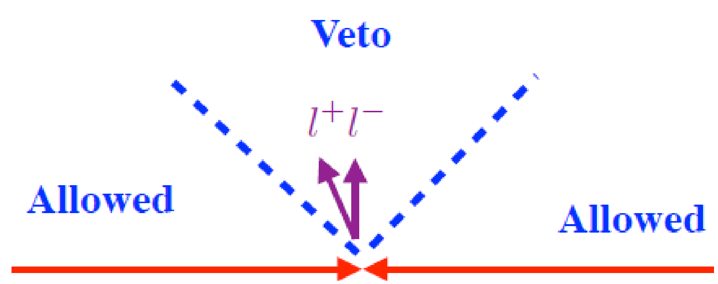






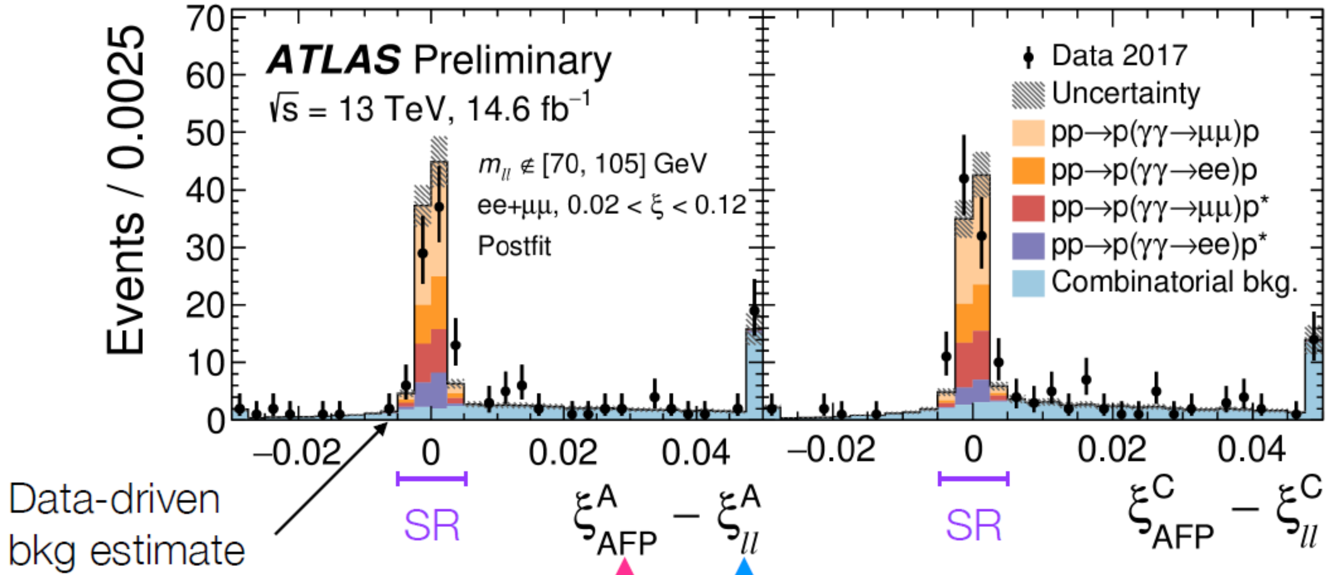


Z→ll+PU



Exclusive $\gamma\gamma \rightarrow ll$ (with FPDs)

Observe ee+p and $\mu\mu$+p > 9σ in each channel



Measured with AFP

$$\xi_{\mathrm{AFP}}^{\mathrm{A,C}} = 1 - E_{\mathrm{forward}}/E_{\mathrm{beam}}$$

Measured with central ATLAS

$$\xi_{ll}^{\pm} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}$$

16

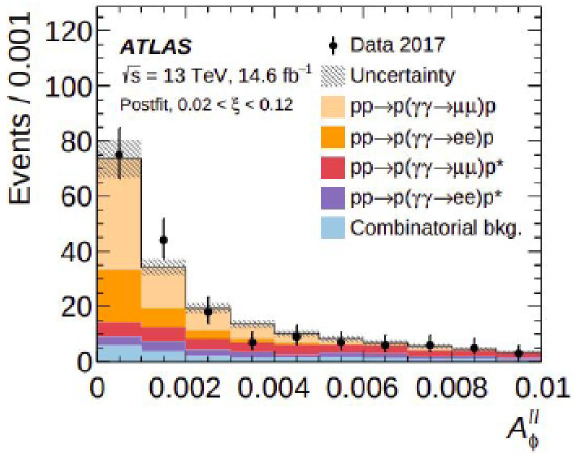
SR = Signal Region = Kinematics matching: $|\xi_{AFP} - \xi_{ll}| < 0.005$ required

Exclusive $\gamma\gamma \rightarrow ll$ (with FPDs)

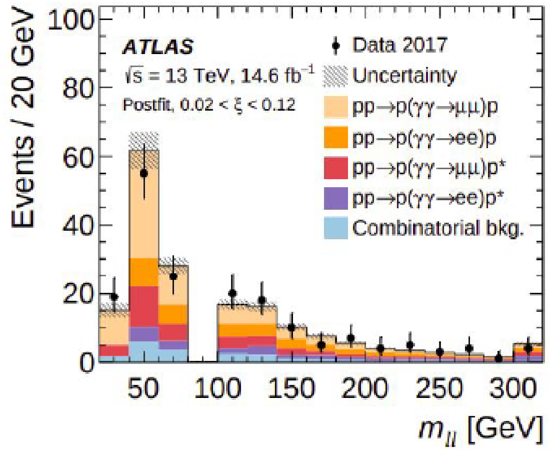
[PRL 125 (2020) 261801]

The background hypothesis rejected with a significance of 9.7σ in the *ee* and 13.0σ in the *μμ* channel

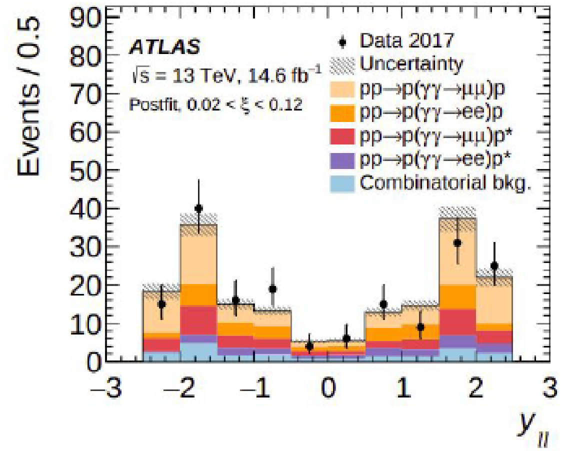
Dilepton acoplanarity



Dilepton mass



Dilepton rapidity



Cross section measurement

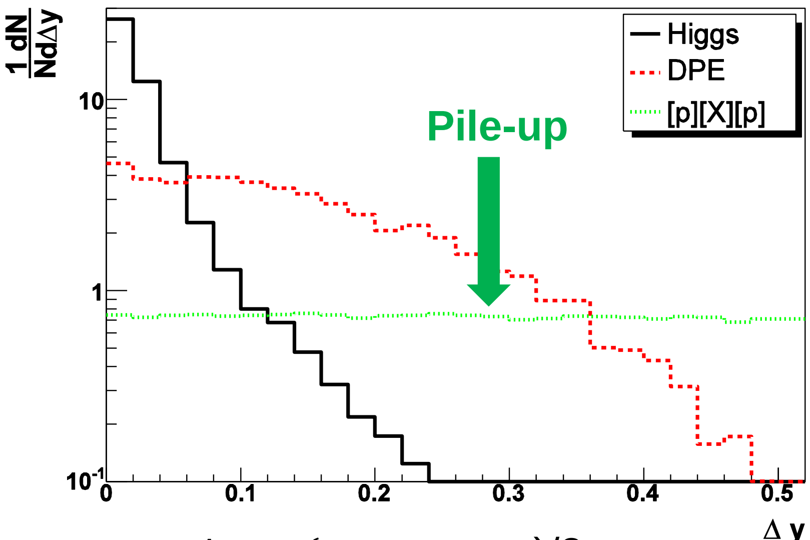
Comparing different proton soft survival modelling:

Accounts for additional proton rescattering effects

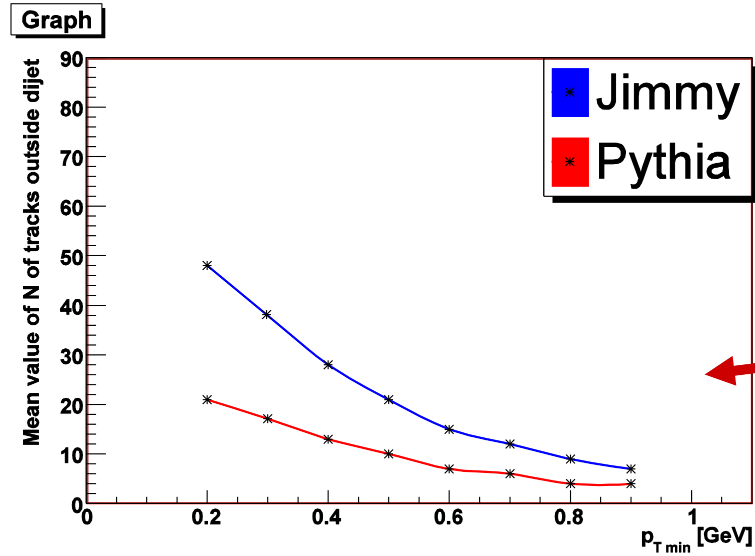
$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [1,2]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [3]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

[1] EPJC 76 (2016) 255 [2] PLB 741 (2015) 66 [3] arXiv:2007.12704

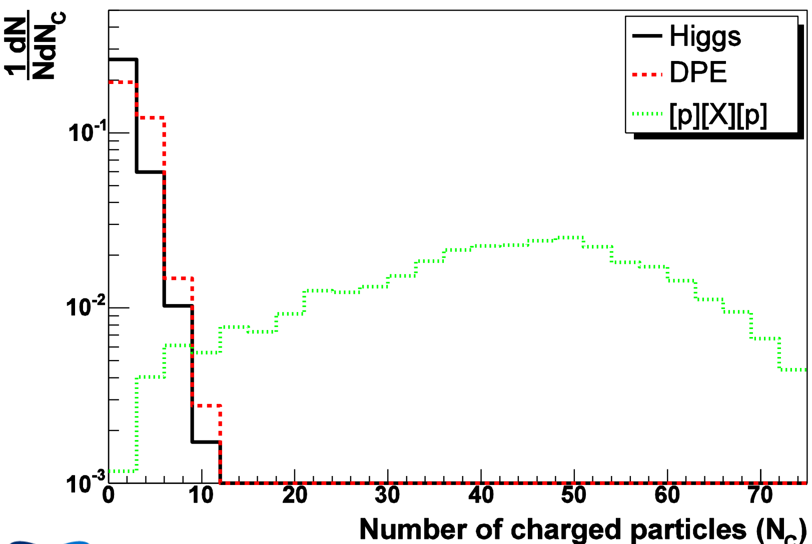
Suppressing Pile-up: kinematics matching

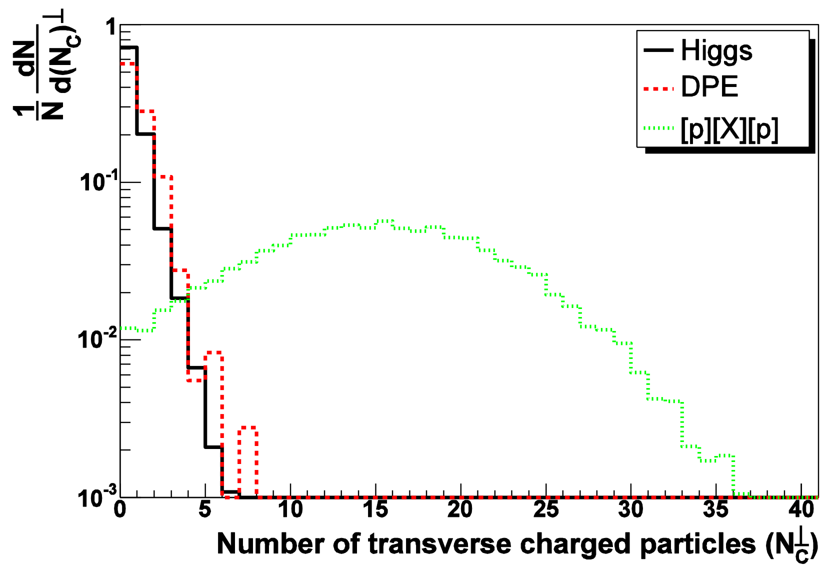


$$\Delta y = (\eta_{jet1} + \eta_{jet2})/2 - y_X$$



This difference has big impact on PU-bg rejection

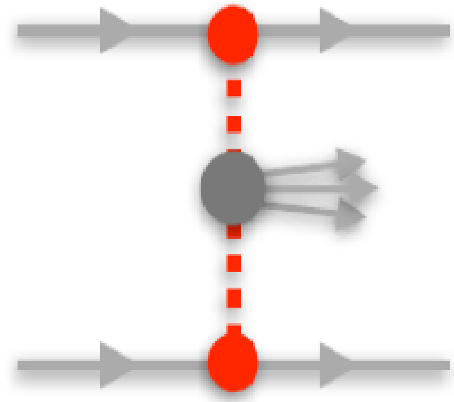


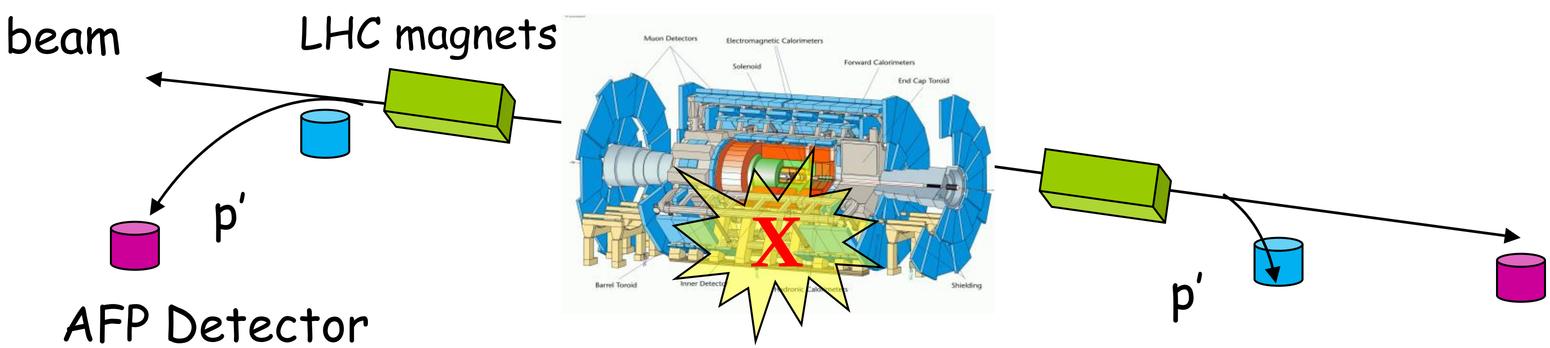


Suppressing Pile-up: Time-of-Flight

JINST 16 (2021) 01, P01030

$$pp \to p \,\square\, X \,\square\, p$$





- Performance of ToF detector for generic double-tag process
- Pile-up suppression, time resolution and granularity of ToF@HL-LHC

Fake Double-Tag events in FPD: Combinatorial background

❑ 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 event = COMBINATORIAL BG.
Time-of-flight (ToF) detectors necessary to suppress this combinatorial background.

