Top quark pair production in photon-photon collisions at the LHC

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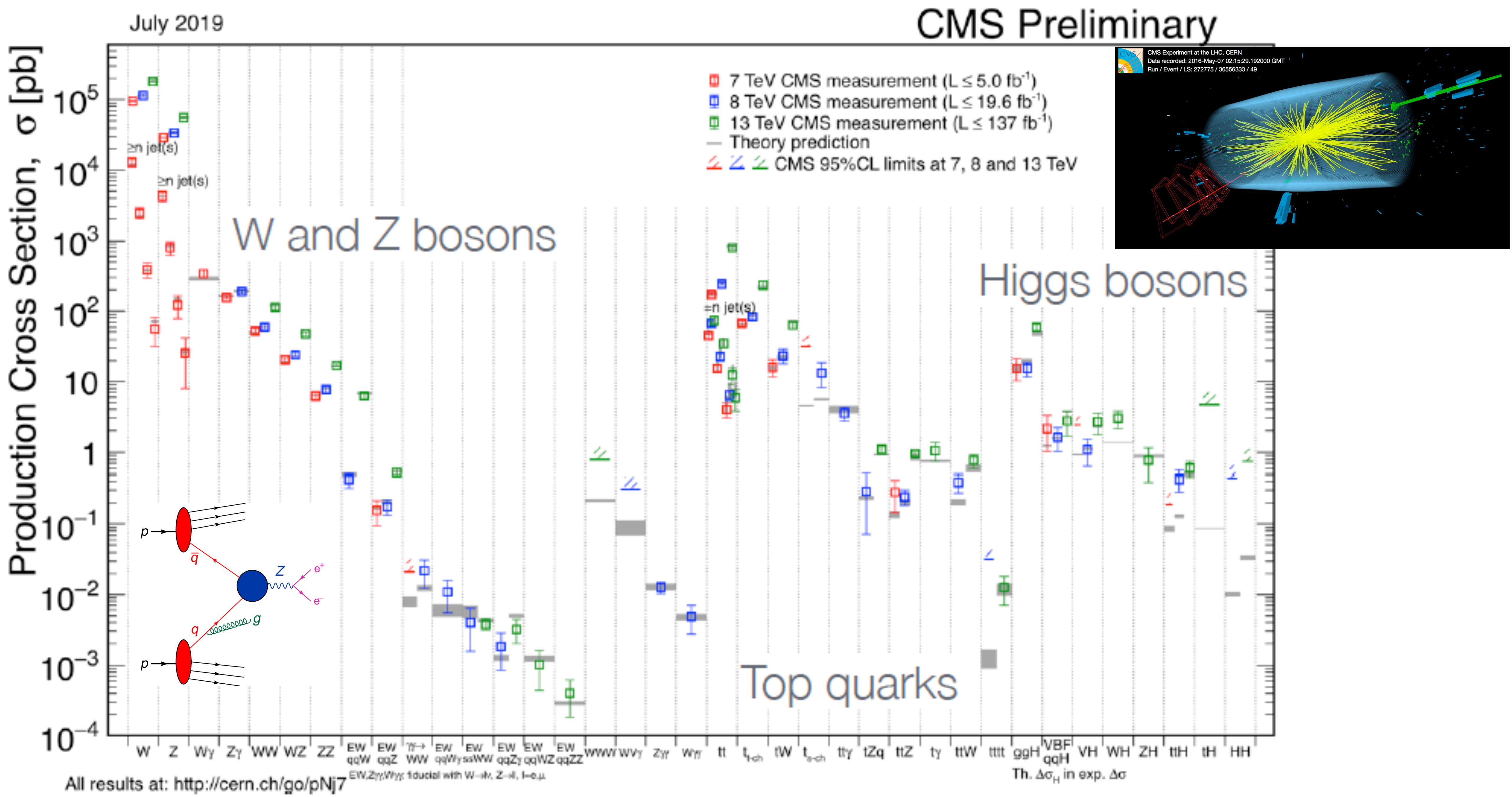
Introduction

- **Very impressive SM cross section measurements at the LHC**
  - **many processes are at percent even subpercent level**

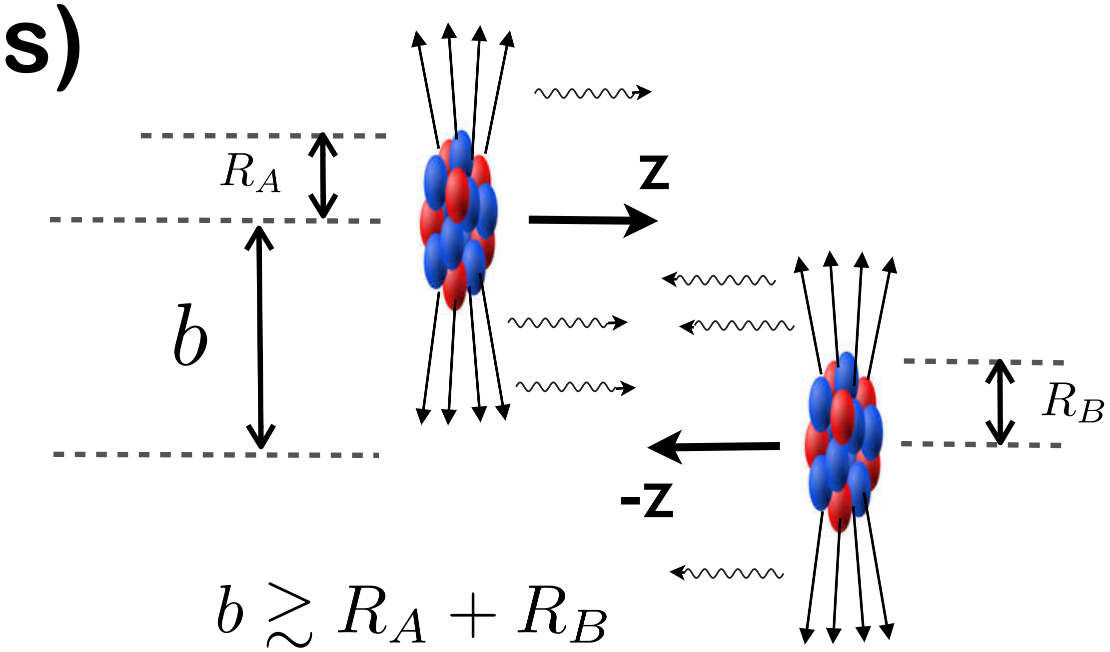


- Mainly quarks and gluons (photon density ~ 1% of quark density)

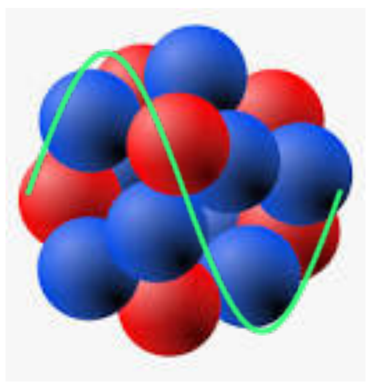
Introduction

- **Ultra-Peripheral Collisions (UPCs)**
- **Large photon flux** $\propto Z^2$
- **Cross section enhanced by** Z^4

  E.g., PbPb is Z^4 = 45M times larger than pp & e+e-



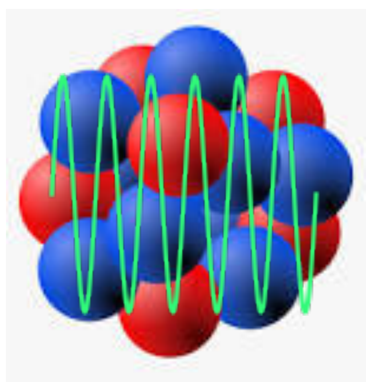
- **Photon may interact either coherently or incoherently**