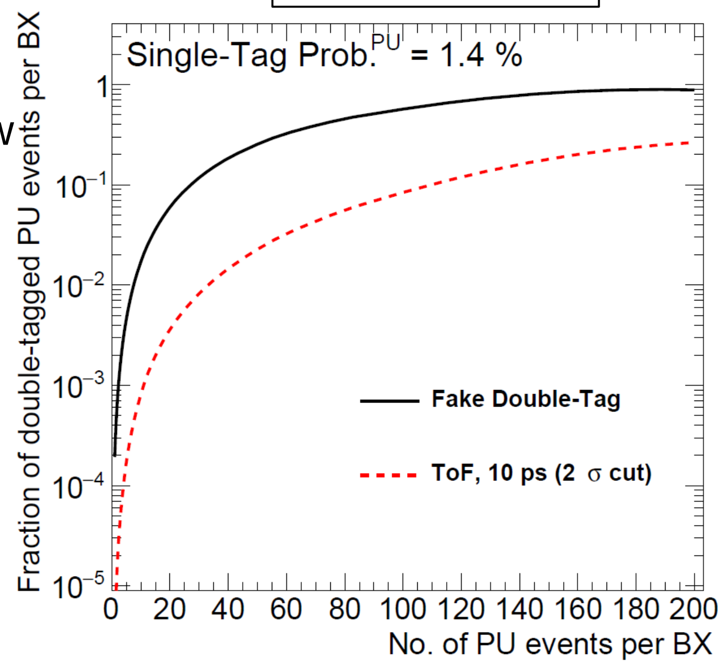
1) Single-Tag probability to find a PU proton in FPD acceptance: 1.4%(PY8.2)

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

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



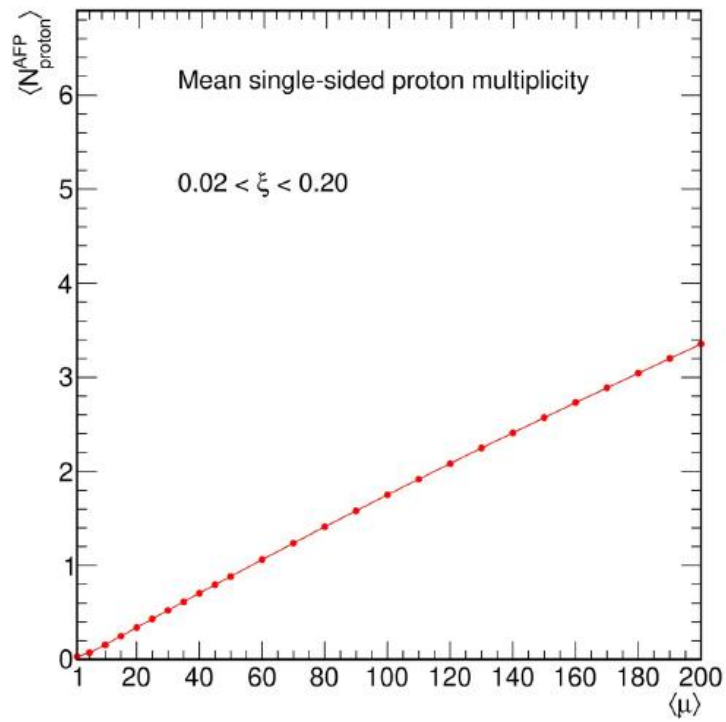
TOF suppression factors

No cut on proton pt

⟨μ⟩\res[ps]	5	10	20	30	50
10	33.2	17.1	8.6	5.8	3.6
50	19.3	10.1	5.5	3.9	2.7
100	10.8	6.0	3.5	2.7	2.0
200	4.6	2.9	2.0	1.7	1.5

proton pt < 0.35 GeV

⟨μ⟩\res[ps]	5	10	20	30	50
10	35.8	18.3	9.3	6.2	3.8
50	26.9	13.7	7.1	4.9	3.2
100	19.2	10.0	5.4	3.9	2.7
200	10.8	5.9	3.5	2.7	2.0

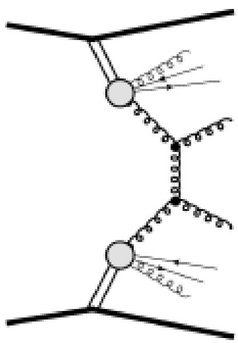


Marek Taševský

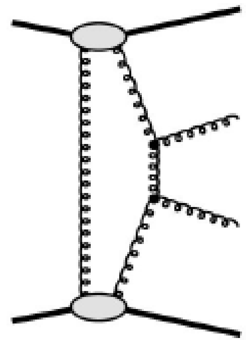
confirmed in arXiv:2010.00237

11/1/21 AFP for HL-LHC 6

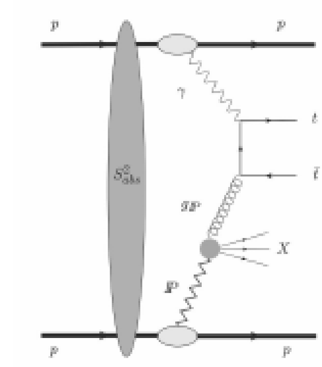
Towards vibrant FPD science program



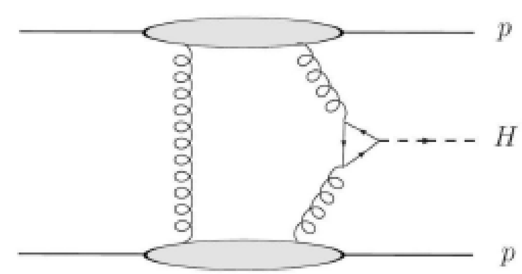
Diffractive jets
ATLAS PHYS-PUB-2017-012
CMS+TOTEM 2002.12146



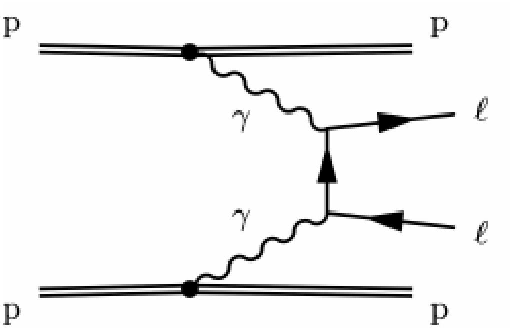
Exclusive jets
Khoze et al hep-ph/0605113
Trzebinski et al 1503.00699



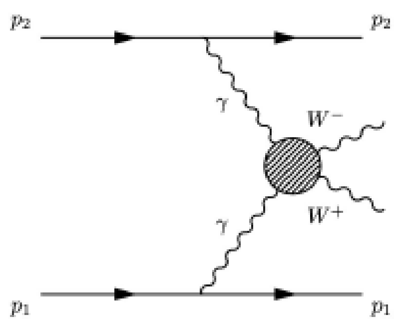
Top quarks
Goncalves et al 2007.04565
Howarth 2008.04249



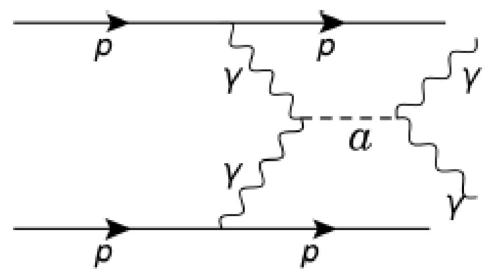
Higgs boson
Cox et al 0709.3035
Heinemeyer et al 0708.3052



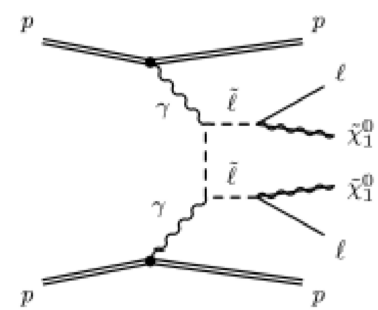
Leptons
CMS+TOTEM 1803.04496
ATLAS 2009.14537



W bosons
Tizchang & Etesami 2004.12203
Baldenegro et al 2009.08331

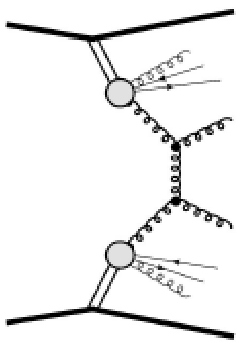


Axion-like particles
Fichet et al 1312.5153
Baldenegro et al 1803.10835

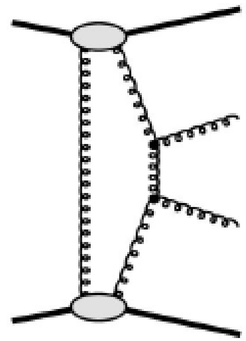


SUSY dark matter
Beresford & JL 1811.06465
Harland-Lang et al 1812.04886

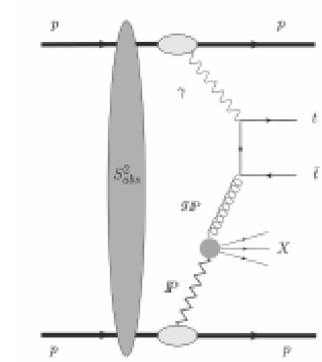
New Physics in exclusive processes



Diffractive jets
ATLAS PHYS-PUB-2017-012
CMS+TOTEM 2002.12146

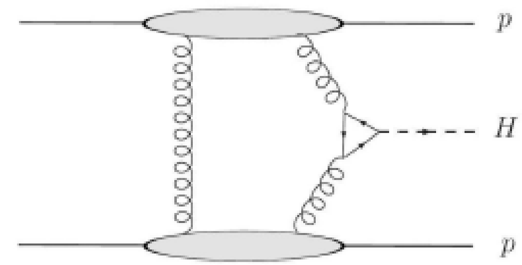


Exclusive jets
Khoze et al hep-ph/0605113
Trzebinski et al 1503.00699



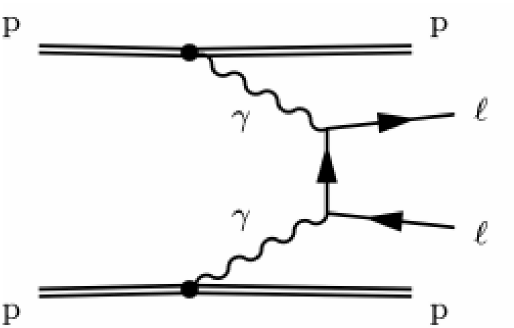
Top quarks
Goncalves et al 2...
Howar... ...49

New Physics

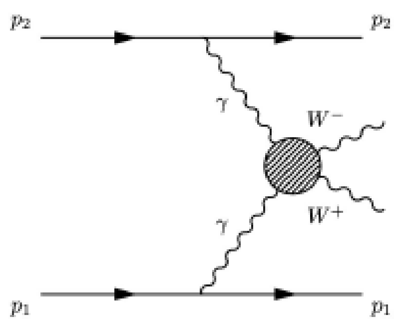


Higgs bos...
Cox et al ...
Heiner... ...708.3052

New Physics

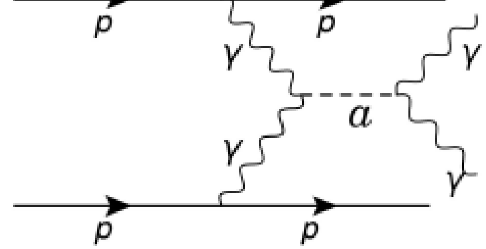


Leptons
CMS+TOTEM 1803.04496
ATLAS 2009.14537



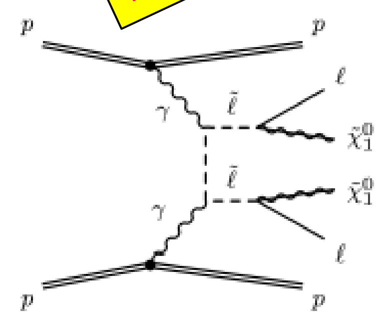
W bosons
Tizchang & Etesami 20...
Baldenegro et al ...1

New Physics



Axion-like particles
Fichet et al 1312.5153
Baldenegro et al 1...

New Physics



SUSY dark matter
Beresford & JL 1811...
Harland-Lang et ...86

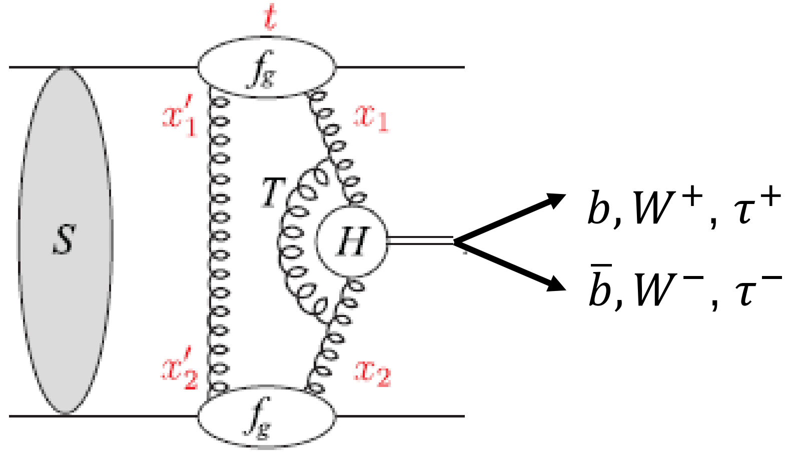
New Physics

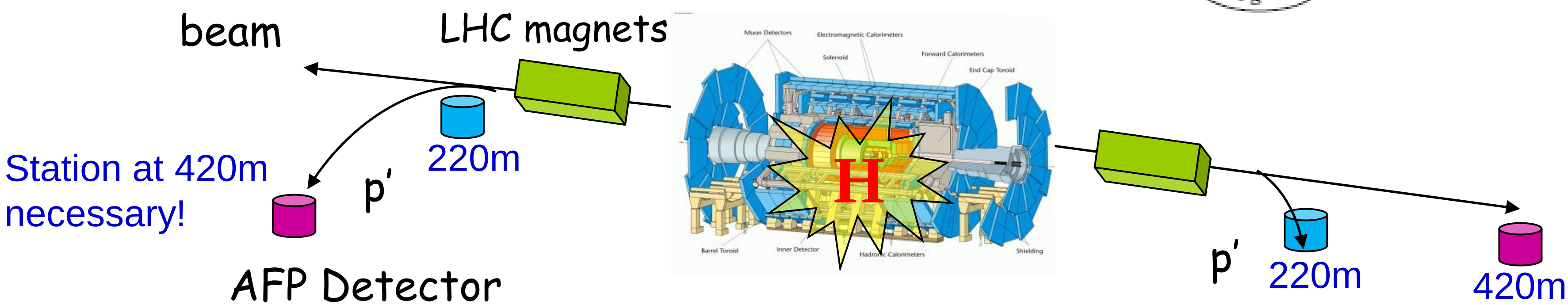
Exclusive Higgs boson

EPJC 53 (2008) 231

JHEP 10 (2007) 090

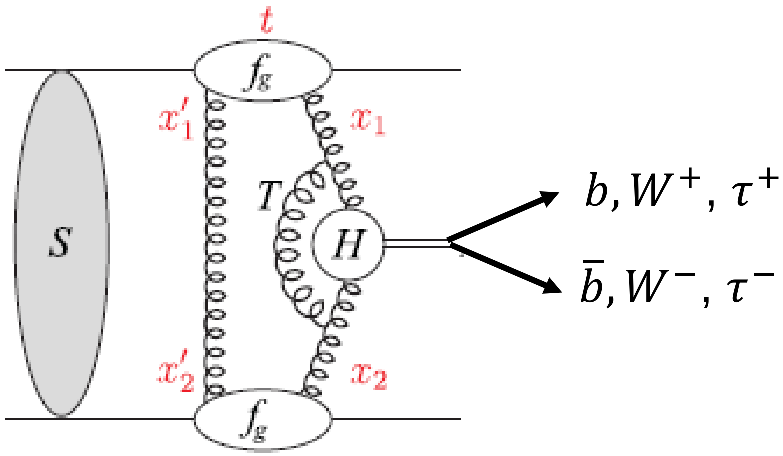
$$pp \to pIPIPp \to p \,\square\, H \,\square\, p$$





- Flagship process for FP420 project (to install Forward Proton Detectors in ATLAS and CMS).
- If Higss detected, then its quantum numbers are known (0++)

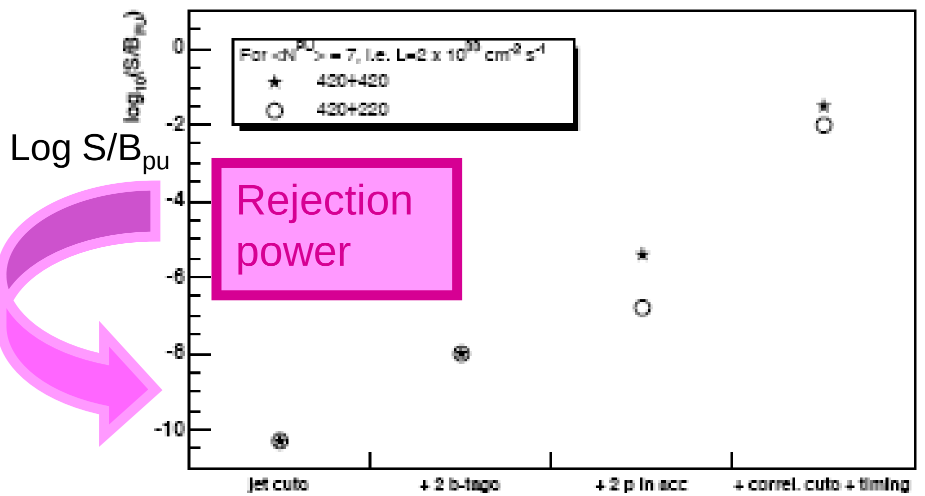
Exclusive Higgs boson



1) Protons remain undestroyed and can be detected in forward detectors
2) Rapidity gaps between leading protons and Higgs decay products

Pile-up is issue for Diffraction at LHC!

[CMS-Totem: Prospects for Diffractive and Fwd physics at LHC]



Offline cuts

But can be kept under control !

Advantages:

I) Roman Pots give much better mass resolution than central detector

II) J_Z = 0, CP-even selection rule:
- strong suppression of QCD bg
- produced central system is 0^{++}

Find a CEP resonance and you have confirmed its quantum numbers!!

III) Access to main Higgs decay modes: bb, WW, tautau → information about Yukawa coupling

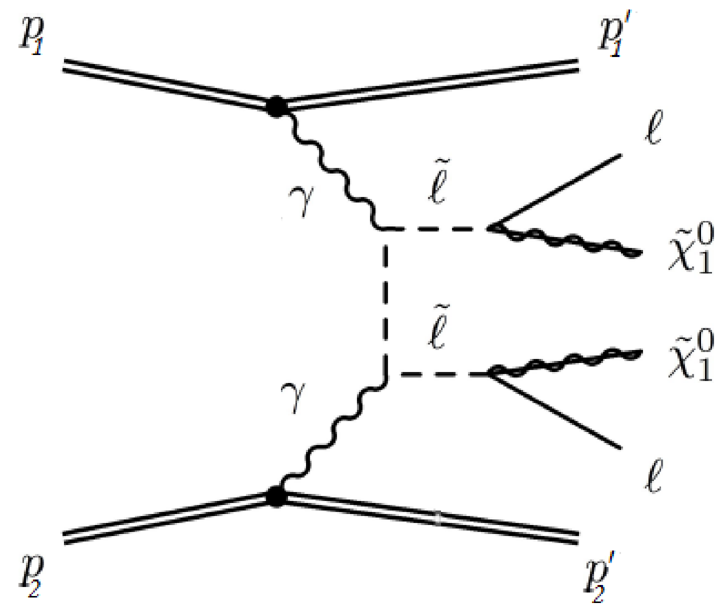
SM Higgs: low signal yield ⟶ try MSSM

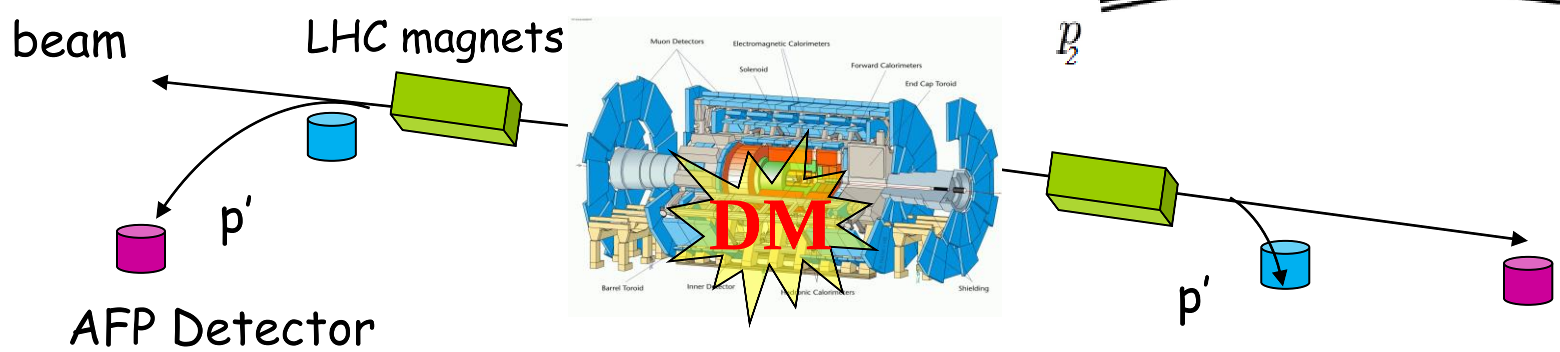
Dark Matter searches in Exclusive Mode

JHEP 04 (2019) 010

PRL 123 (2019) 14, 141801

$$pp \to p\gamma\gamma p \to p \,\square\, \widetilde{l^+}\widetilde{l^-} \,\square\, p$$





- Motivation for use of AFP at high luminosities
- Became topic of PhD thesis

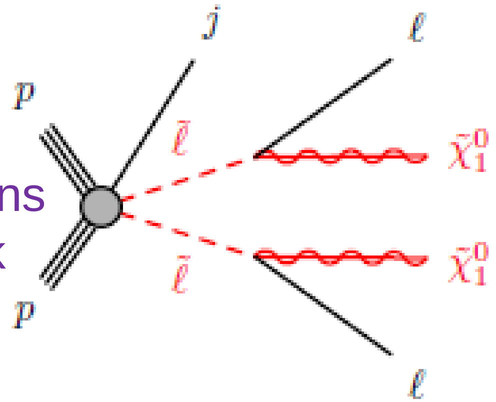
Inclusive slepton searches

Slepton: spin=0 partner of lepton
- decays to fermionic DM + leptons with BR=100%

DM annihilation corridor
AFP chance to contribute

ISR jet (for trigger purposes)

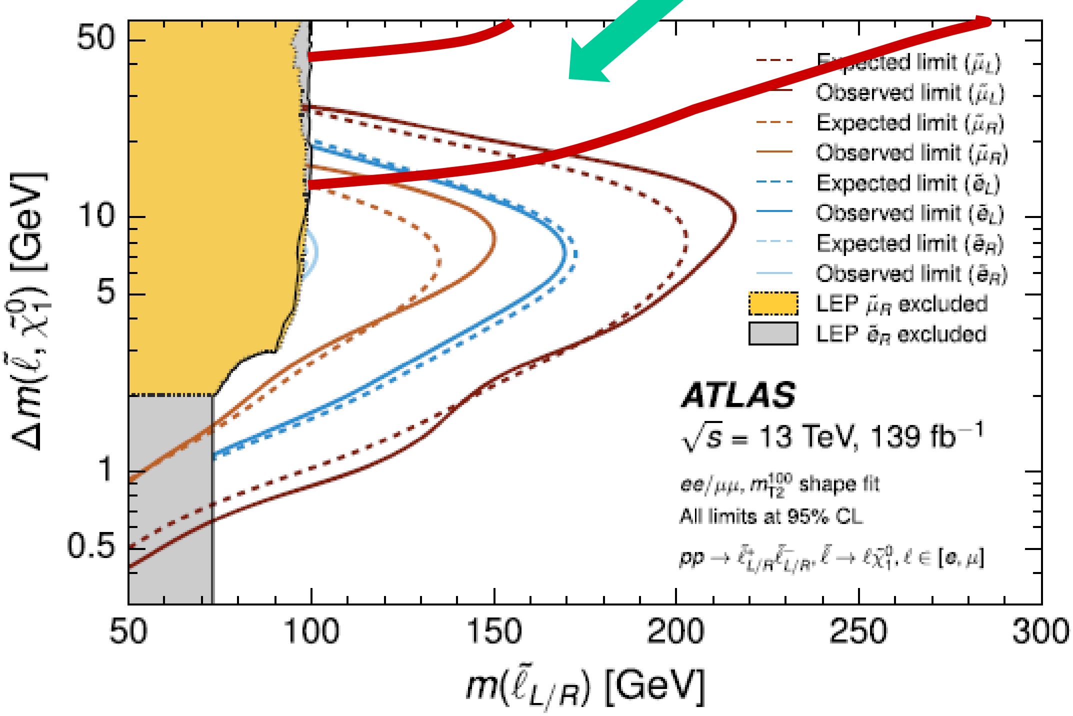
Both protons break up



DM particle candidate. Large missing E_T in Central detector

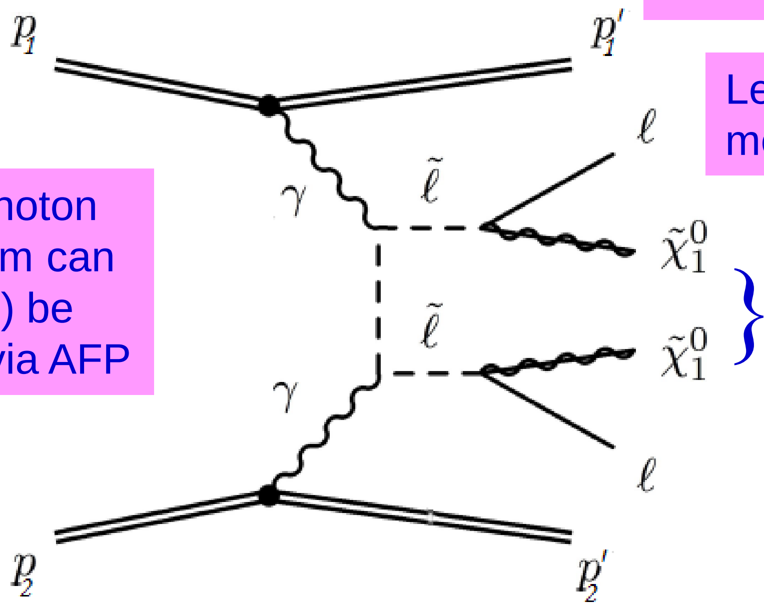
Leptons precisely measured in Central detector

Model dependent



ATLAS compressed mass scenarios 1911.12606

DM searches with AFP



Outgoing proton 4-momentum measured in FPD

$\xi_i = 1 - \frac{E_{p_i'}}{E_{p_i}}$, $i=1,2$ measured precisely in FPD

Lepton 4-momentum measured in Central detector

Incoming photon 4-momentum can (in principle) be measured via AFP

4-momentum of system of 2 DM particles could be constrained from photon & lepton 4-momenta

Model independent

AFP measures precisely mass of central system. If mass splitting $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ low
→ AFP can give quite a precise hint about $2m_{DM}$

Integrated event yields for L=300fb^{-1}

|η| < 2.5

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$ 0	10	50
Excl. sleptons	0.6—3.9	0.5—3.3	0.3—1.9
Excl. l^+l^-	0.4	0.3	0.2
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.1(0.1)	1.8(2.4)

|η| < 4.0

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$ 0	10	50
Excl. sleptons	0.7—4.3	0.6—3.6	0.3—2.1
Excl. l^+l^-	0.1	0.08	0.05
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.03(0.05)	0.6(0.7)

Shows that ITk improves the significance. Updated numbers from new SuperChic 4 (Single+Double Diss)

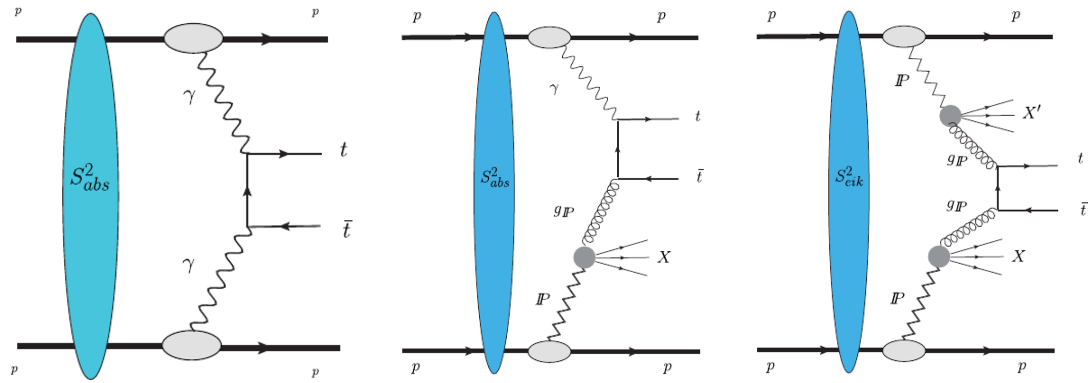
Other potential improvements:

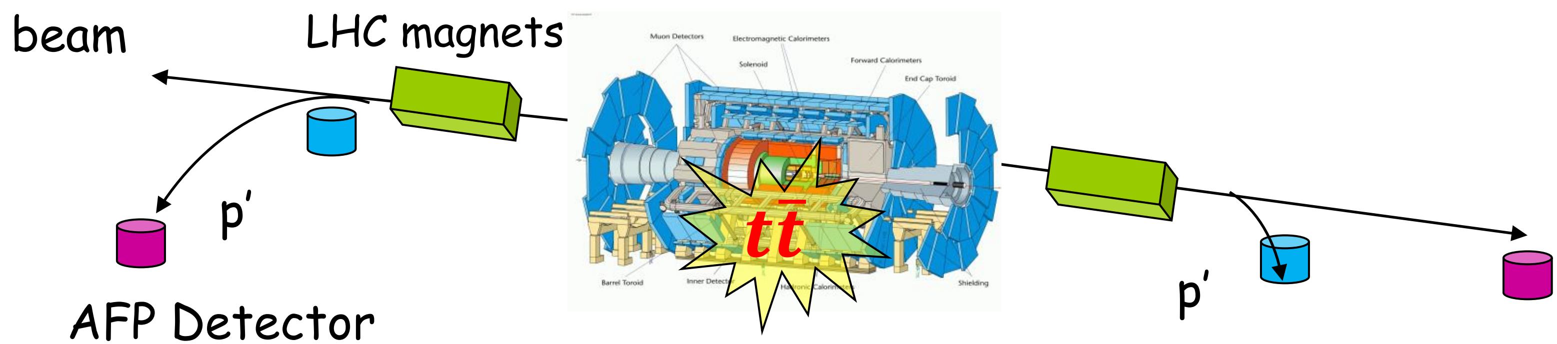
- Cut on the distance between sec. and prim. vertex (or on the pseudo-proper lifetime)
- Improve ToF resolution (ToF rejection increases linearly with σ_t decreasing)
- HGTD: Add timing information in 2.5 < |η| < 4.0 (CMS: MIP Timing Detector in |η|<2.5)
- Exclusive slepton L1 (or HLT) trigger
- Missing E_T for exclusive signal? (very low, around 10-15 GeV)

Top quark production in Exclusive mode

PRD 102 (2020) 7, 074014
PRD 105 (2022) 11, 114002

$$pp \rightarrow p\gamma\gamma p \rightarrow p \,\square\, t\bar{t} \,\square\, p$$

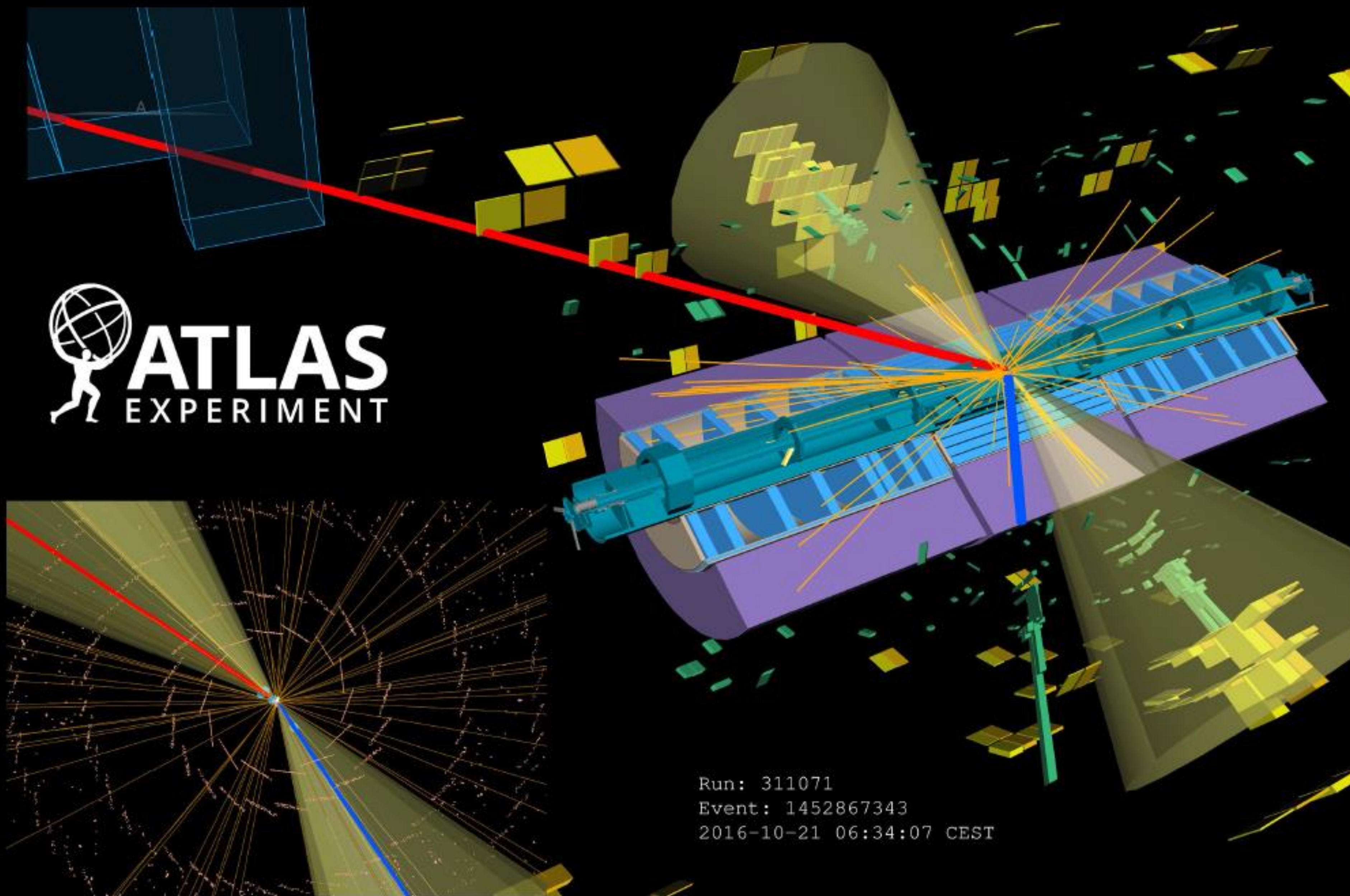




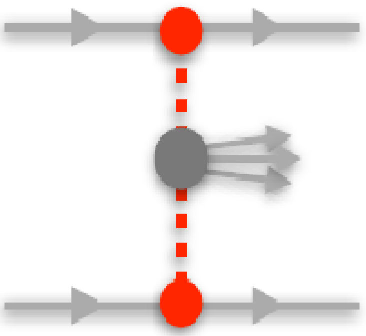
- Source of New Physics
- Best Measurable at low luminosities
- Feasible at HL-LHC as well