$\lambda \gtrsim R_A$

Coherent

vs



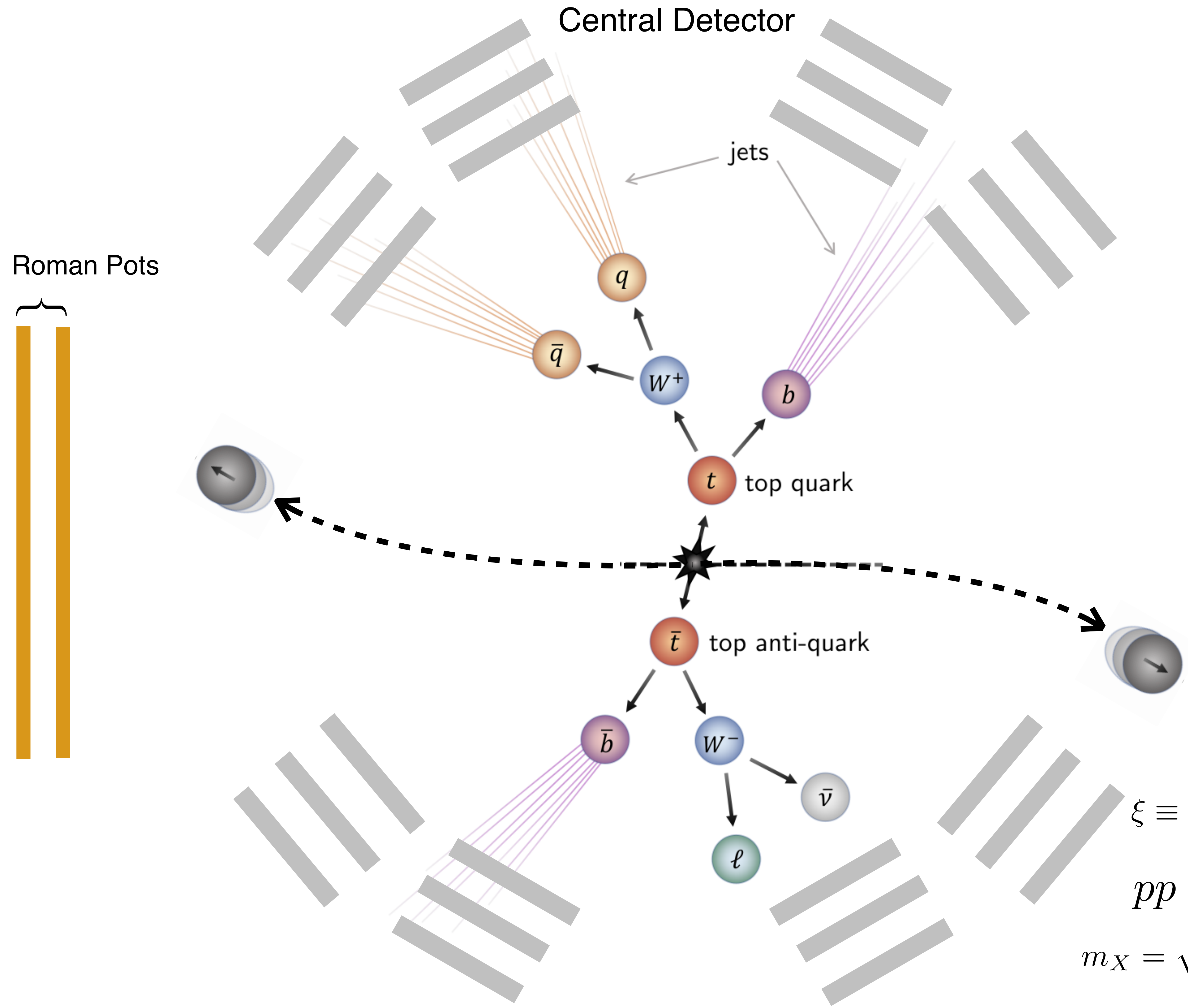
$\lambda < R_A$

Incoherent

- **Coherent photon virtuality** $Q^2 < R_A^{-2}$

⇨ Equivalent Photon Approximation


proton
proton

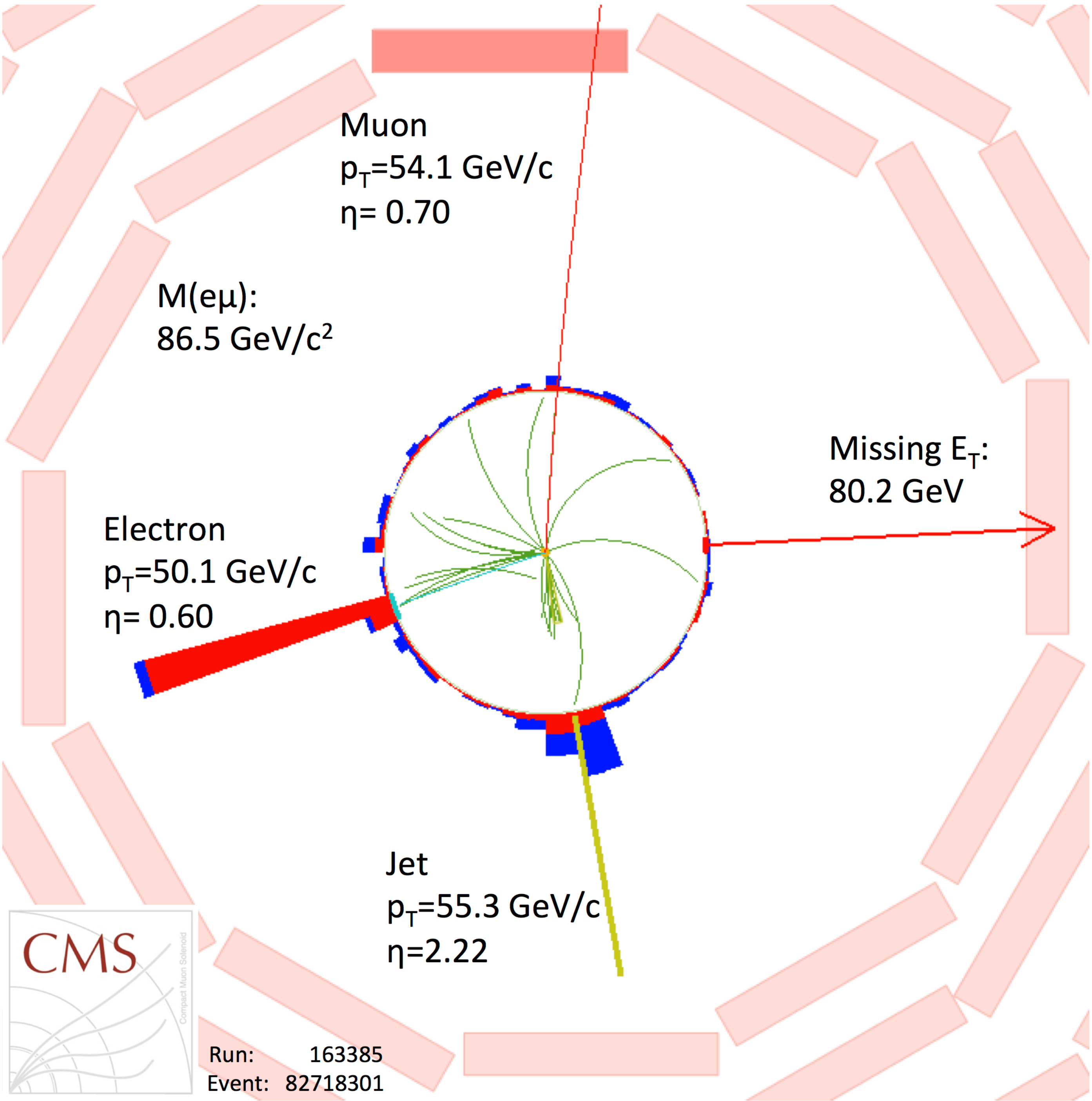


$$\xi \equiv \frac{|\vec{p}_i| - |\vec{p}_o|}{|\vec{p}_i|} \gtrsim 0.02$$

$$pp \to pXp$$

$$m_X = \sqrt{s\xi_1\xi_2} \gtrsim 260 \text{ GeV}$$

How do events look like ?



Most collisions have enormous multiplicities.

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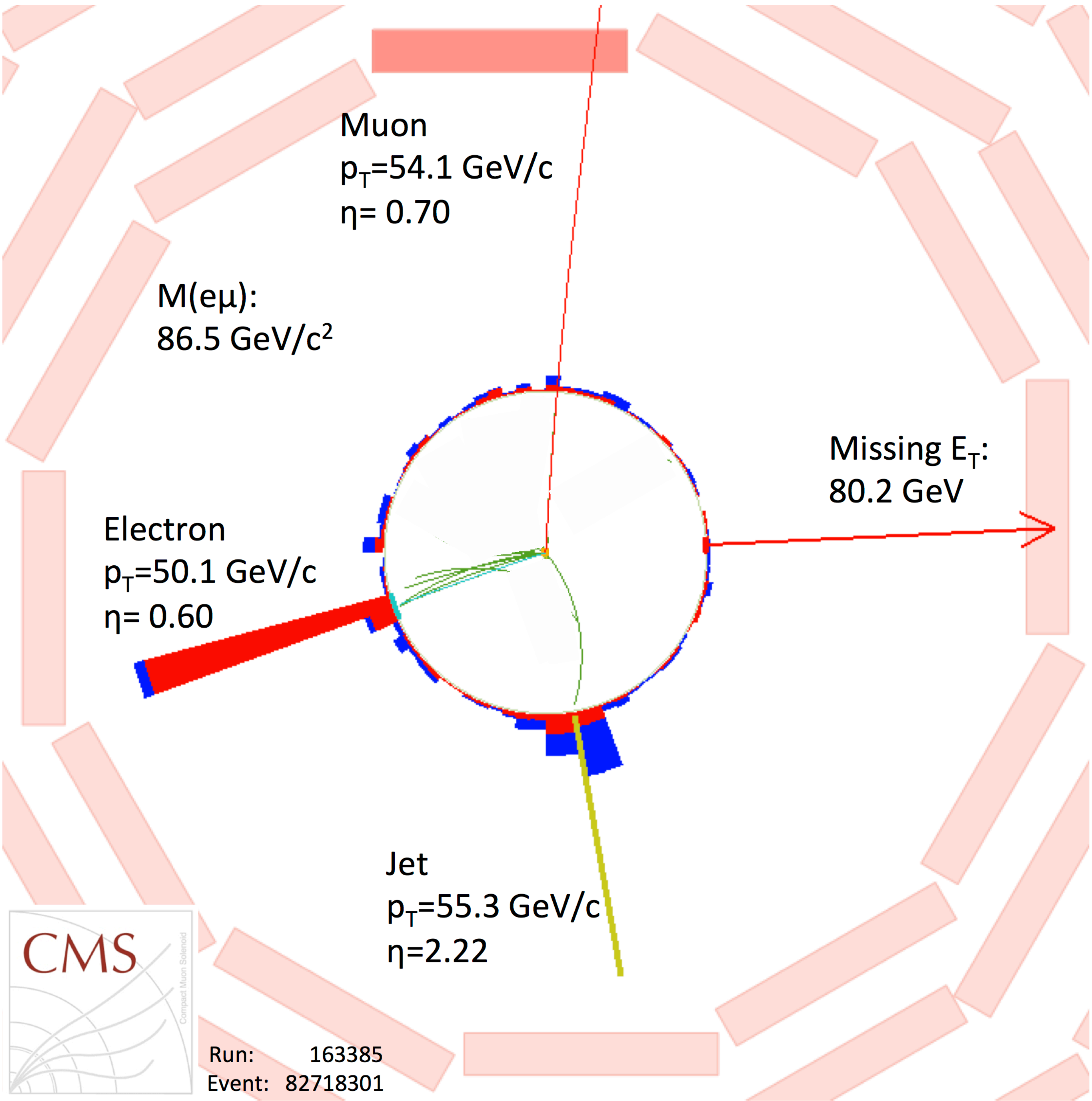
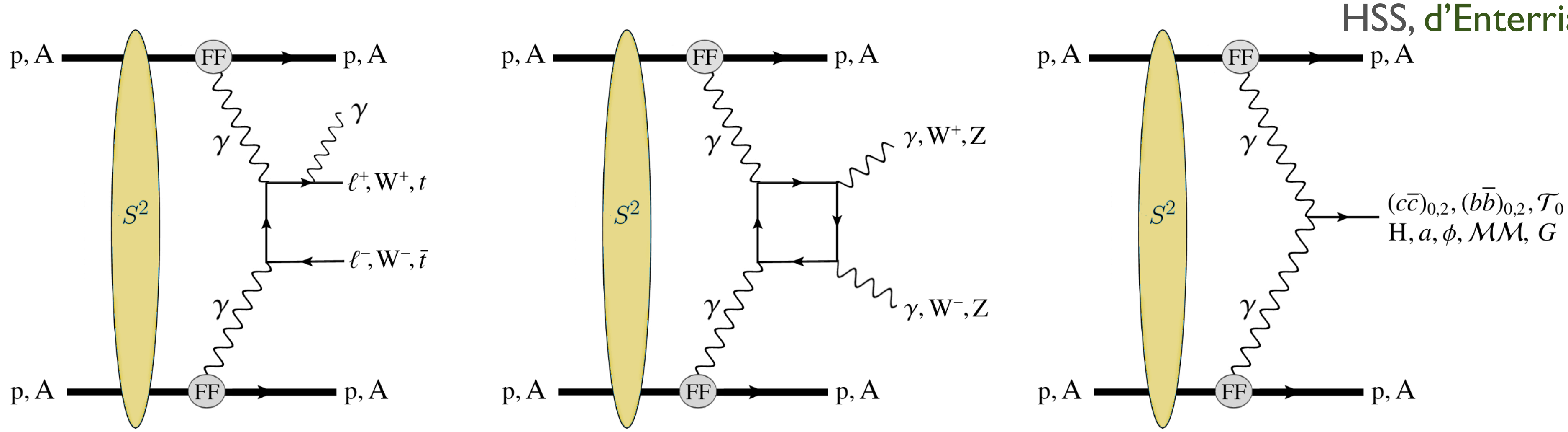


UPC: low multiplicities

- **Gold-plated SM and BSM processes**

Process	Physics motivation
$\gamma\gamma \to e^+e^-, \mu^+\mu^-$	"Standard candles" for proton/nucleus γ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \to \tau^+\tau^-$	Anomalous τ lepton e.m. moments [29–32]
$\gamma\gamma \to \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], noncommut. interactions [36], extra dims. [37],...
$\gamma\gamma \to \mathcal{T}_0$	Ditauonium properties (heaviest QED bound state) [38, 39]
$\gamma\gamma \to (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$	Properties of scalar and tensor charmonia and bottomonia [40, 41]
$\gamma\gamma \to$ XYZ	Properties of spin-even XYZ heavy-quark exotic states [42]
$\gamma\gamma \to$ VM VM	(with VM = ρ, ω, ϕ, J/ψ, Υ): BFKL-Pomeron dynamics [43–46]
$\gamma\gamma \to$ W$^+$W$^-$, ZZ, Zγ, $\cdots$	anomalous quartic gauge couplings [11, 26, 47, 48]
$\gamma\gamma \to$ H	Higgs-γ coupling, total H width [49, 50]
$\gamma\gamma \to$ HH	Higgs potential [51], quartic $\gamma\gamma$HH coupling
$\gamma\gamma \to t\bar{t}$	anomalous top-quark e.m. couplings [11, 49]
$\gamma\gamma \to \tilde{\ell}\tilde{\ell}, \tilde{\chi}^+\tilde{\chi}^-$, H^{++}H^{--}	SUSY pairs: slepton [11, 52, 53], chargino [11, 54], doubly-charged Higgs bosons [11, 55].
$\gamma\gamma \to a, \phi, \mathcal{MM}, G$	ALPs [27, 56], radions [57], monopoles [58–61], gravitons [62–64],...