TOP QUARKS + AFP

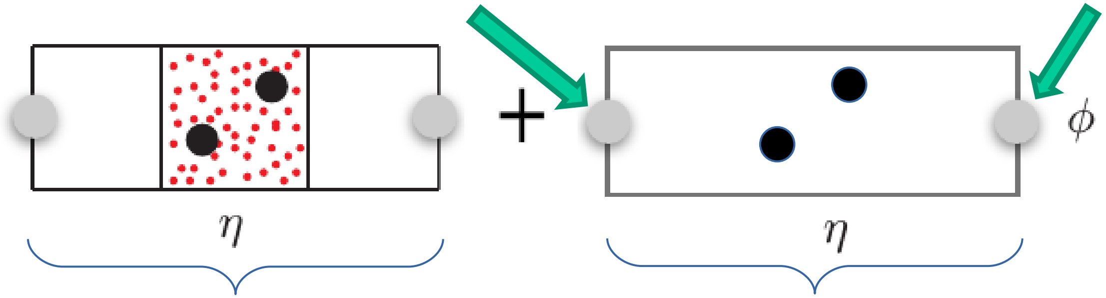
Fully leptonic decay:
$t\bar{t} \rightarrow b l^{+} \nu \; \bar{b} l^{-} \bar{\nu}$



(Semi) exclusive top-pair production



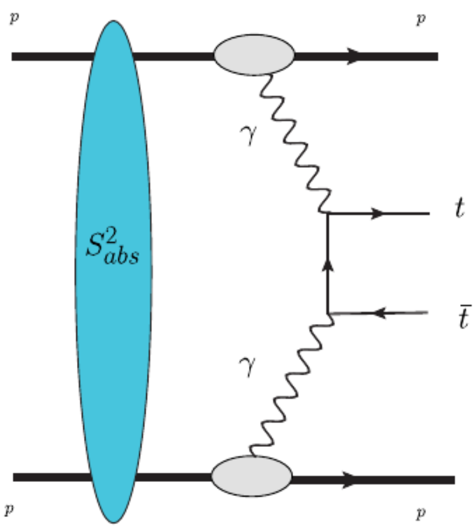
Protons detected in Forward Proton Detector (FPD)



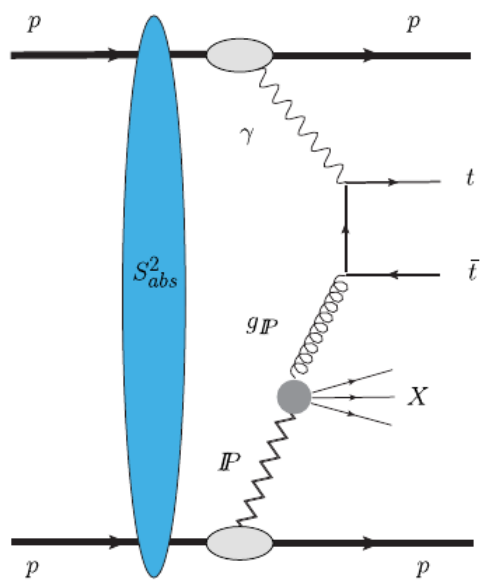
- Semiexclusive production
- Exclusive production

Semileptonic decay:
$t\bar{t} \rightarrow j\,j\,b\,\bar{b}\,l\,\nu$

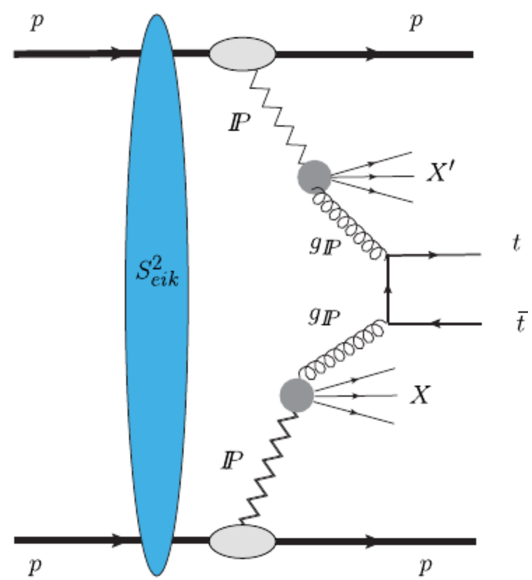
Photon – photon



Photon – Pomeron



Pomeron – Pomeron



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:

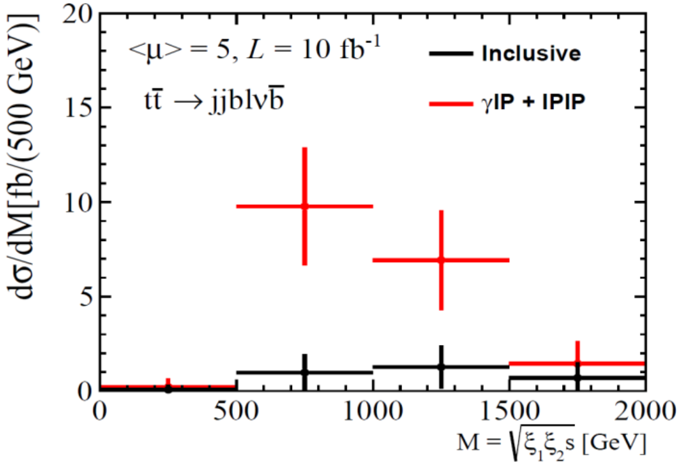
- Reasonable S/B, purities, trigger efficiencies
- Remaining backgrounds < 10%

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)

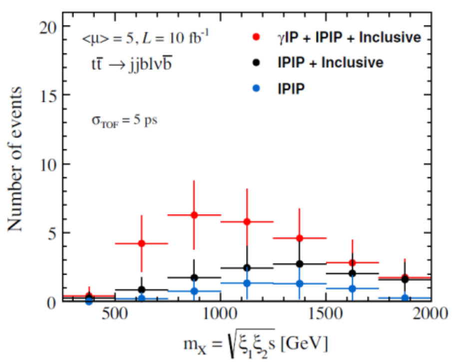
✓ Delphes with proper input cards takes care of applying central detector acceptances, efficiencies, b-tagging, pile-up mixing…

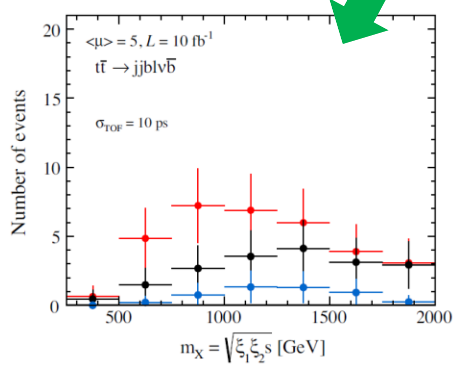
$t\bar{t}$: Simulation of experimental output

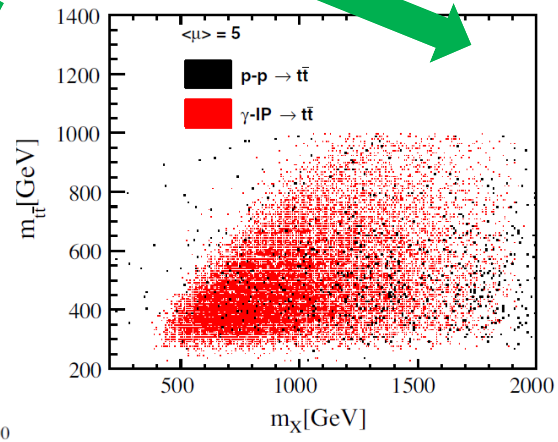


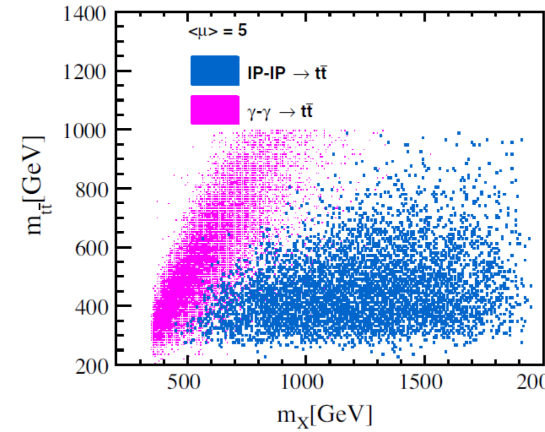
For N_{tracks}< 20 and lumi scenario (5,10):
good separation of signal (γIP + $IPIP$) from combinatorial background

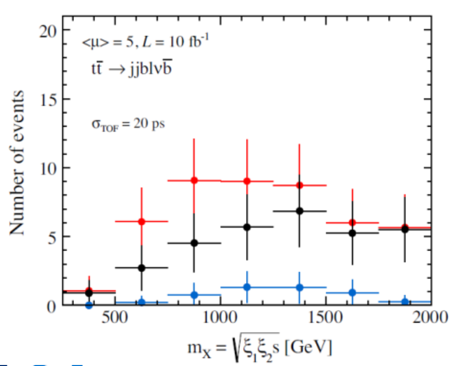
Is it possible to measure γIP and $IPIP$ separately??
It's challenging!

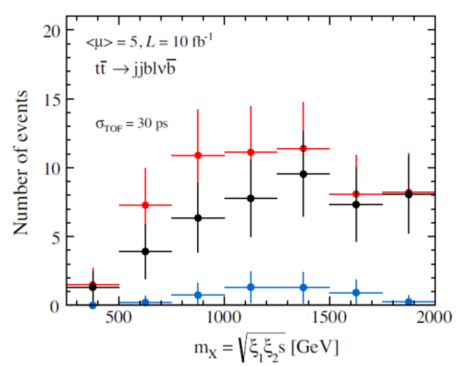


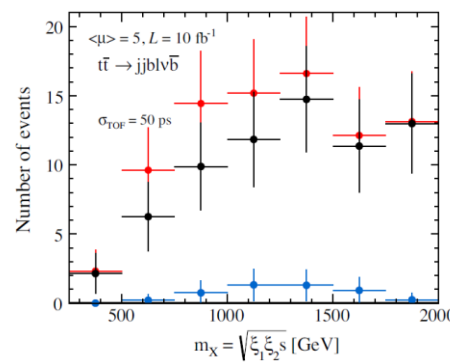












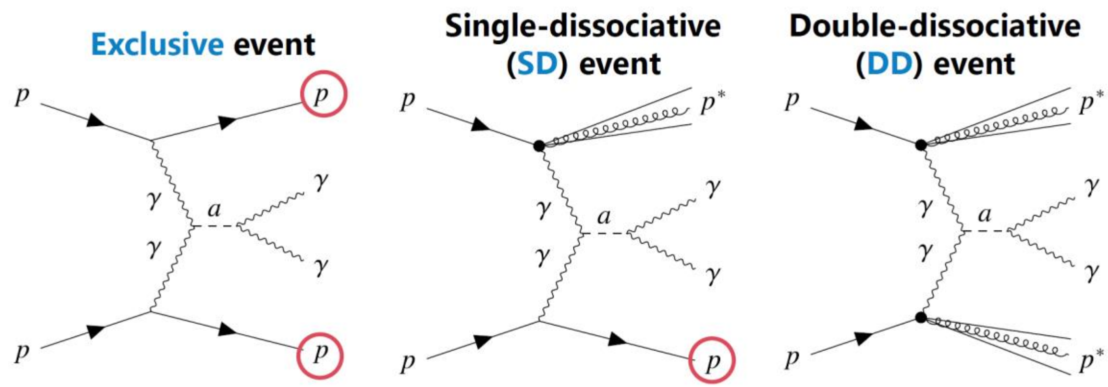
Significance worsens with worsening time resolution (of course)

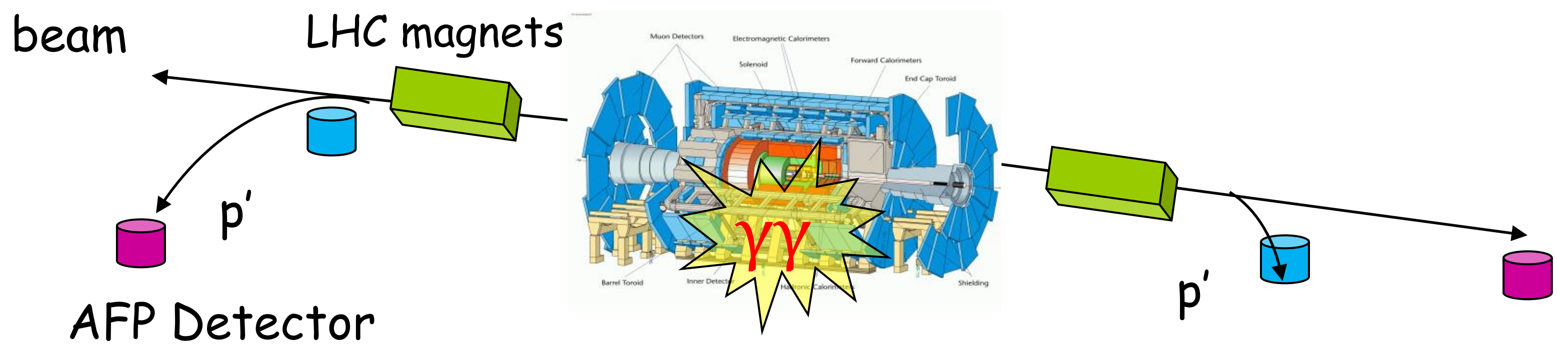
Di-photon resonance search in exclusive mode

JHEP 07 (2023) 234

- At least 1 proton tagged required → signal is a sum of pure exclusive and Single-Dissociation

$$pp \to p\gamma\gamma p \to p \,\square\, \gamma\gamma \,\square\, p$$



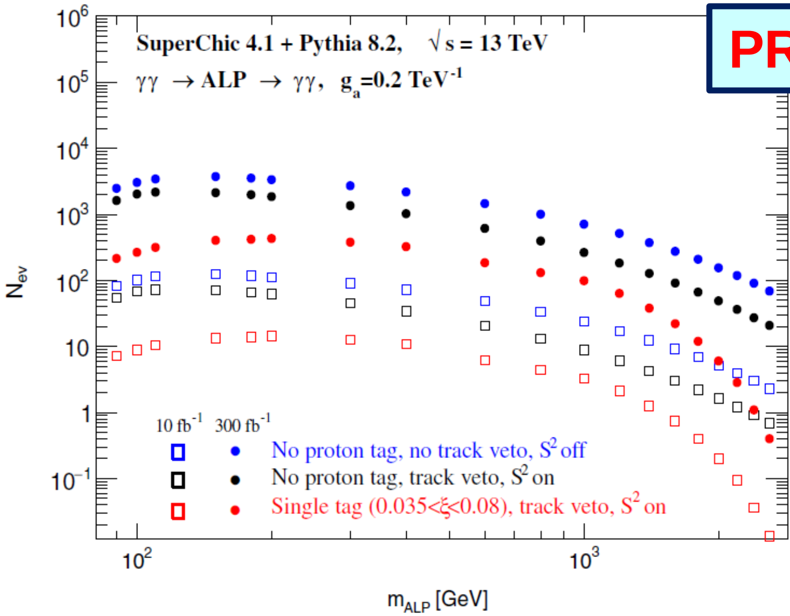


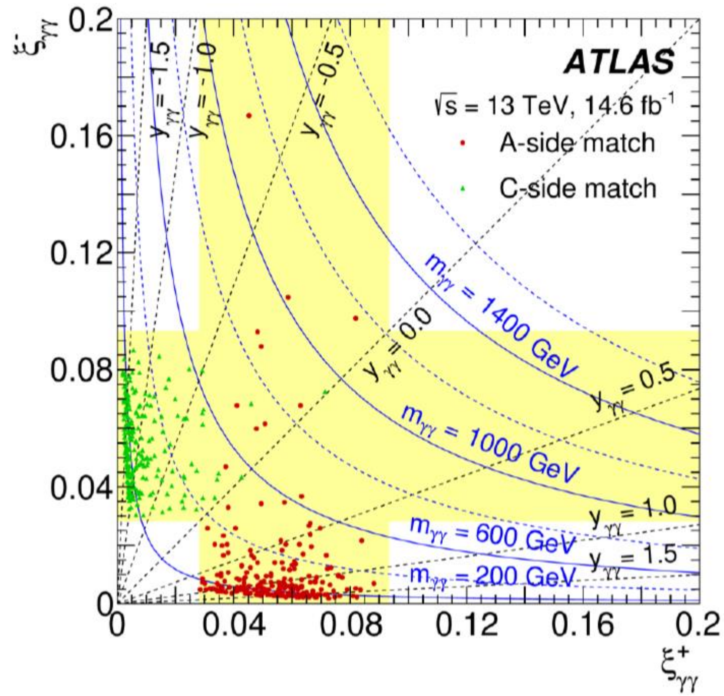
- ➢ Source of New Physics
- ➢ Novel technique for modeling combinatorial background