HSS, d'Enterria (2207.03012, JHEP'22)



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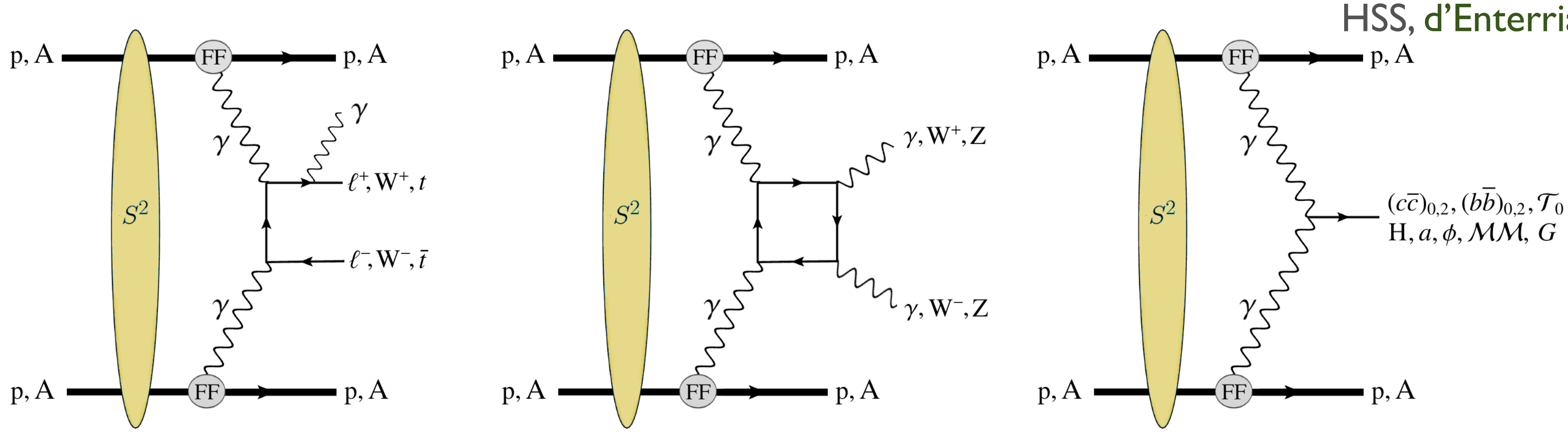
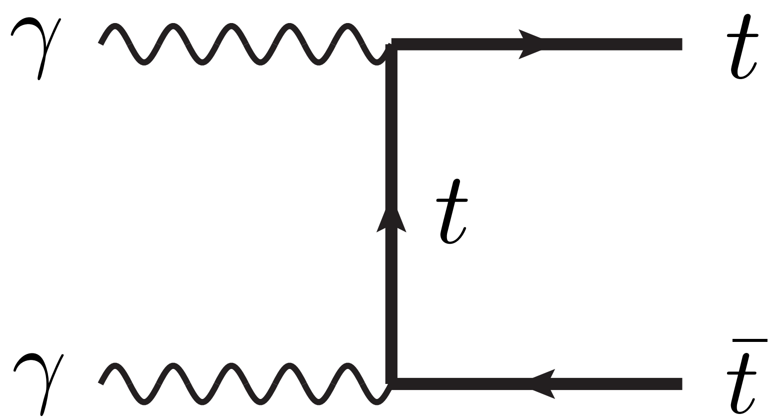


Motivation

- **Why $\gamma\gamma \to t\bar{t}$? Or what we can learn ?**
  - Electric charge and electromagnetic dipole moments

Fayazbakhsh et al. (PRD'15)



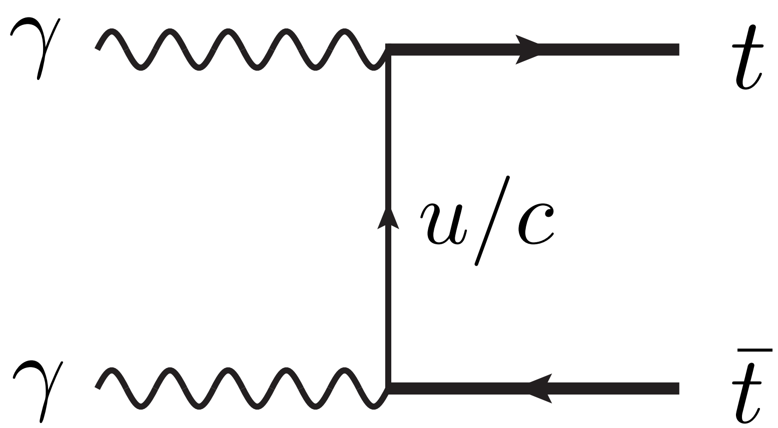
$$\mathcal{L}_{\rm eff} = -ieQ_t \bar{t}\Gamma^\mu t A_\mu$$

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_t}\left[iF_2(q^2) + F_3(q^2)\gamma_5\right]$$

$$F_2(0) = a_t = (g-2)_t/2$$

  - FCNC and anomalous top-photon couplings

Howarth (2008.04249); Baldenegro et al. (JHEP'22)



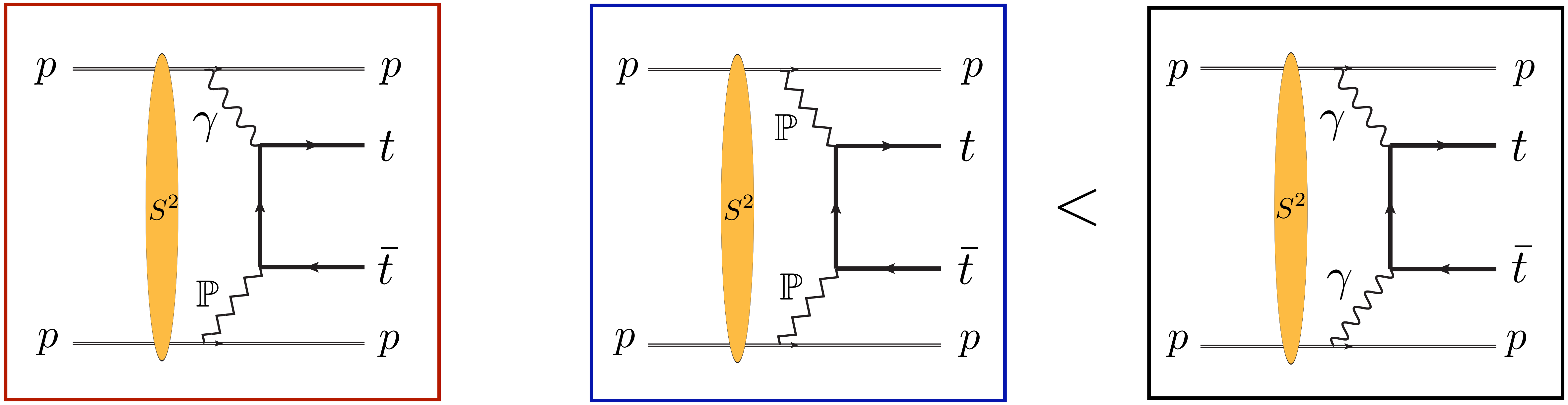
$$\mathcal{L}_{\rm FCNC} = -e\frac{\kappa^\gamma_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}\left(f^\gamma_{tq} + ih^\gamma_{tq}\gamma_5\right)qF_{\mu\nu} + {\rm h.c.}$$

  - Other BSM enhancements, e.g., resonances and extra-dim models

Baldenegro et al. (JHEP'22); Inan, Billur (PRD'11)

  - Elastic photon flux and soft survival probability at large ξ

Central exclusive production



Generator Setting	$\sigma_{(p\mathbb{P}\to t\bar{t})}$ [pb]	$\sigma_{(\gamma p\to t\bar{t})}$ [pb]	$\sigma_{(\gamma\mathbb{P}\to t\bar{t})}$ [pb]	$\sigma_{(\mathbb{P}\mathbb{P}\to t\bar{t})}$ [pb]	$\sigma_{(\gamma\gamma\to t\bar{t})}$ [pb]
SuperChic (isurv = 1)	–	–	–	$1.22(1)\cdot 10^{-5}$	$2.05(2)\cdot 10^{-4}$
(isurv = 2)	–	–	–	$3.21(2)\cdot 10^{-5}$	$2.06(1)\cdot 10^{-4}$
(isurv = 3)	–	–	–	$2.05(1)\cdot 10^{-5}$	$2.05(1)\cdot 10^{-4}$
(isurv = 4)	–	–	–	$1.59(1)\cdot 10^{-5}$	$2.06(1)\cdot 10^{-4}$
(sfaci = false)	–	–	–	$1.73(1)\cdot 10^{-3}$	$2.77(2)\cdot 10^{-4}$
MadGraph	–	1.23	–	–	$3.33\cdot 10^{-4}$
PYTHIA (MPI: unchecked)	90.5(1)	1.45	$1.26(6)\cdot 10^{-1}$	–	$4.56(2)\cdot 10^{-4}$
(MPI: checked)	5.14(5)	1.46	$1.27(6)\cdot 10^{-1}$	–	$4.57(2)\cdot 10^{-4}$
FPMC[7]	–	–	$5.2\cdot 10^{-2}$	$2.84\cdot 10^{-2}$	$3.4\cdot 10^{-4}$

- Pomeron related processes have large uncertainties
- Photon-photon is relatively well understood theoretically

Howarth (2008.04249)

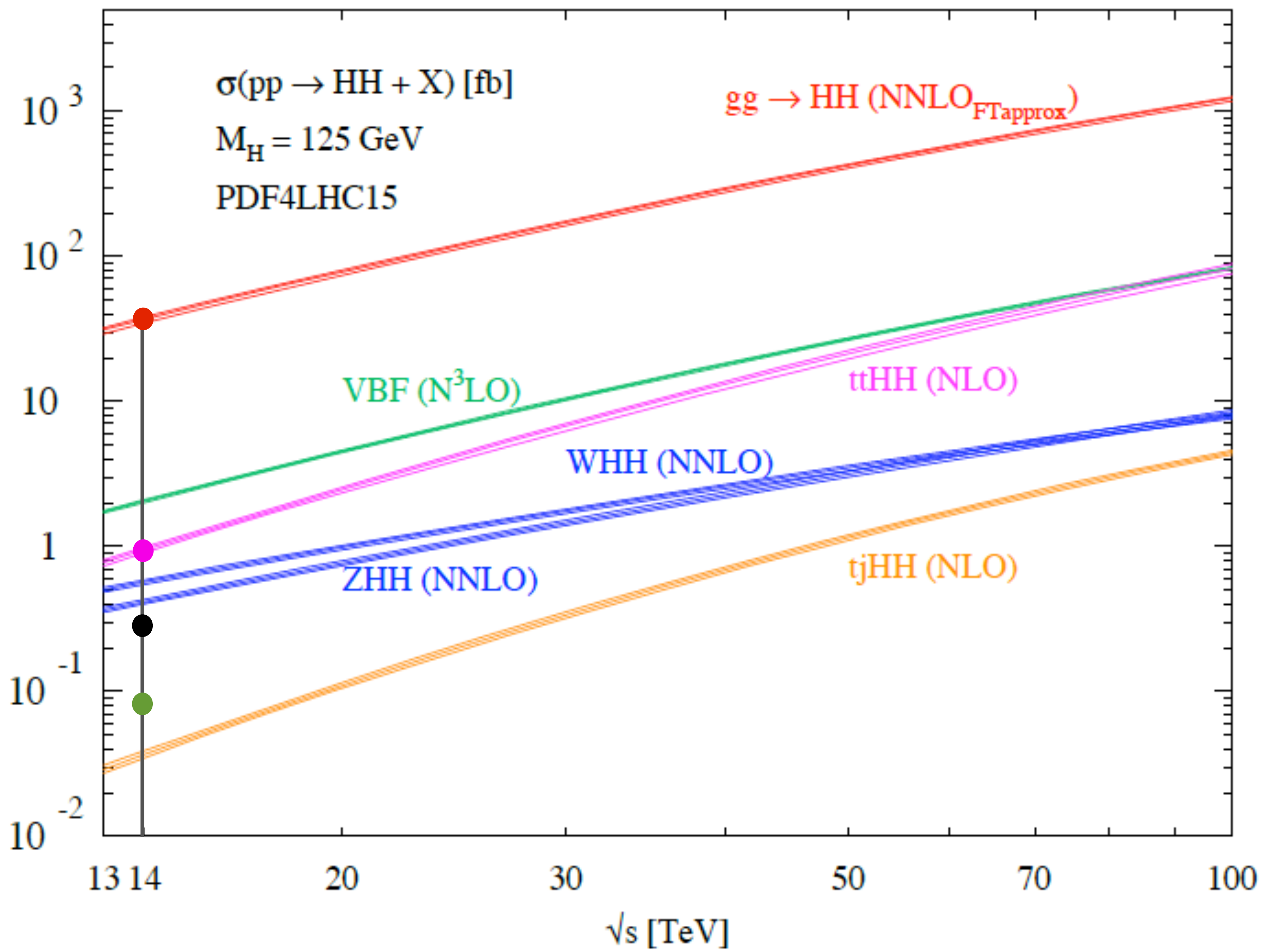
Feasibility at the LHC

- $\gamma\gamma \to t\bar{t}$ **is a (very) rare process in the SM** CMS (2103.02752)

but can be observed at HL-LHC

$$\sigma(\gamma\gamma \to t\bar{t}) \simeq 0.3 \text{ fb}$$

in pp at 13-14 TeV



$$\sigma_{hh}^{\text{NNLO}_{\text{FTapprox}}} = 36.69 \text{ fb}$$

$$\sigma_{t\bar{t}hh}^{\text{NLO}} = 0.98 \text{ fb}$$

$$\sigma_{hhh}^{\text{NLO}_{\text{FTapprox}}} = 89.4 \text{ ab}$$

https://hshao.web.cern.ch/hshao/gammaupc.html

Why do we need gamma-UPC ?

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- **Our aim is to generate any final state of interest**

MadGraph5_aMC@NLO

- Final state of elementary particles in SM and BSM both at LO and NLO QCD+EW

HELAC-Onia

- Final state of elementary particles and quarkonia (including B_c) in SM at tree level

✦ Both can generate the standard Les Houches event files to allow to interface to general-purpose Monte Carlo tools (e.g. Pythia)

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- **We need (realistic) photon-photon flux in UPC**

→ **gamma-UPC**

Theoretical Framework

- **Cross section:**

$$\sigma(\mathrm{A}\ \mathrm{B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

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- **Effective two-photon luminosity:**

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$$\times\theta(b_1 - \epsilon R_{\mathrm{A}})\theta(b_2 - \epsilon R_{\mathrm{B}})$$

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- **No hadronic/inelastic interaction probability density:**

$$P_{\mathrm{no\,inel}}(b) = \begin{cases} e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{AB}}(b)}, & \text{nucleus-nucleus} \\ e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{A}}(b)}, & \text{proton-nucleus} \\ \left|1-\Gamma(s_{\mathrm{NN}},b)\right|^2, \quad \text{with} \ \ \Gamma(s_{\mathrm{NN}},b) \propto e^{-b^2/(2b_0)} & \text{p-p} \end{cases}$$

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Glauber model

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- **No hadronic/inela**

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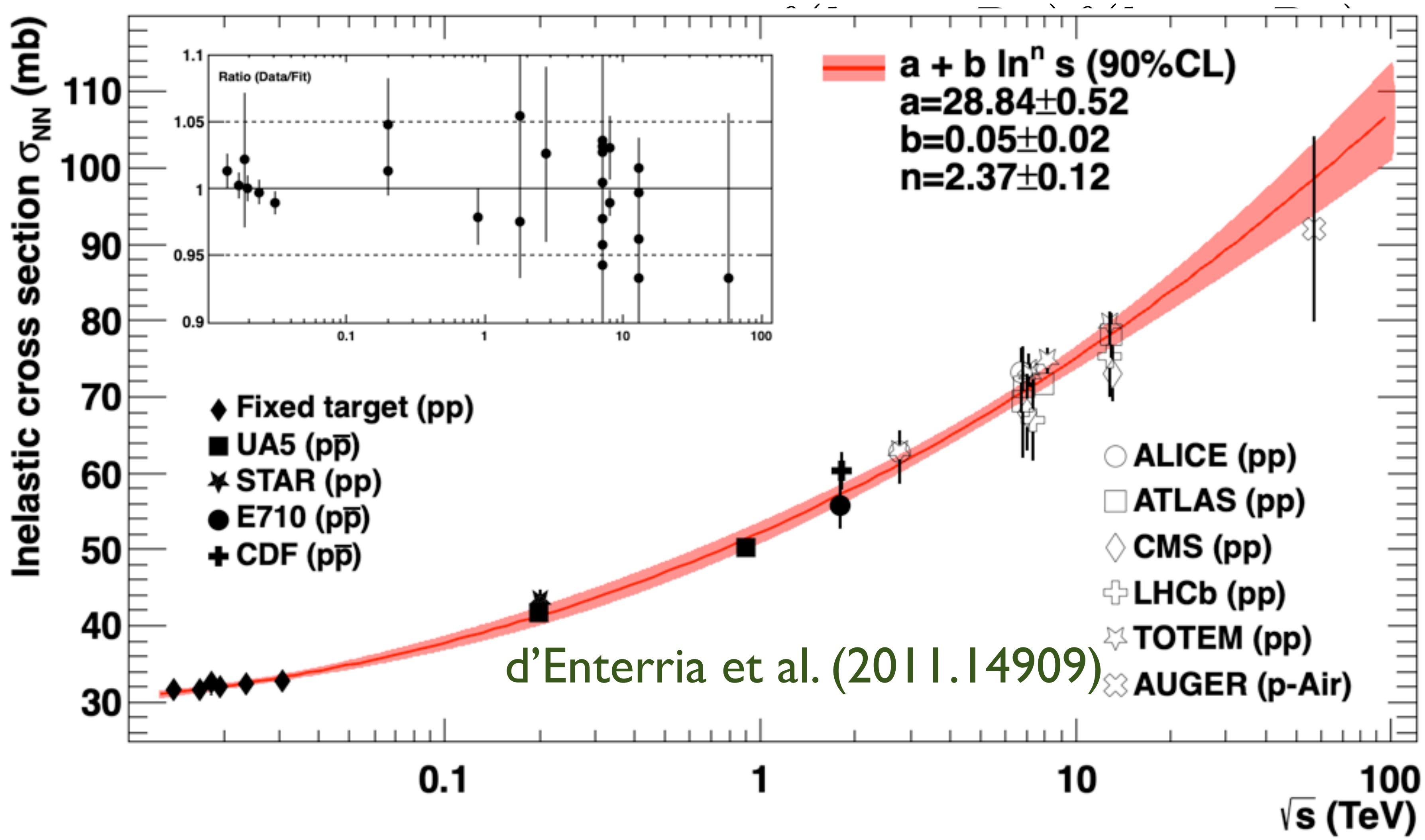


d'Enterria et al. (2011.14909)

Theoretical Framework

- **Cross**

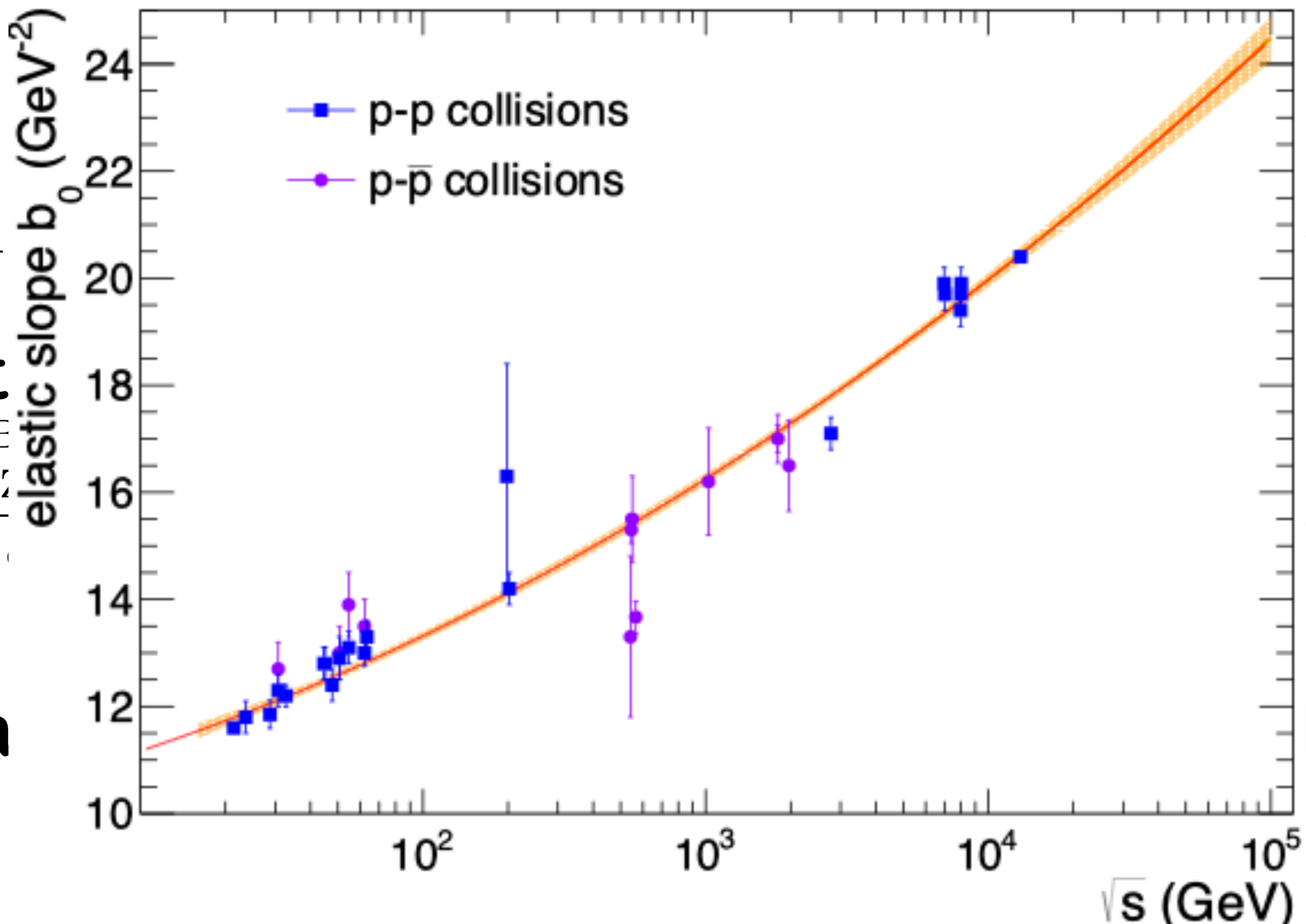
$\sigma(\mathrm{A}$ … $\cdot\sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$