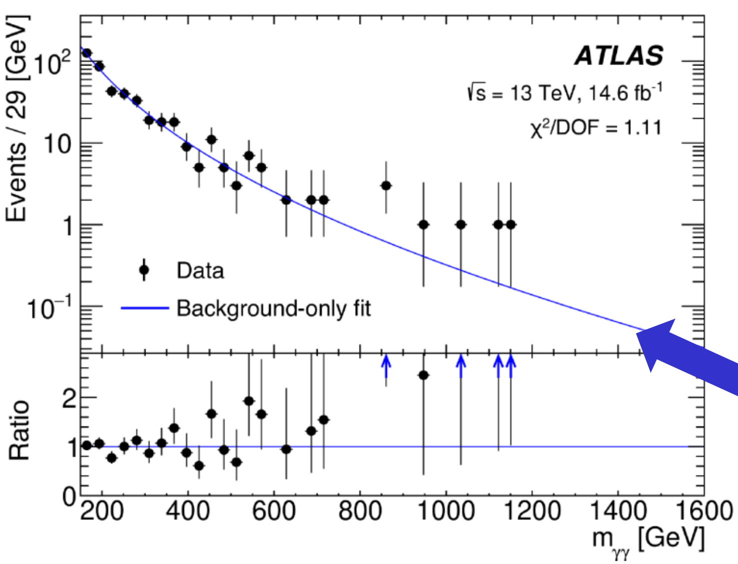
Di-photon resonance search with FPD

Predicted signal event yields from SuperChic 4.1+Pythia 8.2

PRD 107 (2023) 033001





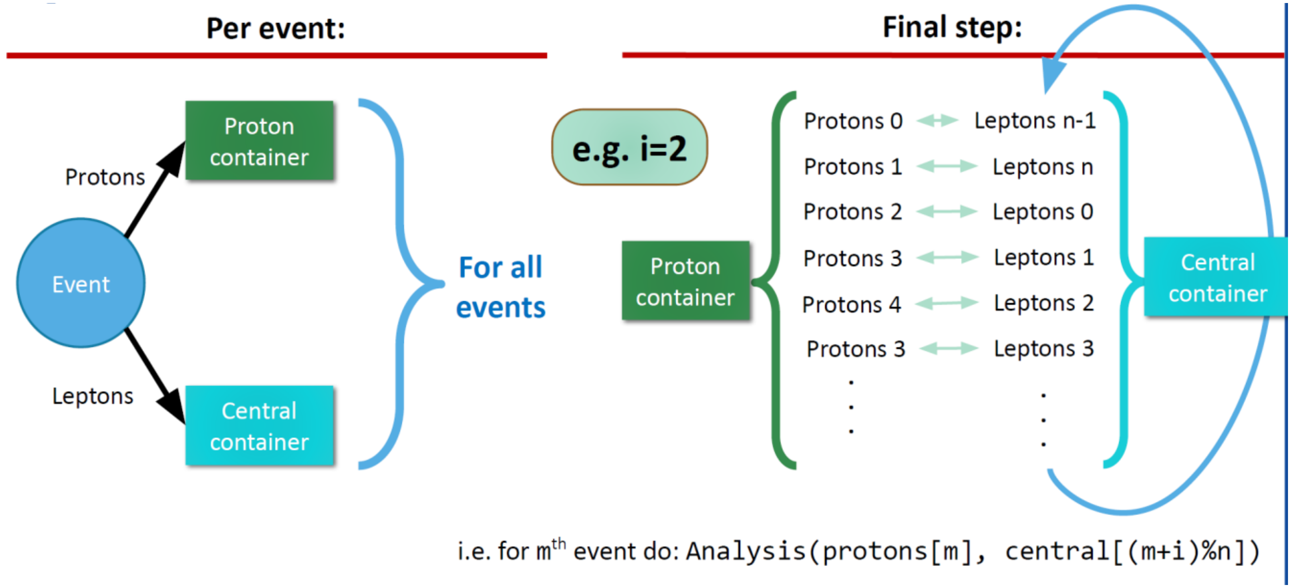


Background: estimated by mixed events (shifted events).
→ novel technique at LHC to model the combinatorial bg.

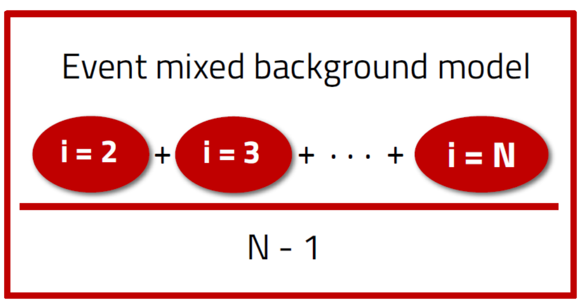
Data-driven estimate of combinatorial bg

Combinatorial background can be estimated by the so called **EVENT MIXING**:

- combine protons from the nth event with central data from the (n+i)th event
- Protons and leptons are uncorrelated, as in background



- run the analysis with event shifts of i = 2, 3, 4….N and then take the average of the resulting distributions, bin by bin

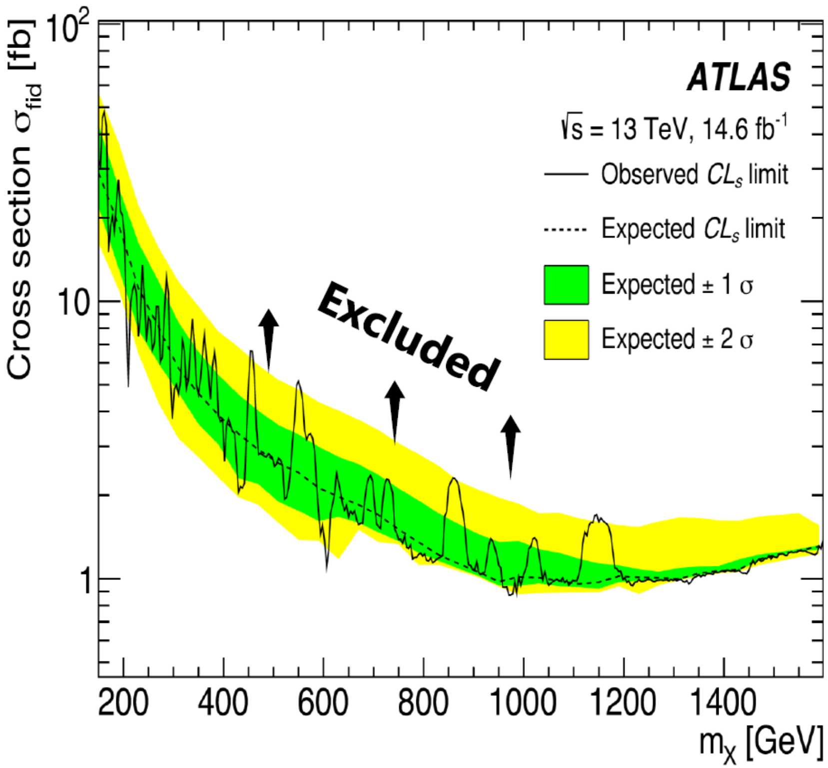


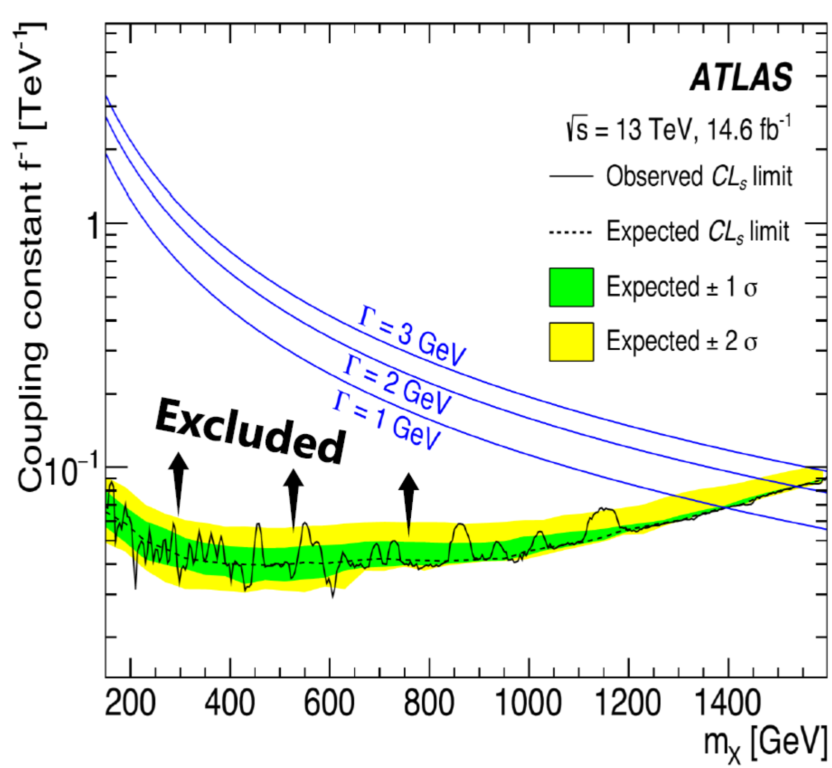
Such data, e.g. for i=1, can be used as blinded data!
(So no need to define control regions and verification regions)

used in AFP exclusive publications
PRL 125 (2021) 261801, JHEP 07 (2023) 234

Di-photon resonance search with FPD

Exclusion limits



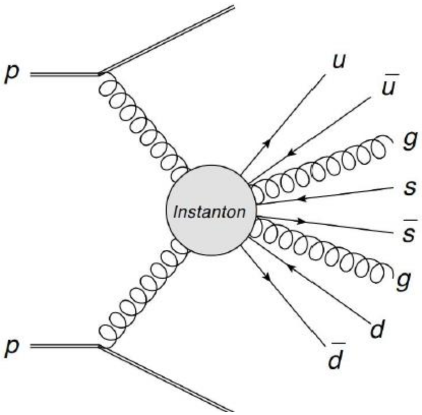


QCD instanton searches with proton tagging

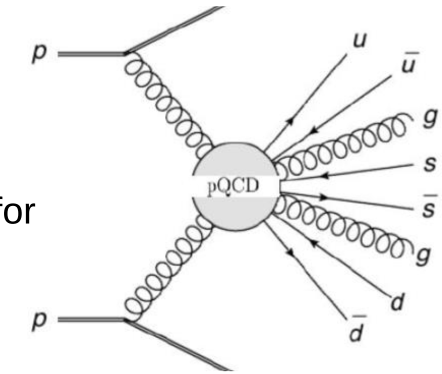
EPJC 83 (2023) 1, 35

- Single-tag and Double-tag signatures studied

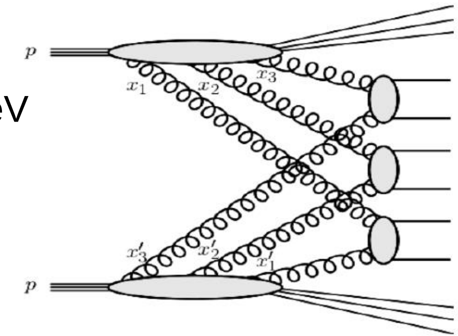
S: g+g $\rightarrow n_g$x g + $\sum_{f=1}^{N_f}(q_{Rf}+q_{Lf})$ **BG1: minijets** $\sigma_{\mathrm{pQCD}}(gg\rightarrow N\,\mathrm{jets})\sim\frac{16\pi}{M^2}\left(\frac{N_c}{\pi}\alpha_s(M)\right)^N$ **BG2: Multi-parton int.**



High trans. sphericity S_T.
Large x-sections for M_{inst} < 200 GeV

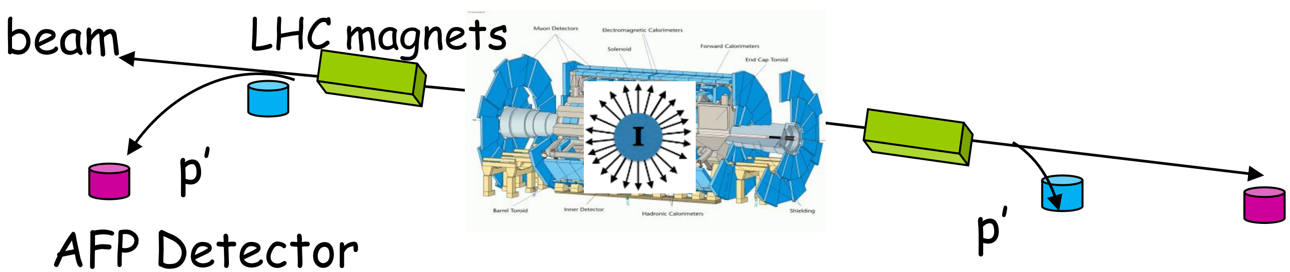


Dominant at M_{inst} > 200 GeV



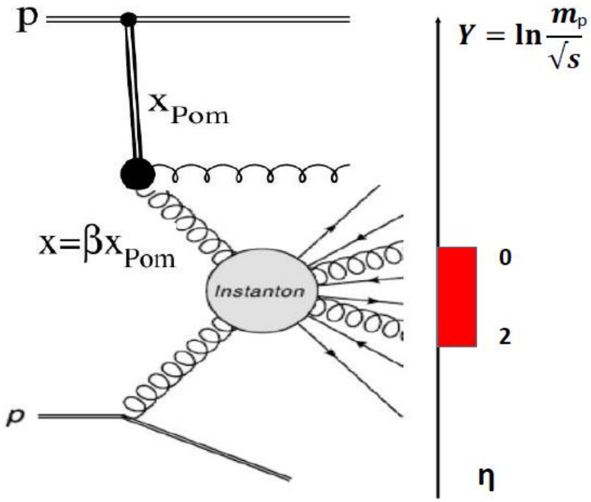
High S_T.
Dominant at M_{inst} < 200 GeV

Reach M_{inst} < 200 GeV and suppress MPI? Go to large rapidity gaps (or proton tagging)!



- Interplay between soft QCD and hard QCD
- Challenging and long sought object (HERA, now at LHC)

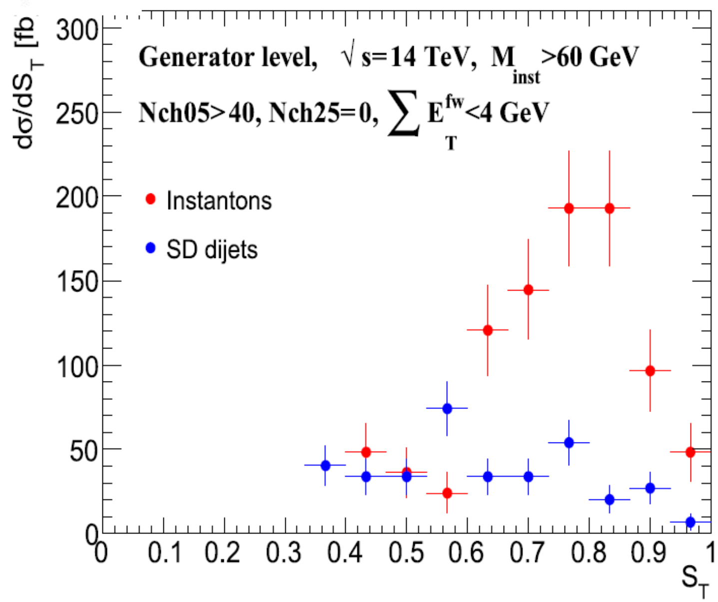
Single-tag: results at generator level



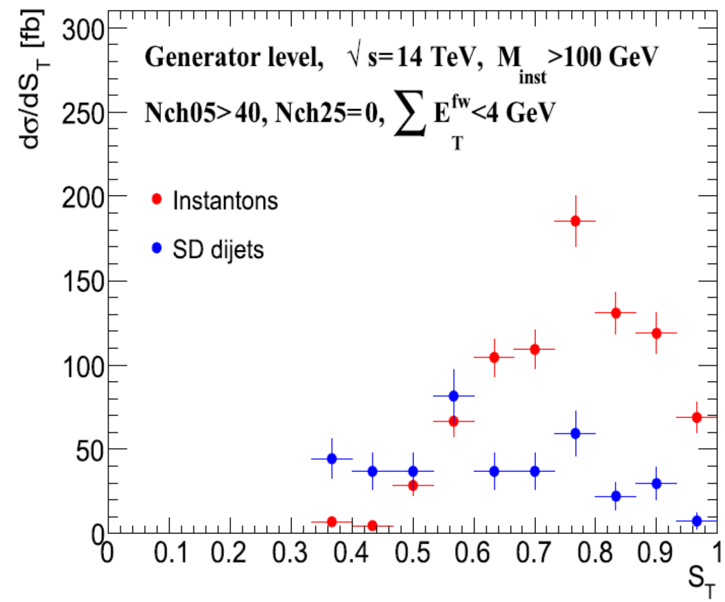
Inclusive searches very challenging. Study what requiring one large rapidity gap ($0 < \eta < 2$) brings and be as realistic as possible → include:

- MPI
- Pile-up
- Detector simulation

$N_{ch05} > 40 \wedge N_{ch25} = 0 \wedge \sum E_T^{fw} < 4$ GeV



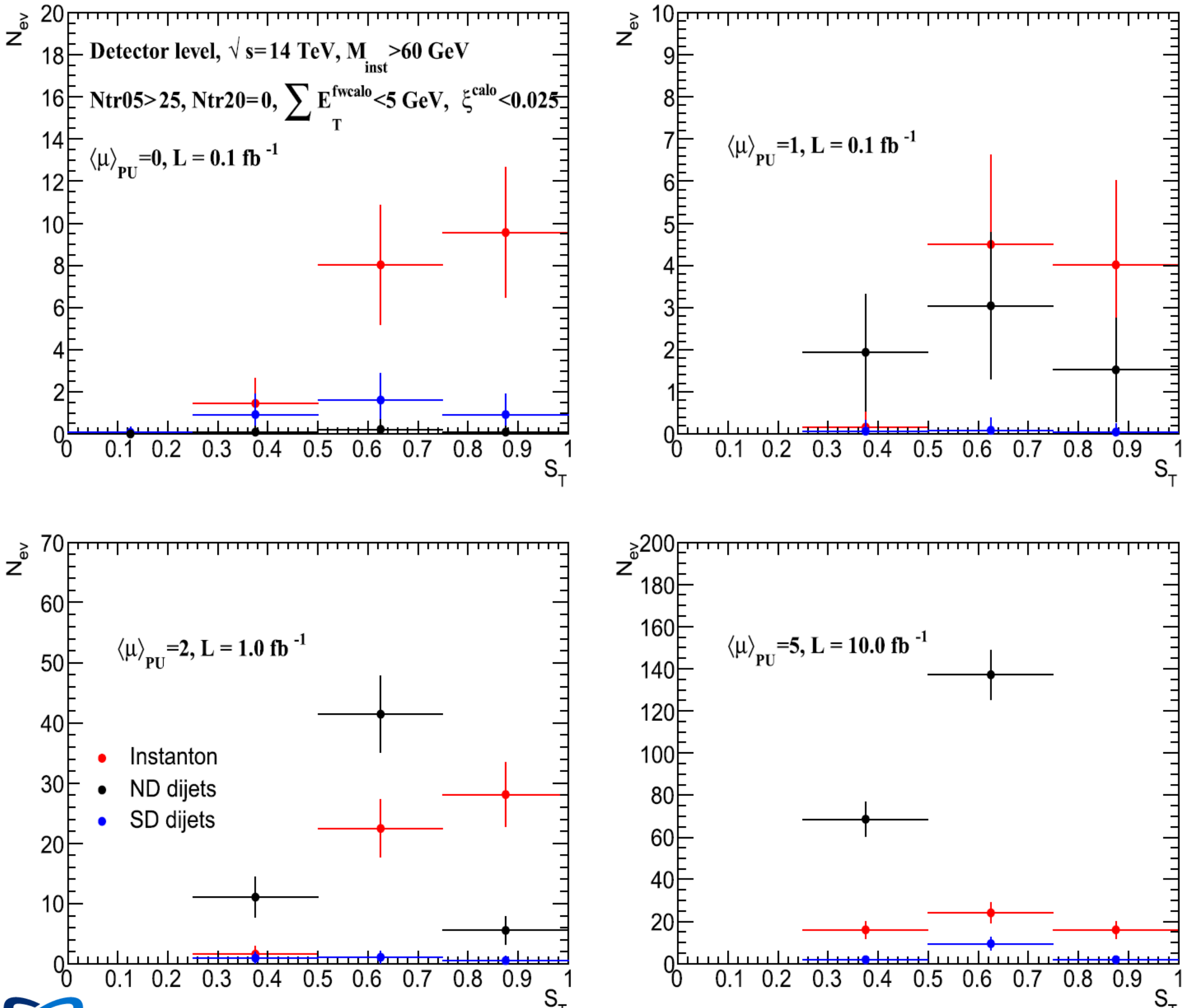
$M_{inst} > 60$ GeV: S/B = 2.3



$M_{inst} > 100$ GeV: S/B = 2.1

Single-tag: results at detector level

$N_{tr05} > 25 \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV $\wedge\ \xi^{calo} < 0.025$



M_{inst} > 60 GeV

- Fast simulation of detector effects using DELPHES
- Pile-up effects included in signal as well as SD and ND backgrounds
- Four luminosity scenarios Evaluated

Event yields:

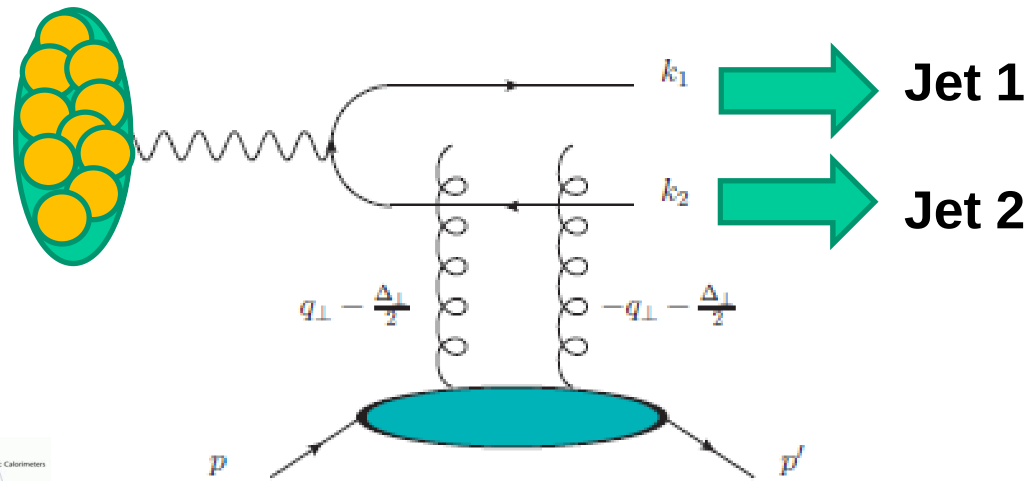
$(\langle\mu\rangle, \mathcal{L}\ [\mathrm{fb}^{-1}])$	$M_{\mathrm{inst}} > 60$ GeV	$M_{\mathrm{inst}} > 100$ GeV
(0, 0.1)	19.0/(0.4+3.5)	5.8/(0.2+3.5)
(1.0, 0.1)	8.7/(6.5+0.2)	3.2/(4.7+0.2)
(2.0, 1.0)	52.2/(58.1+2.5)	15.4/(55.3+2.2)
(5.0, 10.0)	56.2/(205.6+13.3)	23.8/(137.1+7.6)

Gluon Wigner function using Exclusive process

PRD 96 (2017) 3, 034009

Phys.Rept. 1084 (2024) 3 (review)

$$pPb \to p\gamma X \to p \square jj \square X$$



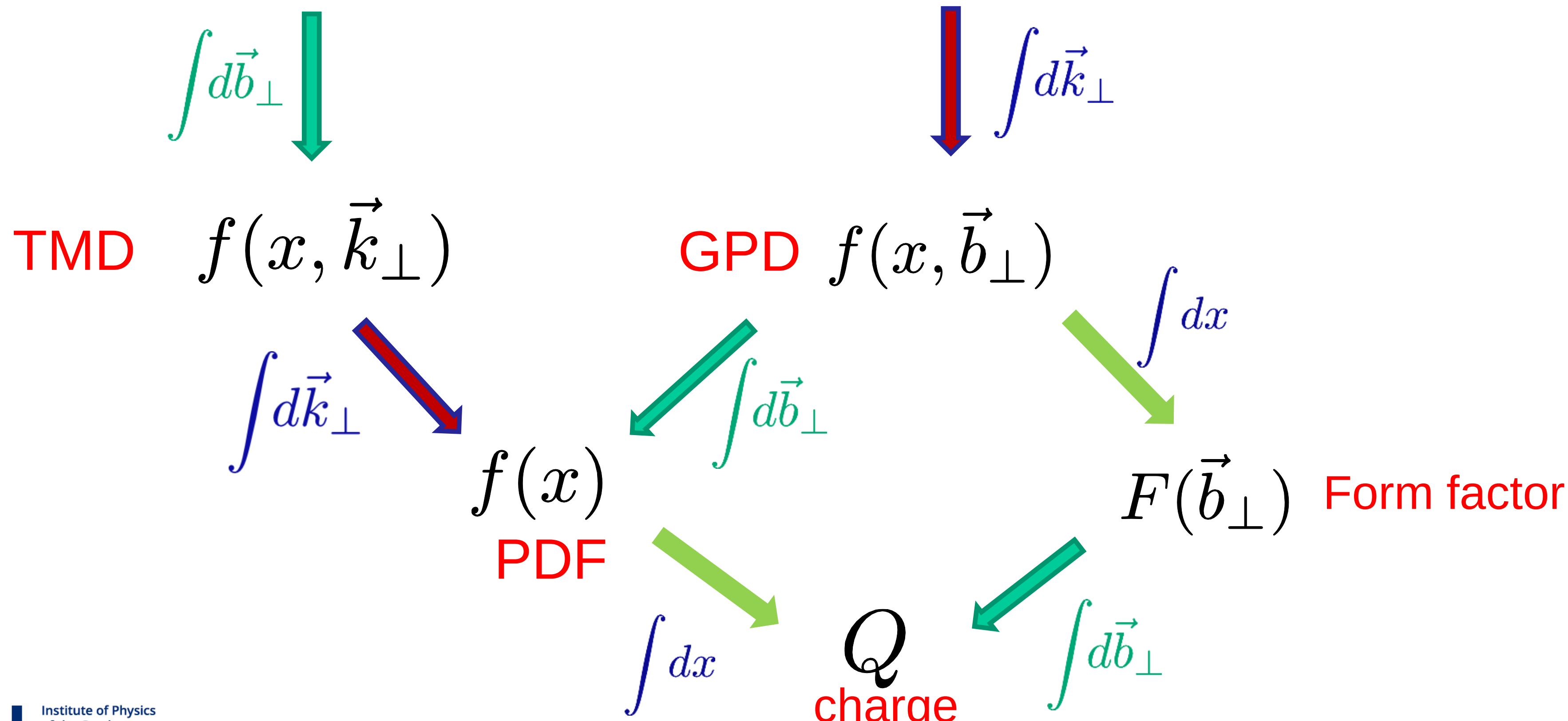
- ➢ Included in:
- prospects for measuring quarkonia@HL-LHC
- opportunities for photon-energy frontier
- Yellow Report for future Electron Ion Collider
- CDR of Spin Detector
- CMS measurement (published)

Measuring Wigner distribution in diffractive photoproduction

Belitsky, Ji, Yuan (2003);
Lorce, Pasquini (2011)

5D Tomography: Wigner distribution = the mother distribution

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P - \frac{\Delta}{2} | \bar{q}(-z/2)\gamma^+ q(z/2) | P + \frac{\Delta}{2} \rangle$$



SUMMARY on (Semi) Exclusive Processes

- **Advantages:**

1) simple final state:
   i) two intact protons that can be detected in forward proton detectors (cheap to build)
   ii) final state of interest and no additional activity

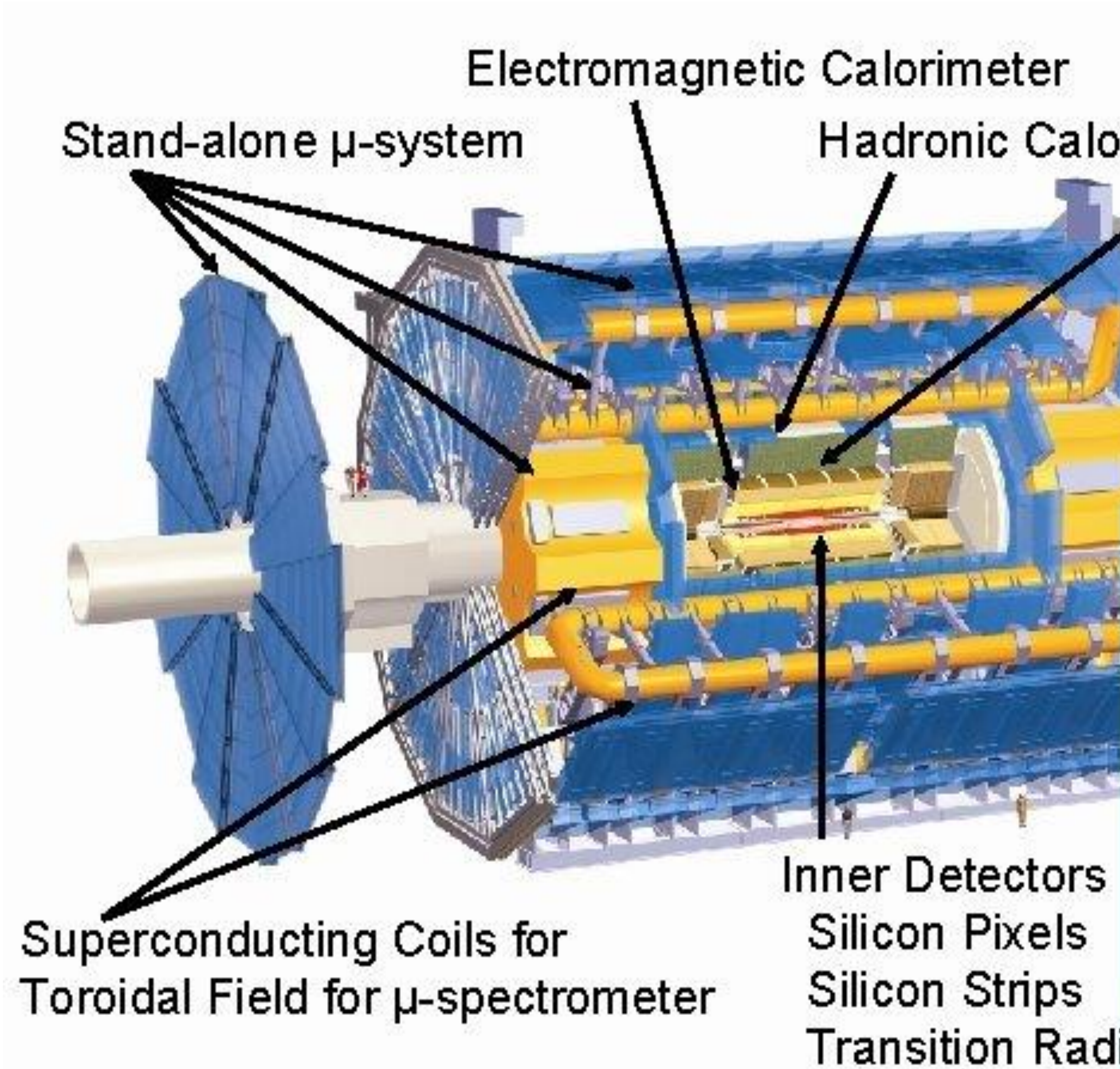
2) Important constraints on the final state – kinematics matching
   -- time of flight
   -- large rapidity gaps / track veto
3) Useful to search for New Physics
4) But even in SM, theorists need measurements of several inputs (soft survival, gluon un-integrated functions, Sudakov formfactors, …)

- **Disadvantages:**

1) Low production cross sections
2) Combinatorial background

BACKUP SLIDES

The ATLAS detector



Length 44m

Height 22m

Some striking features:

Hermetic calorimeter $|\eta|<4.9$

Fine granularity and 3 longitudinal segmentations (both in EM and hadronic) + a pre-sampler

Large μ-spectrometer $|\eta|<2.7$

Silicon Tracker $|\eta|<2.5$

Summary on Exclusive Higgs

M_H [GeV]	σ (bb) [fb]	σ (WW*) [fb]	Acc (420+420)	Acc(420+220)
120	1.9	0.37	0.20	0.17
130		0.70	0.15	0.24
140	0.6	0.87	0.11	0.31
160	0.045	1.10	0.04	0.43
180	0.0042	0.76	0.01	0.53

AFP 220/420: 2.5mm/4mm from the beam (1mm dead space)

Cross-sections by KMR group

Experimental analyses:

CMS:

H→bb: fast simulation, 100 < M_H < 300 GeV, d_{220}~1.5mm, d_{420}~4.5mm, Acc=Acc(ξ,t,φ)

- published in CMS-Totem document **CERN/LHCC 2006-039/G-124**
- signal selection efficiencies used in MSSM studies (EPJC 53 (2008) 231, EPJC 71 (2011) 1649, EPJC 73 (2013) 2672)

ATLAS:

H→bb: 1) gen.level + smearing of basic quantities, M_H = 120 GeV

- one MSSM point (tanβ = 40): JHEP 0710 (2007)090

2) fast simulation, M_H = 120 GeV: ATL-COM-PHYS-2010-337

3) Dedicated L1 trigger for H→bb: ATL-DAQ-PUB-2009-006

All analyses on H→bb get very similar yields for signal and background

H→WW: fast + full simulation, M_H = 160 GeV:

ATL-COM-PHYS-2010-337 EPJC 45 (2006) 401

Efficiencies for SM H→bb (CMS+Totem)

Mh [GeV]	Acc_{420}	Acc_{comb}	Acc_{220}	ε_{420}	ε_{comb}	ε_{220}
100	0.37	0.13	0.0	0.012	0.008	0.0
120	0.31	0.25	0.0	0.017	0.025	0.0
140	0.25	0.37	0.0	0.016	0.051	0.0
160	0.19	0.49	0.0	0.015	0.076	0.0
180	0.14	0.60	0.0	0.012	0.096	0.0
200	0.09	0.69	0.0	0.004	0.11	0.0
300	0.0	0.76	0.13	0.0	0.125	0.02

27

Due to stringent cuts to suppress PU bg, experimental efficiencies for SM Higgs and hence significances are modest. Try MSSM !