- **Effect**

$\frac{\mathrm{d}^2 N^{(\mathrm{AE}}_{\gamma_1/\mathrm{Z}}}{\mathrm{d}E_{\gamma_1}}$ … $_{\gamma_1},\boldsymbol{b}_1)N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2},\boldsymbol{b}_2)$

… $_1-\epsilon R_\mathrm{A})\theta(b_2-\epsilon R_\mathrm{B})$

- **No ha** … **ity density:**



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- **The photon number density:**
  - Two form factors

Two Form Factors

- **Electric dipole form factor (EDFF)**
  - Same as STARlight

$$N^{\rm EDFF}_{\gamma/{\rm Z}}(E_\gamma,b)=\frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi)+\frac{1}{\gamma_{\rm L}^2}K_0^2(\xi)\right]\qquad \xi=\frac{E_\gamma b}{\gamma_{\rm L}}$$

- **Charge form factor (ChFF)**

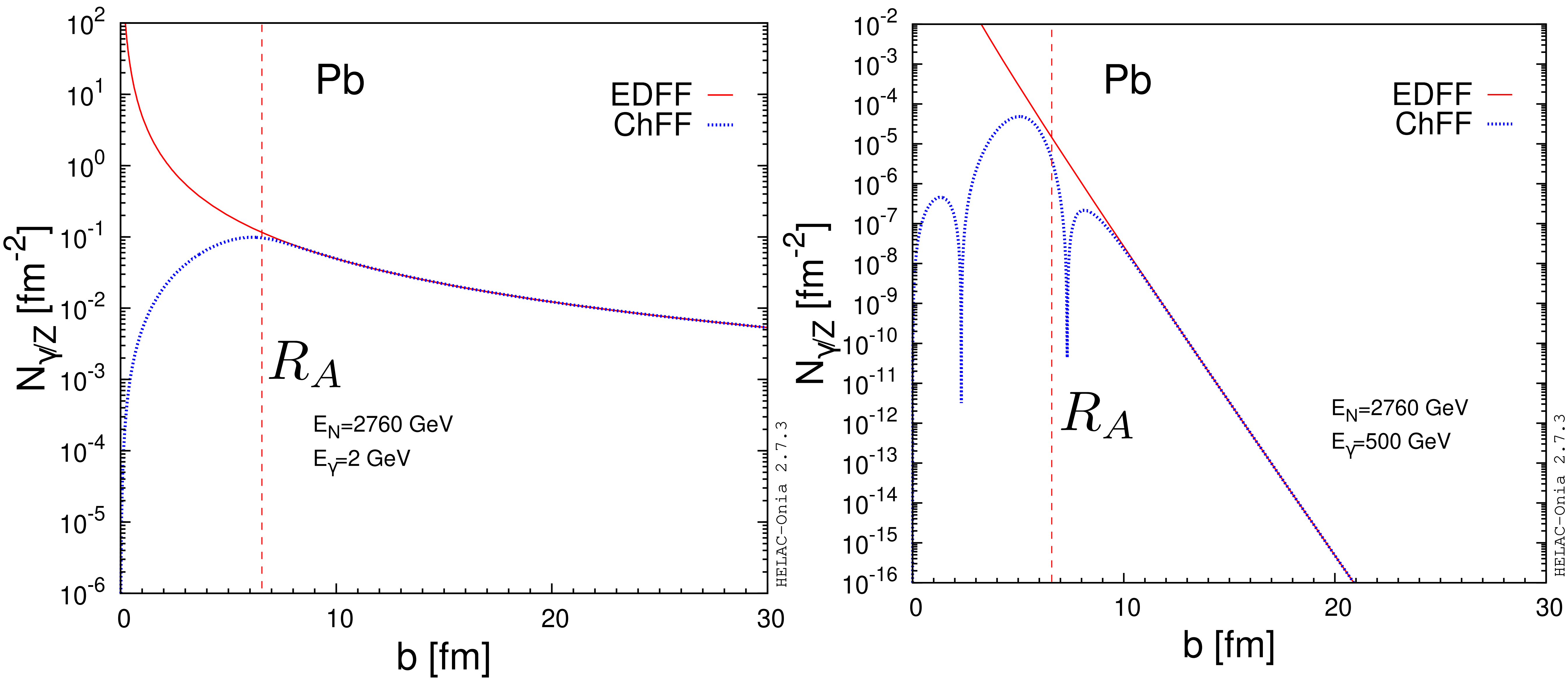
$$N^{\rm ChFF}_{\gamma/{\rm Z}}(E_\gamma,b)=\frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty}\frac{dk_\perp k_\perp^2}{k_\perp^2+E_\gamma^2/\gamma_{\rm L}^2}F_{\rm ch,A}\left(\sqrt{k_\perp^2+E_\gamma^2/\gamma_{\rm L}^2}\right)J_1\left(bk_\perp\right)\right|^2$$

$$F_{\rm ch,A}(q)=\int {\rm d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\underline{\rho_{\rm A}(\boldsymbol{r})}=\frac{4\pi}{q}\int_0^{+\infty}{\rm d}r\rho_{\rm A}(r)r\sin\left(qr\right)$$

density profile of nuclei normalised to unity

Photon number density

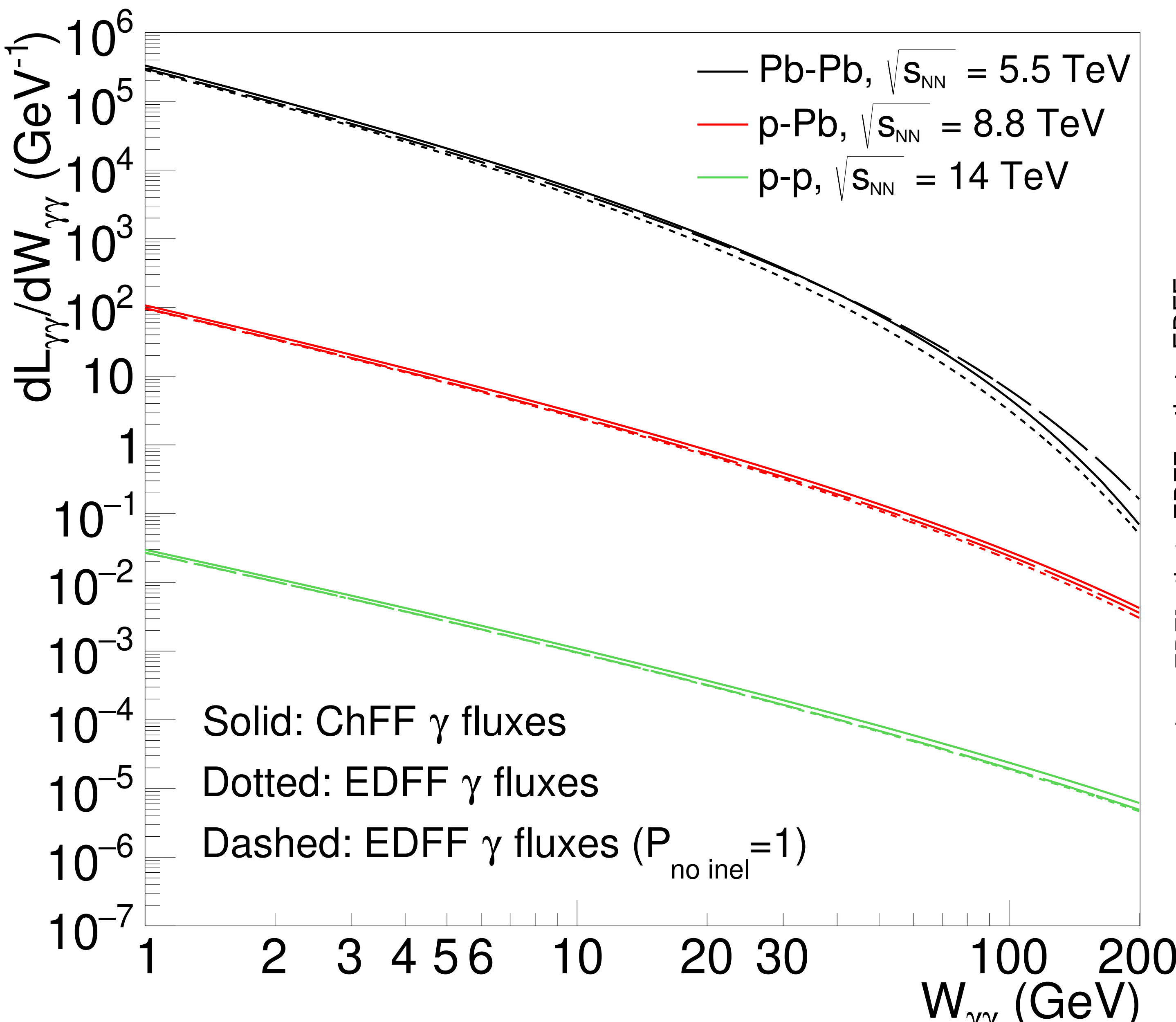
- **EDFF vs ChFF**

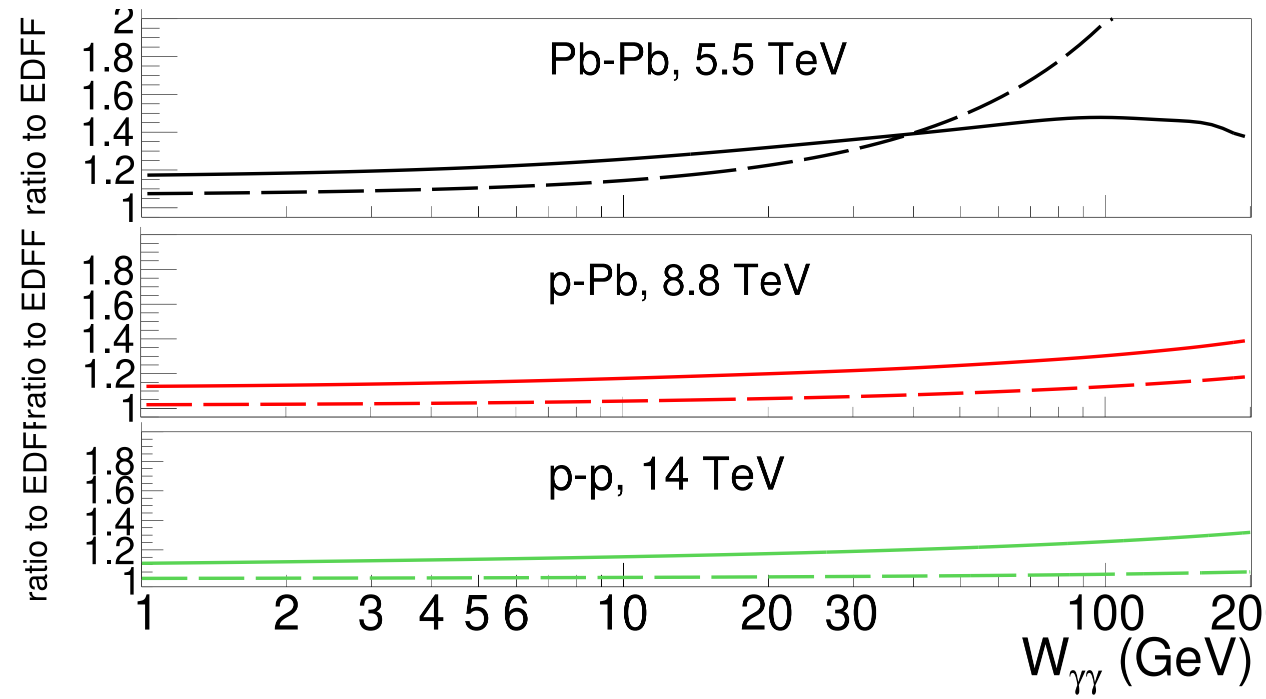


- Main difference comes from the $b < R_A$ regime
- EDFF photon number density is divergent at $b = 0$
  - Need a (arbitrary) cutoff when convoluting with ME

Effective two-photon luminosity

- **EDFF vs ChFF**





- Survival probability reduces luminosity

  impact: $\mathrm{AA} > \mathrm{pA} > \mathrm{pp}$ *and increase with* $\mathrm{W}_{\gamma\gamma}$

- ChFF > EDFF and enhancement increases slowly with $\mathrm{W}_{\gamma\gamma}$

gamma-UPC+MadGraph5_aMC@NLO

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- Leading Order (already in version >= 3.5.0)

HSS, d'Enterria (JHEP'22)

```
./bin/mg5_aMC
MG5_aMC> import model <a model>
MG5_aMC> generate a a > t t~
MG5_aMC> output; launch
```

- Next-to-Leading Order QCD and/or EW (to be released)

HSS, Simon (2504.10104)

```
./bin/mg5_aMC
MG5_aMC> import model loop_qcd_qed_sm_Gmu-a0
MG5_aMC> generate !a! !a! > t t~ [QCD QED]
MG5_aMC> output; launch
```

Total Cross Sections

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Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC+MG5_aMC		
Colliding system, c.m. energy	σ_{LO}	$\sigma_{\text{NLO QCD}}$	$\sigma_{\text{NLO QCD+EW}}$
p-p at 13 TeV	212.40(6) ab	$256.43(9)^{+4.5}_{-3.7}$ ab	$244.8(1)^{+4.5}_{-3.7}$ ab
p-p at 13.6 TeV	228.53(6) ab	$275.5(1)^{+4.8}_{-4.0}$ ab	$263.1(1)^{+4.8}_{-4.0}$ ab
p-p at 14 TeV	239.58(7) ab	$288.7(1)^{+5.0}_{-4.2}$ ab	$275.5(1)^{+5.0}_{-4.2}$ ab
p-Pb at 8.8 TeV	46.89(1) fb	$59.87(2)^{+1.3}_{-1.1}$ fb	$57.32(2)^{+1.3}_{-1.1}$ fb
Pb-Pb at 5.52 TeV	30.64(1) fb	$39.08(1)^{+0.87}_{-0.72}$ fb	$37.43(1)^{+0.87}_{-0.72}$ fb
p-p at 100 TeV	2.3080(2) fb	$2.7111(2)^{+0.041}_{-0.034}$ fb	$2.5816(2)^{+0.041}_{-0.034}$ fb
p-Pb at 62.8 TeV	3.0742(2) pb	$3.6721(3)^{+0.061}_{-0.050}$ pb	$3.5045(3)^{+0.061}_{-0.050}$ pb
Pb-Pb at 39.4 TeV	0.9583(1) nb	$1.2062(2)^{+0.026}_{-0.021}$ nb	$1.1545(2)^{+0.026}_{-0.021}$ nb
K factor		$\sigma_{\text{NLO QCD}}/\sigma_{\text{LO}}$	$\sigma_{\text{NLO QCD+EW}}/\sigma_{\text{LO}}$
p-p at 13 TeV		1.207	1.153
p-p at 13.6 TeV		1.205	1.151
p-p at 14 TeV		1.205	1.151
p-Pb at 8.8 TeV		1.277	1.222
Pb-Pb at 5.52 TeV		1.276	1.222
p-p at 100 TeV		1.175	1.119
p-Pb at 62.8 TeV		1.194	1.140
Pb-Pb at 39.4 TeV		1.259	1.205

HSS, Simon (2504.10104)

- Sizable NLO QCD:

  +20%

- Non-negligible NLO EW:

  -5%

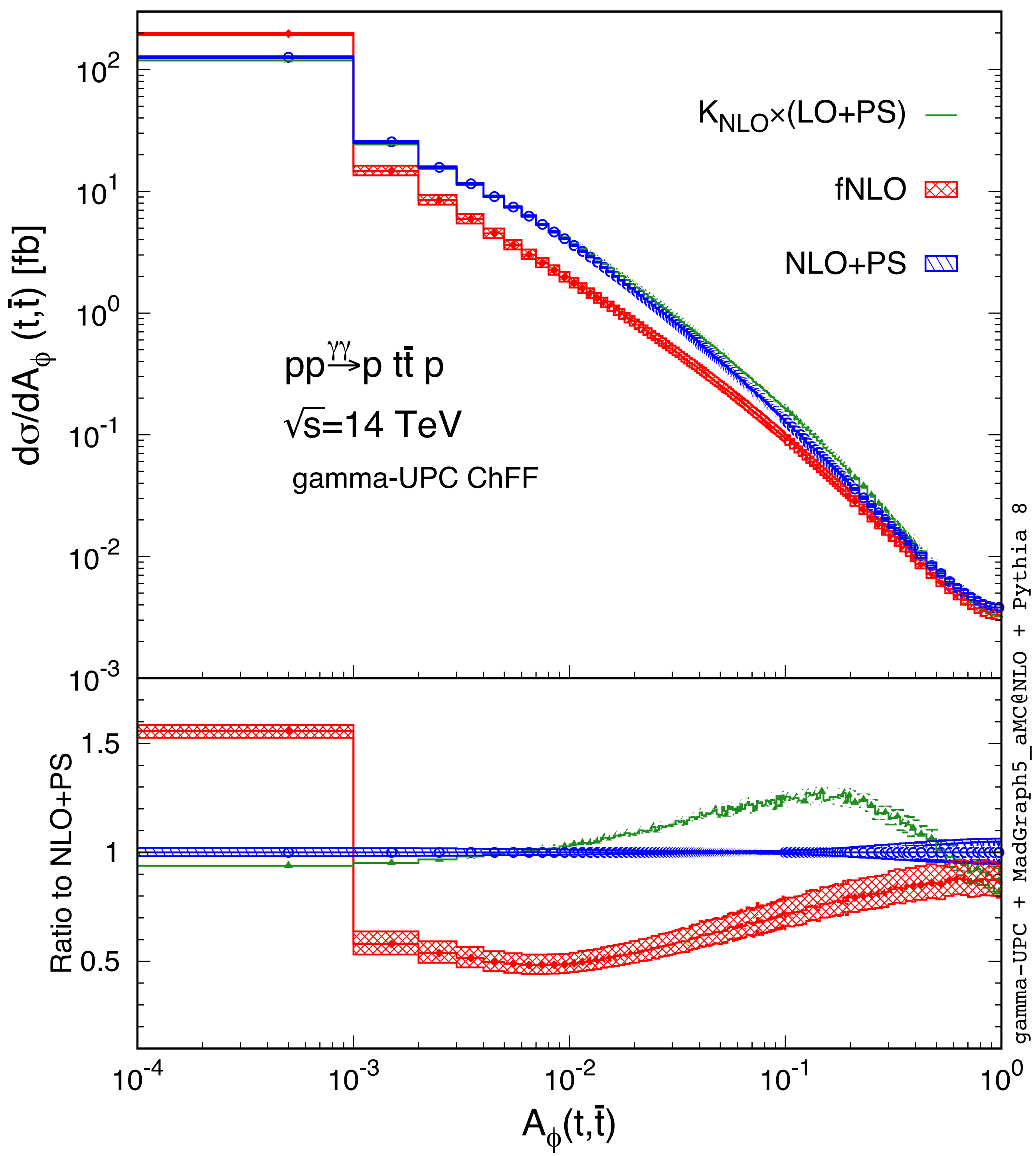
$$\sigma^{\text{NLO QCD+EW}}_{\gamma\gamma\to t\bar{t}} = 0.275 \text{ fb}$$

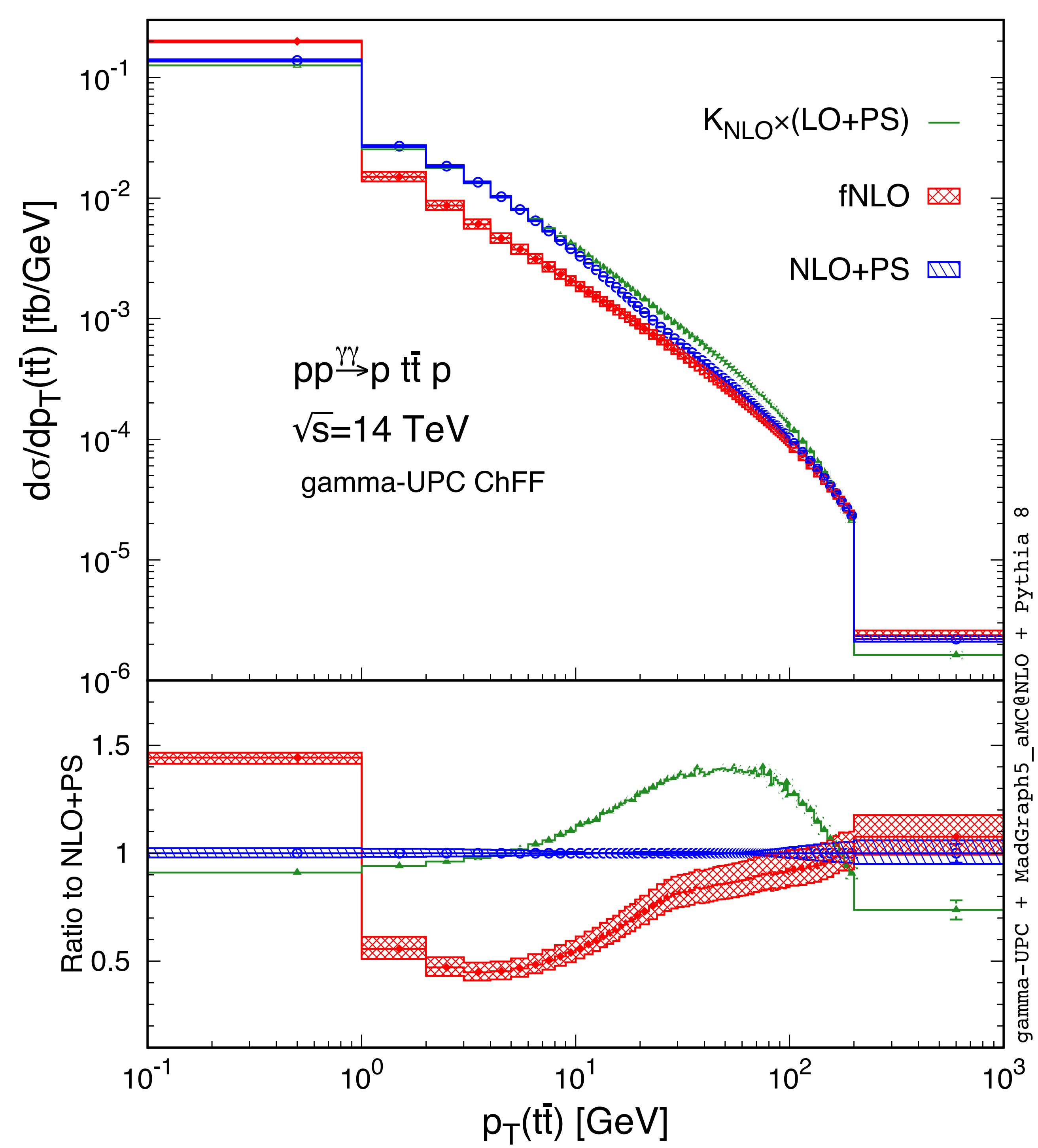
@pp 14 TeV

NLO+PS Event Simulation

- At NLO QCD (no NLO EW), we can have NLO+PS simulations

HSS, Simon (2504.10104)