Summary on Exclusive SM/BSM Higgs

CEP Higgs production has a decent potential compared to standard LHC searches:

IJMP A29 (2014) 1446012

- **excellent mass resolution**
- **good S/B**
- **complementary information about Higgs sector in MSSM**
- **complementary information about quantum numbers (a few events are enough and no need for coupling to vector bosons)**
- **information about CP-violation effects**
- **information about Yukawa Hbb coupling**

Since the Higgs boson discovery, many BSM scenarios were scrutinized by ATLAS and CMS in numerous channels:

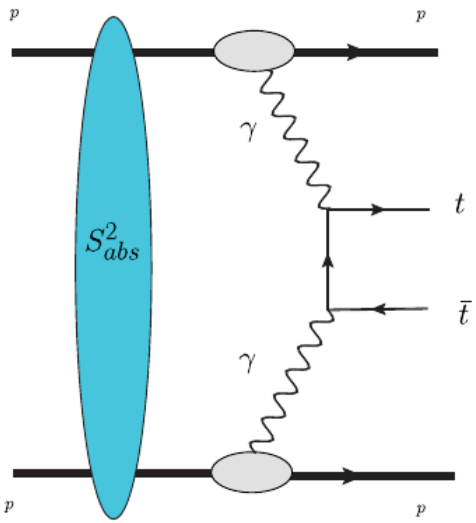
- Heavy Higgs boson excluded for m_H< 400 GeV, except for a few fine-tuned points in Mh125 alignment scenario. In M_H^{125}scenario, mass of light CP-even Higgs < 125 GeV and discovered Higgs is the heavy CP-even MSSM Higgs (triggered by CMS observation of 3σ excess at 96 GeV in $\gamma\gamma$ channel – still to be confirmed by full Run2 data. ATLAS sees weaker excess).

1) Allowed MSSM phase space is very limited. LHC analyses show that the discovered Higgs is more and more SM like. Event yield for the exclusive SM Higgs is low but may be increased by tuning the selection procedure (we know the mass of Higgs). There is room for improvement.

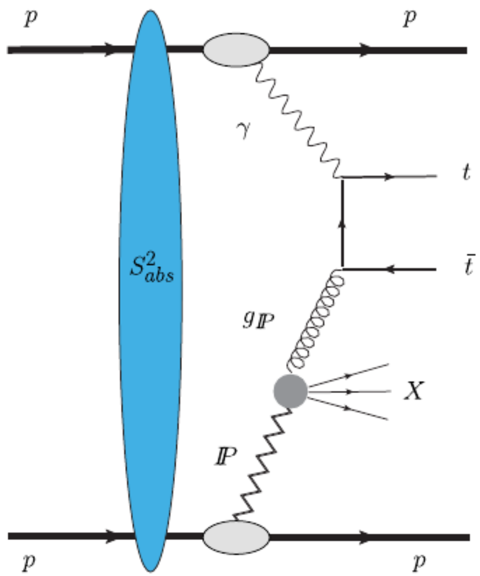
2) Whether Higgs is SM or MSSM, the low-mass exclusive Higgs needs stations at 420 m.

Top-pair production in (semi)exclusive processes

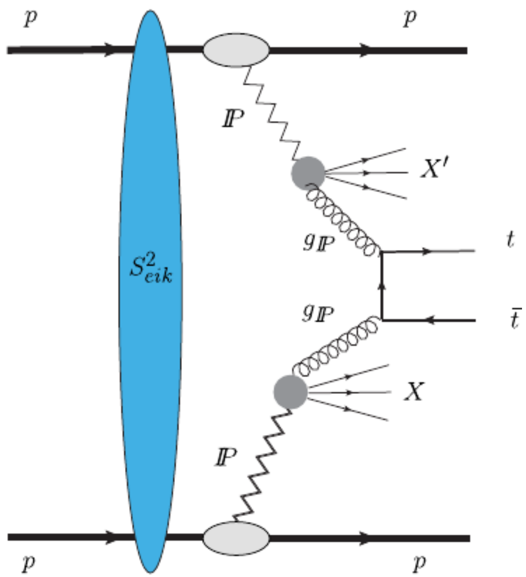
Photon – photon



Photon – Pomeron



Pomeron – Pomeron



Cross section:

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

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

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

Photon flux:

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

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

New Physics in (Semi)exclusive ttbar

SM: Top pair production in diffractive photoproduction never measured!
Single top production: direct measurement of CKM matrix element Vtb, study Wtb vertex

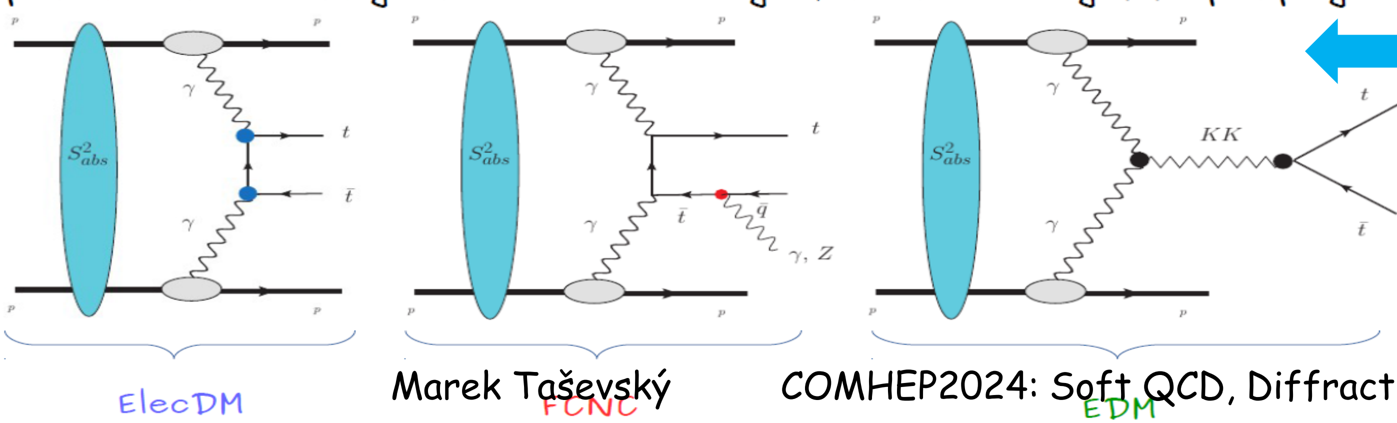
BSM: – Probe the FLAVOUR – CHANGING NEUTRAL CURRENTS (FCNC), and constrain the anomalous $tq\gamma$ and tqZ couplings;

$$-\mathcal{L}_{\rm eff} = e\frac{\kappa_{q\gamma}}{\Lambda}\bar{q}i\sigma^{\mu\nu}k_\nu[\gamma_L P_L + \gamma_R P_R]tA_\mu + \frac{g}{2\cos\theta_w}\frac{\kappa_{qZ}}{\Lambda}\bar{q}i\sigma^{\mu\nu}k_\nu[z_L P_L + z_R P_R]tZ_\mu$$

– Probe the ELECTROMAGNETIC DIPOLE MOMENTS (ElecDM) OF THE TOP QUARK, present when we consider anomalous $t\bar{t}\gamma$ couplings;

$$\mathcal{L}_{t\bar{t}\gamma} = -eQ_t\bar{t}\Gamma^\mu_{t\bar{t}\gamma}tA_\mu \quad \text{with} \quad \Gamma^\mu_{t\bar{t}\gamma} = \gamma^\mu + \frac{i}{2m_t}(a_V + ia_A\gamma_5)q_\nu\sigma^{\mu\nu}$$

– Probe the EXTRA DIMENSION MODELS (EDM), which imply the ttbar production through s– channel diagrams containing KK propagators.

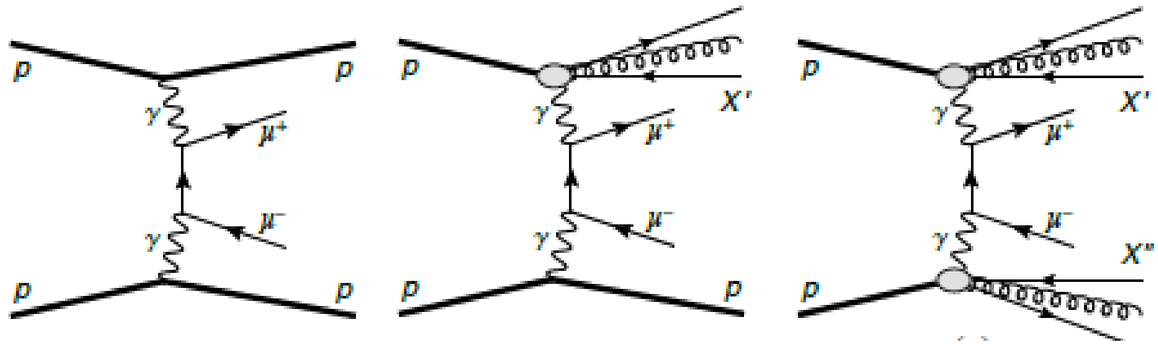


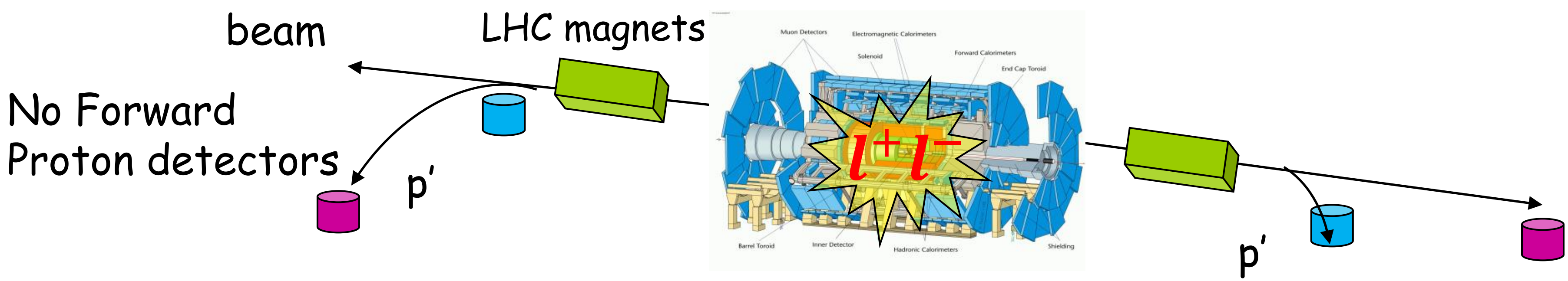
Photon-photon

Similarly for Photon-Pomeron & Pomeron-Pomeron

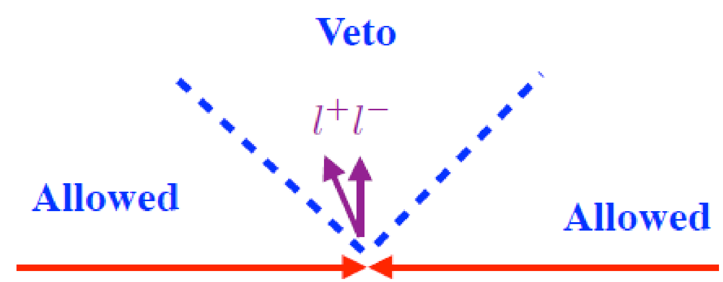
Use SuperChic4 for Exclusive γγ → ll

$$pp \rightarrow p\gamma\gamma p \rightarrow p \,\square\, l^{+}l^{-} \,\square\, p$$





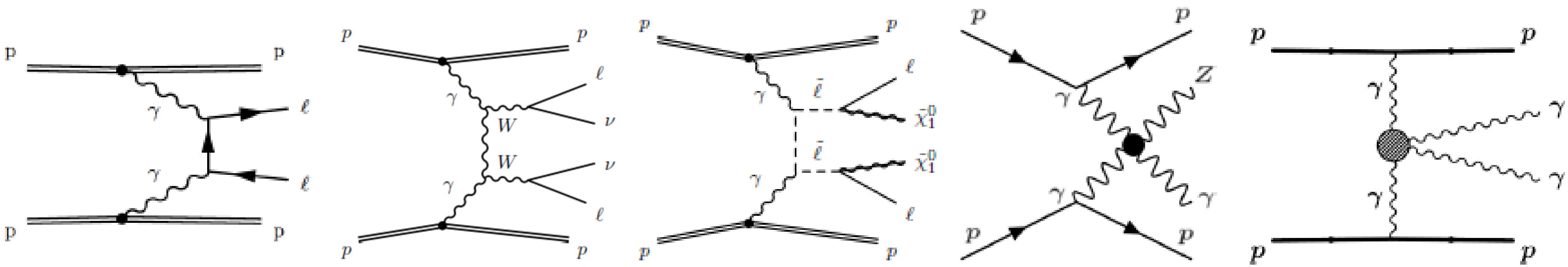
- Better modeling of Single and Double Dissociation
- Better modeling of LRG veto condition
- Fully kinematically-dependent soft survival S^2



SUPERCHIC

- ❑ MC event generator for Central Exclusive Processes (CEP). Common platform for:
  - **1) QCD-induced CEP**
  - **2) Photon-Photon CEP**
  - **3) Photoproduction**
- ❑ For pp, pA and AA collisions
- ❑ In LHE, HEPMC format – can be interfaced with Pythia, Herwig, …
- ❑ Applies Structure Function calculation: parameterizes all physics that goes on in the $\gamma p \to X$ vertex and uses precisely measured q/g PDFs from DIS data → get precision x, Q^2 for photon.
- ❑ Used in numerous LHC and Tevatron data analyses

- ❑ E.g. photon-photon CEP

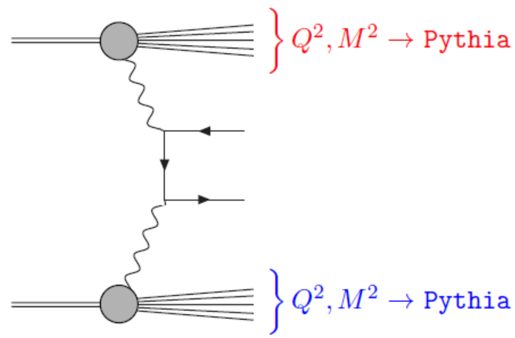


- ❑ All are elastic. SuperChic 4 provides Single-Dissociation (SD) and Double-Dissociation (DD) to dilepton production. SD/DD to other processes to be implemented soon.

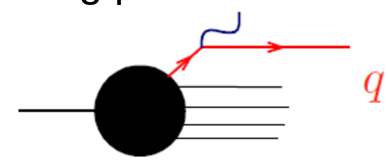
SUPERCHIC 4

Based on modern Structure Function approach (gives precision photon x, Q^2) – uniquely suited to deal with situation where we ask for limited hadronic activity / intact protons in photon interactions.

SuperChic 4 generates (semi)-exclusive dilepton events and interfaces to Pythia for showering / hadronization of dissociated system:



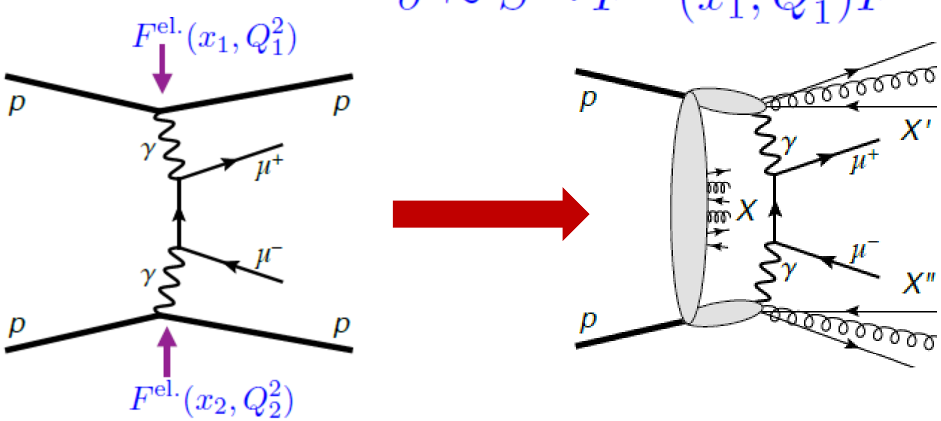
Showering: take LO q→qγ vertex and generate outgoing quark acc. to momentum conservation, preserving photon 4-momentum



Then simply impose veto at particle level after passing to Pythia.