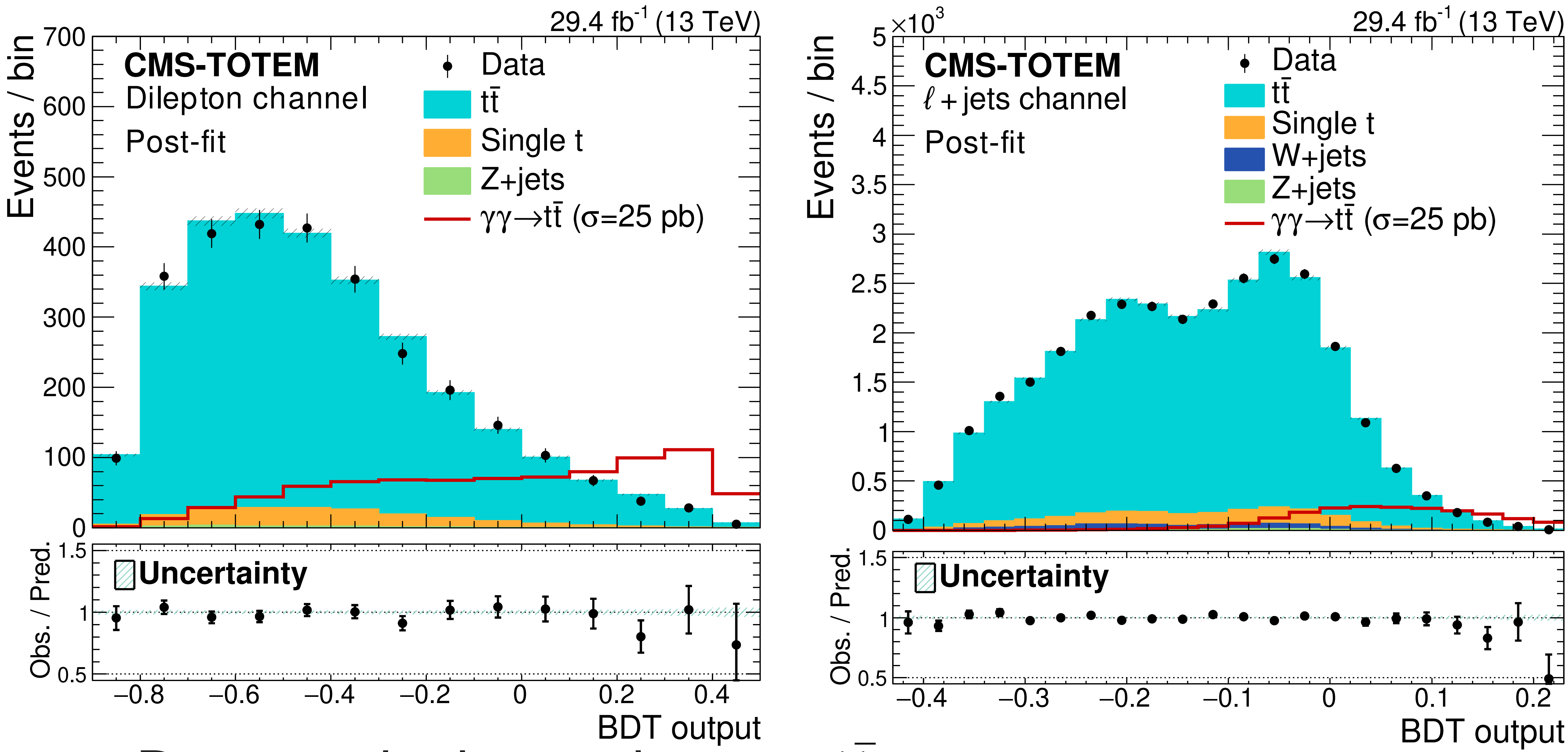


The first measurement

- The first measurement by CMS with data collected in 2017 (29.4 fb^{-1})

where all CT-PPS strip and pixel detectors were operational

CMS-TOTEM (JHEP'24)



- Dominant background: $pp \to t\bar{t}$
- Signal and backgrounds are well separated by BDT

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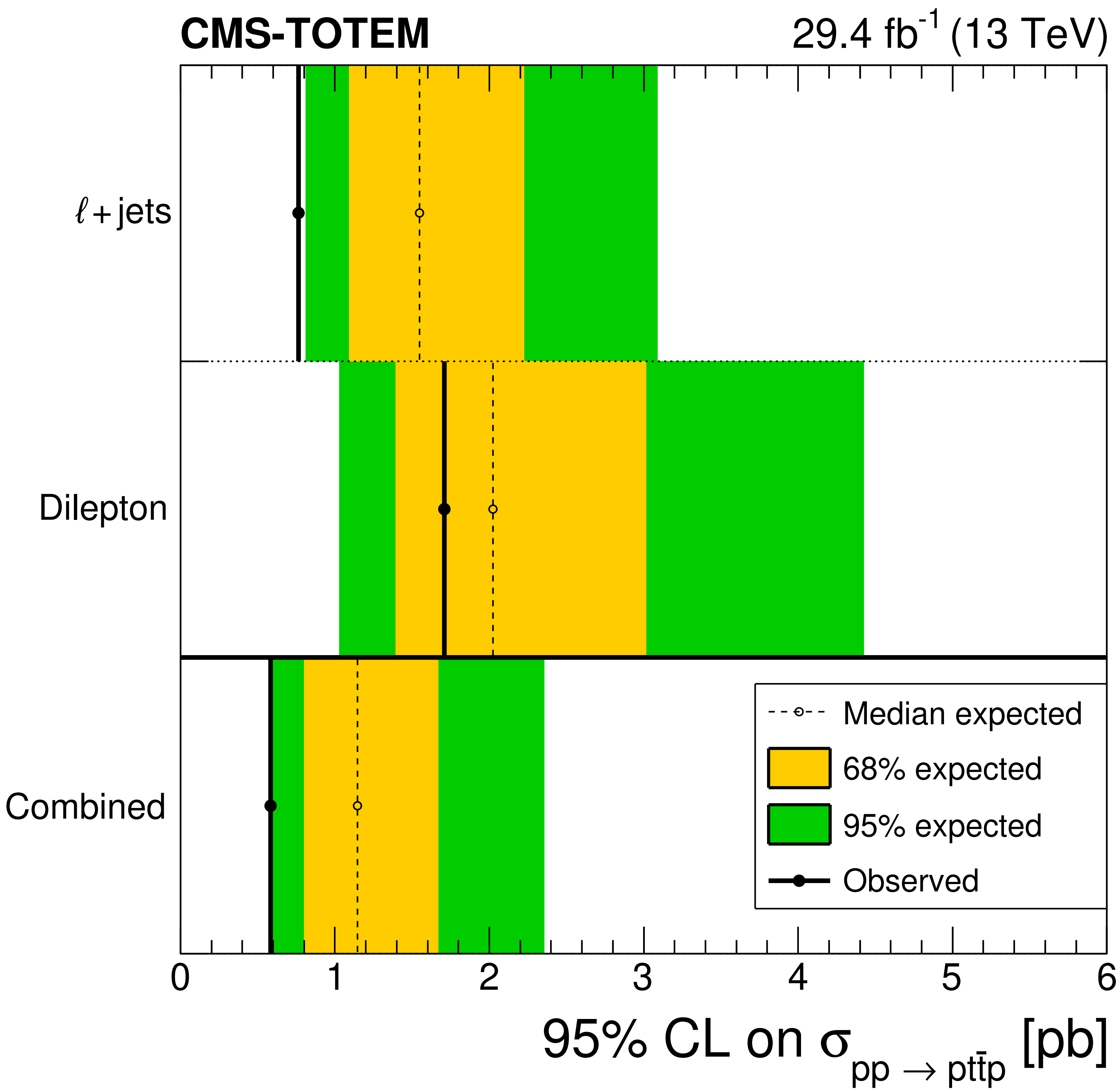
where all CT-PPS strip and pixel detectors were operational

CMS-TOTEM (JHEP'24)



semi-leptonic channel:

$$\sigma^{\ell+\text{jets}} < 0.78 \text{ pb}$$ @95% CL

leptonic channel:

$$\sigma^{\text{Dilepton}} < 1.71 \text{ pb}$$ @95% CL

Two channels combination:

$$\sigma^{\text{Combined}} < 0.59 \text{ pb}$$ @95% CL

Conclusion

- LHC is a unique photon-photon collider
  - Novel BSM programmes: axions, gravitons, monopole, anomalous couplings, ...
  - Increasing number of SM rare/precise measure: LbL, tau g-2, WW, top pair, ...
- gamma-UPC+MadGraph5_aMC@NLO enables NLO QCD+EW calculations and NLO QCD+PS simulations
- First measurement of $pp \stackrel{\gamma\gamma}{\to} p\ t\bar{t}\ p$ by CMS-TOTEM collaboration using CT-PPS based on 2017 Run 2 data (29.4 fb^{-1})
- What about ATLAS using AFP ? Run 3 data ?

Conclusion

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Thank you !