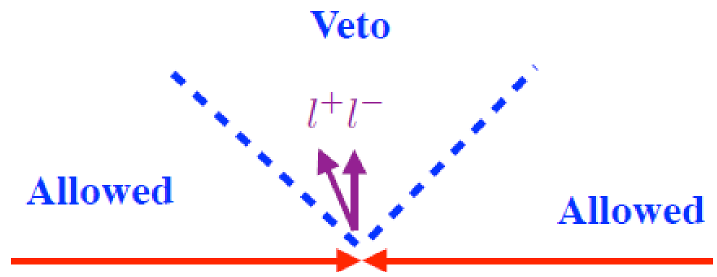
Survival factor S^2 = probability of no additional inelastic hadron-hadron interactions

$$\sigma \sim S^2 \cdot F^{\mathrm{el.}}(x_1, Q_1^2) F^{\mathrm{el.}}(x_2, Q_2^2)$$



- Depends on σ^{inel} in soft regime, so on understanding of proton+strong interactions in non-perturbative regime.
- Phenomenological model tuned on wealth of elastic and inelastic data.
- Depends on type of process (EL/SD/DD) and precise kinematics.

SUPERCHIC 4: (Semi)-Exclusive l^+l^-

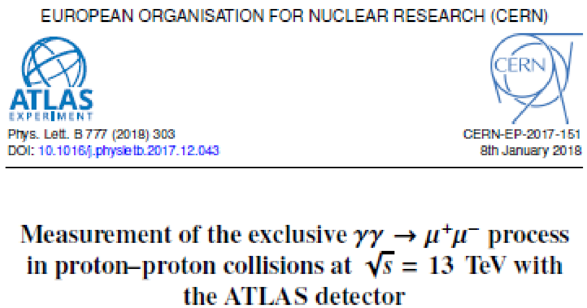


- Basic observable: fraction of events that pass veto on additional particles in certain region

- Very relevant experimentally: e.g. in selection of exclusive events without proton tagging.

Example: z-vertex veto: no additional tracks (so |η|<2.5) in region $|z_{vtx}$ - $z_{trk}|$ < 1 mm.

Like in



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

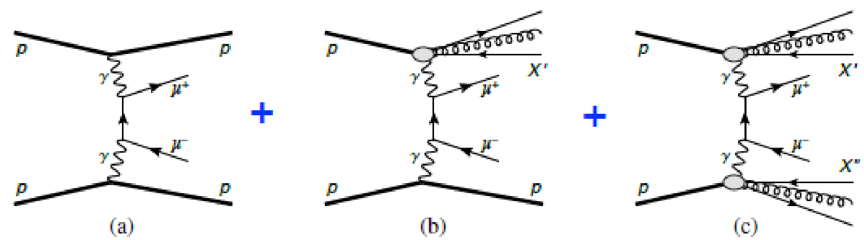
CERN

Phys. Lett. B 777 (2018) 303
DOI: 10.1016/j.physletb.2017.12.043

CERN-EP-2017-151
8th January 2018

Measurement of the exclusive $\gamma\gamma \to \mu^+\mu^-$ process in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

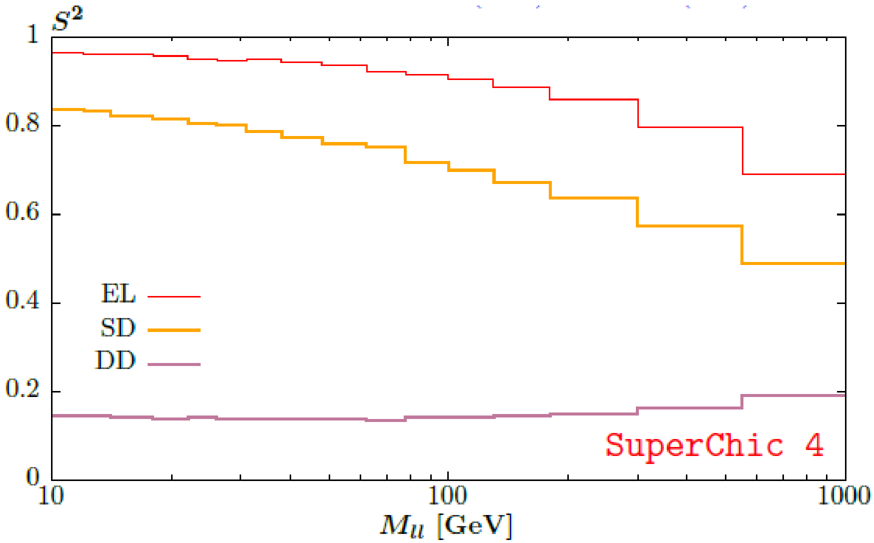
=



BUT: events where proton dissociation is outside the veto region pass this requirement!

Proton-dissociation background reduced by the cut on dilepton p_T and the exclusive signal extracted by subtracting SD and DD backgrounds using outdated models. SuperChic 4 provides more exact and more inclusive modelling.

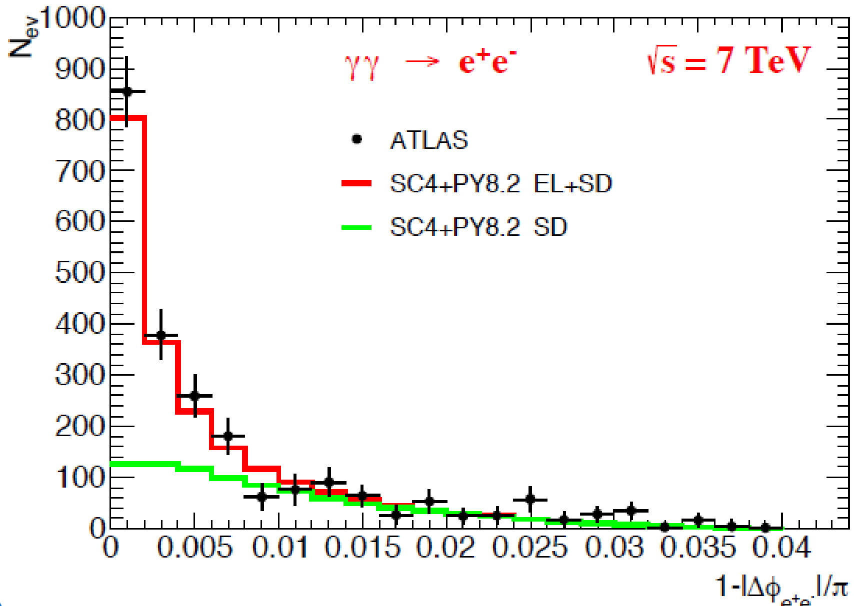
SUPERCHIC 4: Results

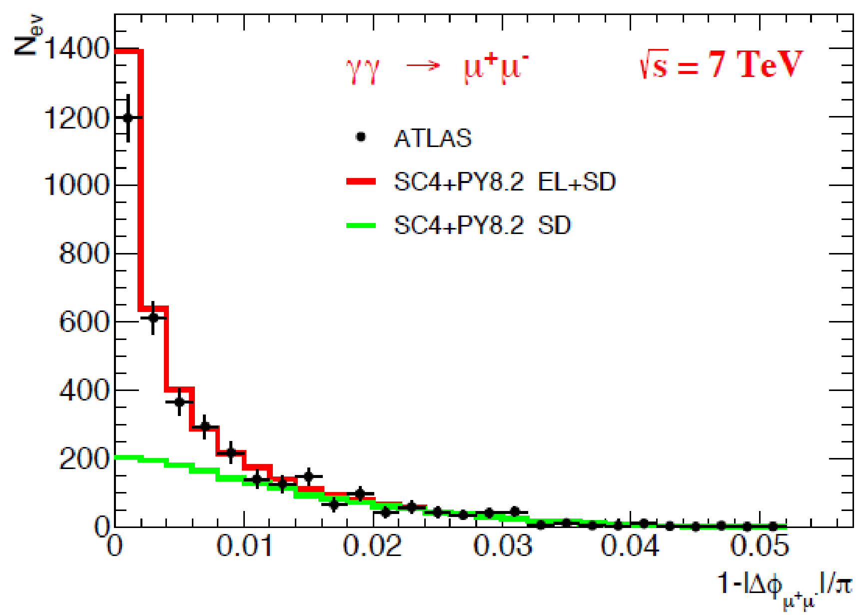


$S^2(EL) > S^2(SD) > S^2(DD)$: expected, since $b_\perp(EL) > b_\perp(SD) > b_\perp(DD)$.

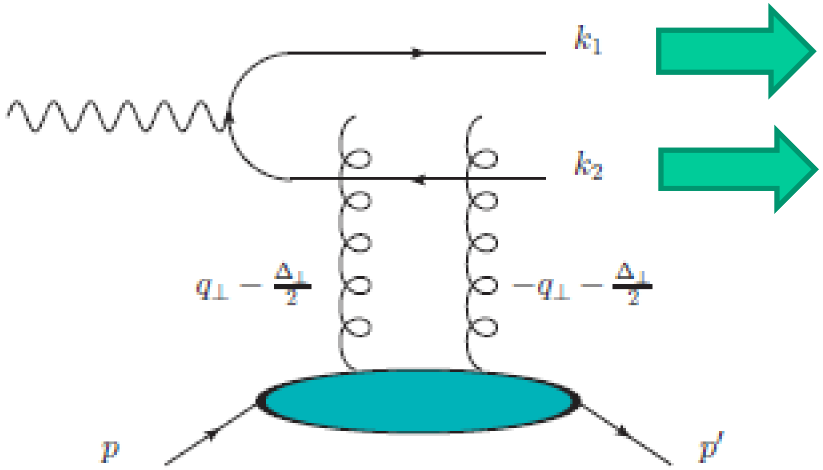
$Q^2 \sim 0 \rightarrow b_\perp(EL)$ large $\rightarrow S^2 \sim 1$

Comparison to data : ATLAS 7 TeV semi-exclusive dilepton selected by z-vertex veto on tracks.
DD subtracted from data using an outdated model.
Overall a good description by SuperChic 4.





Diffractive dijet production



Altinoluk, Armesto, Beuf, Rezaeian (2015)
YH, Xiao, Yuan (2016)

$$\vec{\Delta}_\perp = -(\vec{k}_{1\perp} + \vec{k}_{2\perp})$$

Proton recoil momentum

$$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$$

Dijet relative momentum

Fourier transform of $S(\vec{r}_\perp, \vec{b}_\perp)$

$$\frac{d\sigma^{\gamma_T^* A \to q\bar{q}X}}{dy_1 d^2k_{1\perp} dy_2 d^2k_{2\perp}} \propto z(1-z)[z^2+(1-z)^2] \int d^2q_\perp d^2q'_\perp S(q_\perp, \Delta_\perp) S(q'_\perp, \Delta_\perp)$$

$$\times \left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp - \vec{q}_\perp}{(P_\perp - q_\perp)^2+\epsilon^2}\right] \cdot \left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp - \vec{q}'_\perp}{(P_\perp - q'_\perp)^2+\epsilon^2}\right]$$

$$\sim \left(S(\vec{P}_\perp, \vec{\Delta}_\perp)\right)^2$$

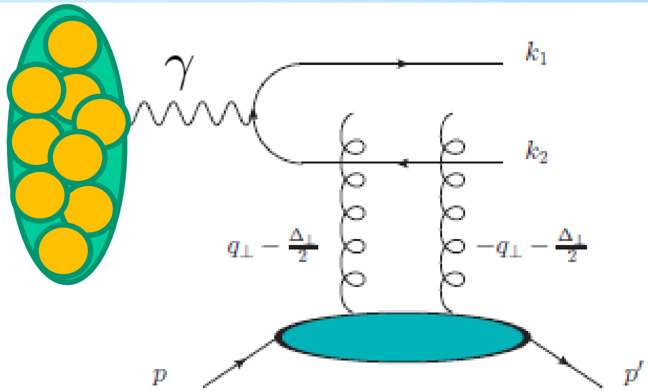
dominated by $q_\perp \sim P_\perp$ for small-Q^2

\`Elliptic' Wigner distribution: $\cos 2\phi$ correlation between $\vec{P}_\perp$ and $\vec{\Delta}_\perp$ expected at small-x

$$W(x, \vec{k}_\perp, \vec{b}_\perp) = W_0(x, k_\perp, b_\perp) + 2\cos 2(\phi_k - \phi_b) W_1(x, k_\perp, b_\perp) + \cdots$$

$$\frac{d\sigma}{d^2k_{1\perp} d^2k_{2\perp}} \sim d\sigma_0 + 2\cos 2(\phi_P - \phi_\Delta) d\tilde{\sigma}$$

Measuring Wigner in ultra-peripheral pA collisions



Q^2 preferably small   YH, Xiao, Yuan (2016)

Use the Weiszäcker-Williams photons in UPC!

Hagiwara, Hatta et al. (2017)

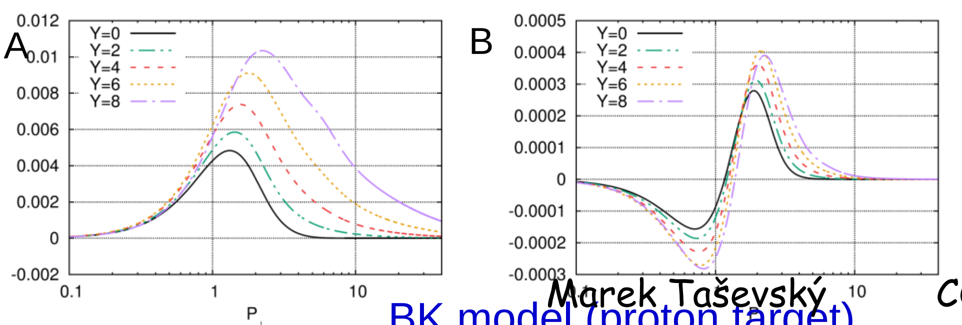
$$\frac{d\sigma^{pA}}{dy_1 dy_2 d^2\vec{k}_{1\perp} d^2\vec{k}_{2\perp}} = \omega \frac{dN}{d\omega} \frac{N_c \alpha_{em} (2\pi)^4}{P_\perp^2} \sum_f e_f^2 2z(1-z)(z^2+(1-z)^2)\left(A^2 + 2\cos 2(\phi_P - \phi_\Delta) AB\right)$$

photon flux $\propto Z^2$

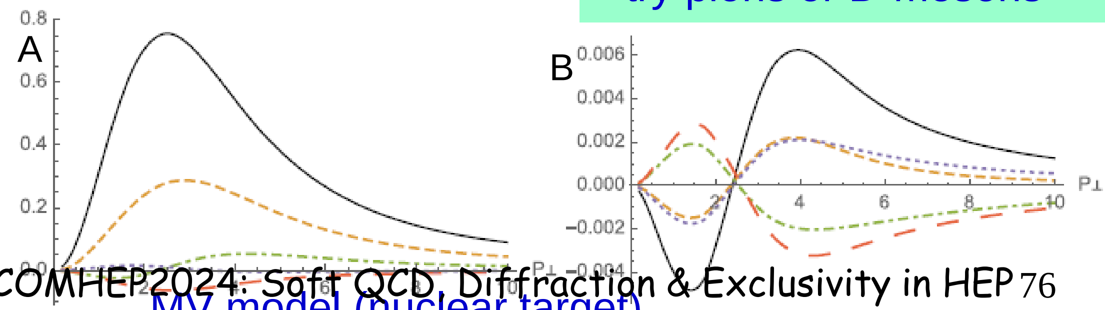
1) Integrate over all Φ_P & Φ_Δ angles → term ~AB disappears
2) Measure x-sec as a function of $P_\perp$ & integrated over $\Delta_\perp$ and vice versa → get A($p_\perp$,$\Delta_\perp$)
3) Measure (Φ_P-Φ_Δ)-dependence of x-sec in bins of $P_\perp$& $\Delta_\perp$ → B($p_\perp$,$\Delta_\perp$)
4) From S_0 and S_1 get Wigner function

Effect visible only at low scales → dijets at LHC not favorable
- try pions or D-mesons

$$S_0(P_\perp, \Delta_\perp) = \frac{1}{P_\perp} \frac{\partial}{\partial P_\perp} A(P_\perp, \Delta_\perp). \quad S_1(P_\perp, \Delta_\perp) = \frac{\partial B(P_\perp, \Delta_\perp)}{\partial P_\perp^2} - \frac{2}{P_\perp^2} \int^{P_\perp^2} \frac{dP_\perp'^2}{P_\perp'^2} B(P_\perp', \Delta_\perp)$$



BK model (proton target)



MV model (nuclear target)