Backup Slides

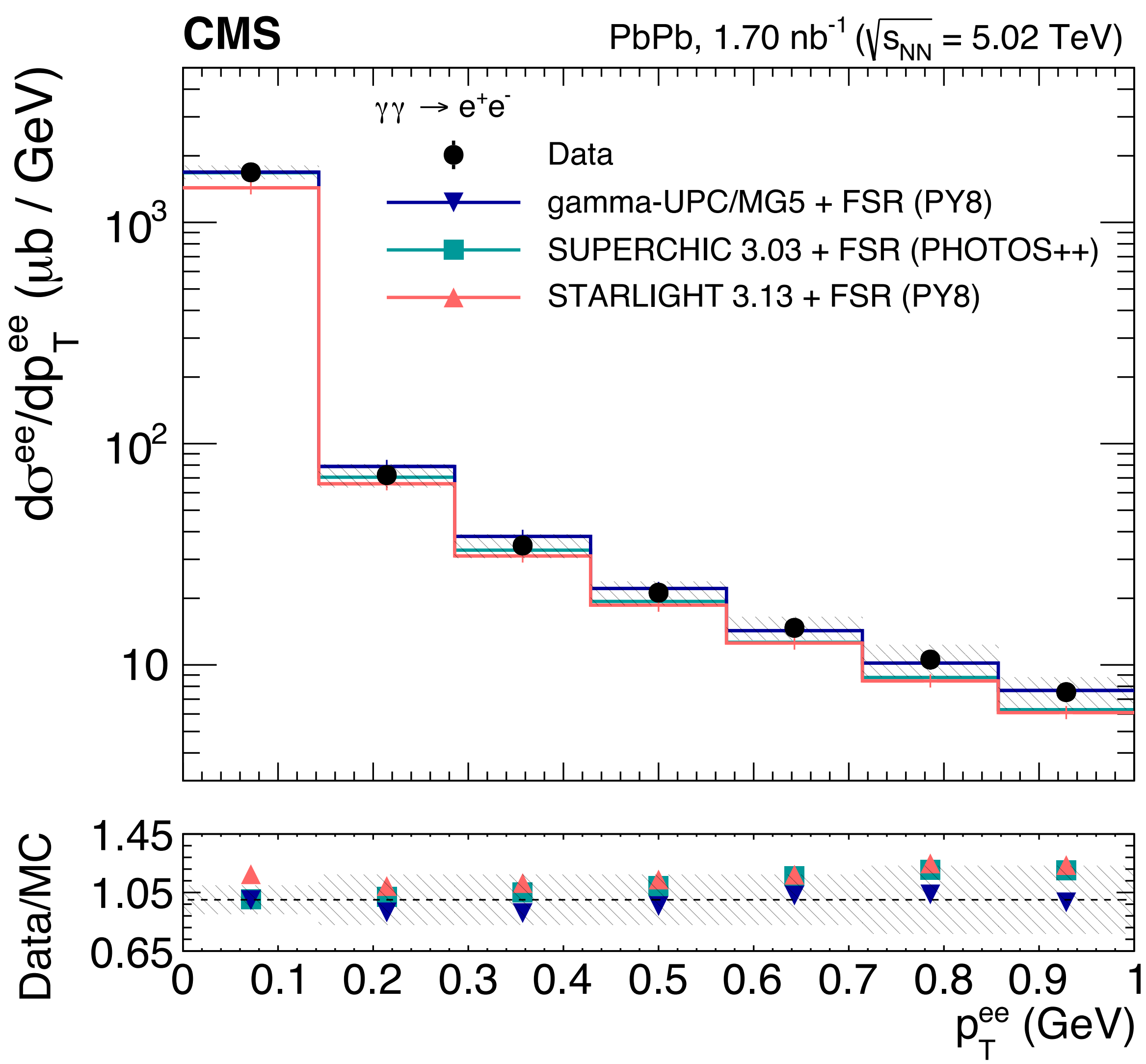
A few selected results

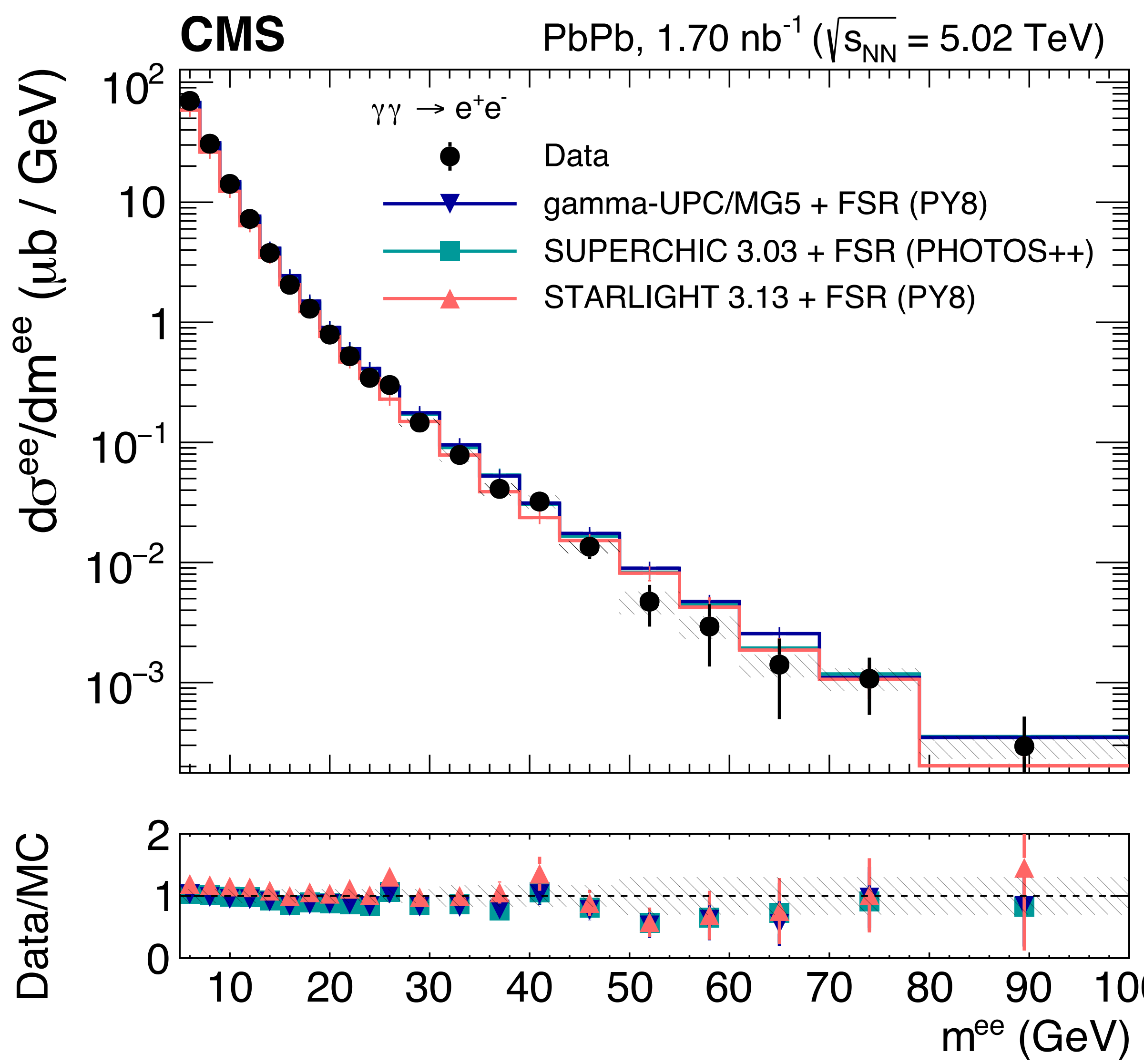
- **Fiducial and differential cross sections**
  - Electron-positron

CMS (2412.15413)

$$\sigma_{\rm CMS} = 263.5 \pm 1.8_{\rm stat} \pm 17.8_{\rm syst}\ \mu{\rm b}$$

STARlight+PY8	SuperChic+Photos++	gamma-UPC (ChFF)+PY8
$225\ \mu$b	$261\ \mu$b	$265\ \mu$b



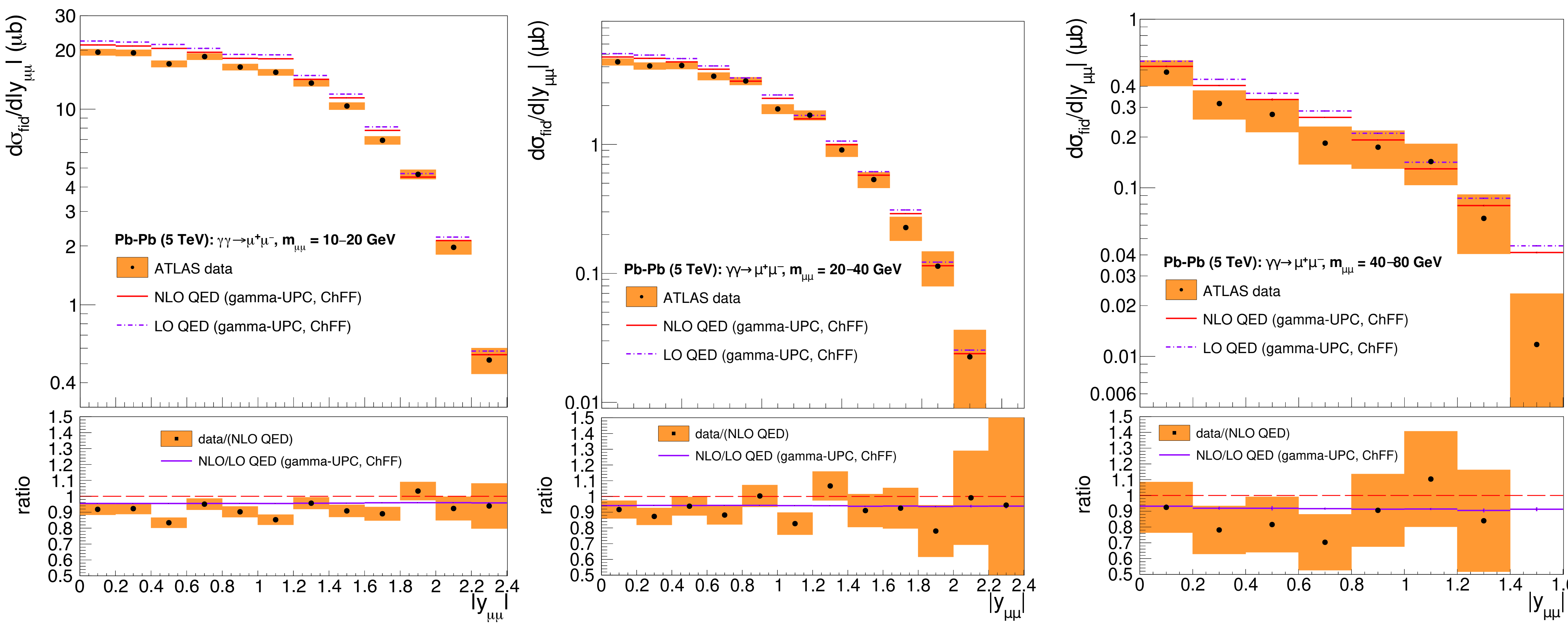


ChFF(~SuperChic) is definitely better than EDFF (~STARlight) !

- **Fiducial and differential cross sections**
  - Dimuon

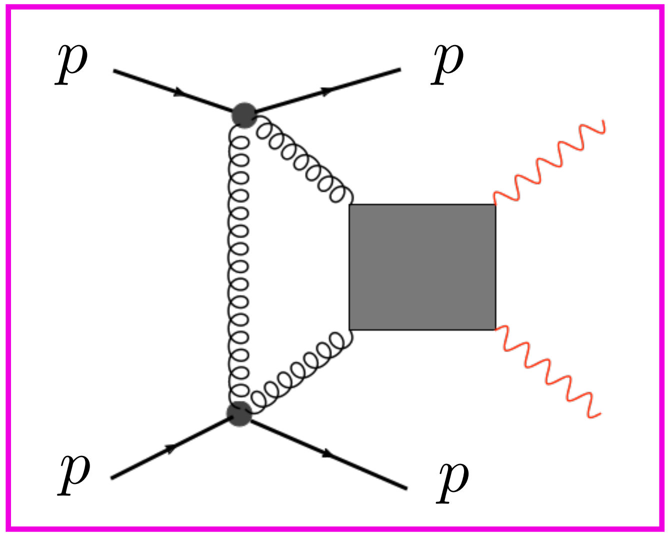
HSS, d'Enterria (JHEP'25)

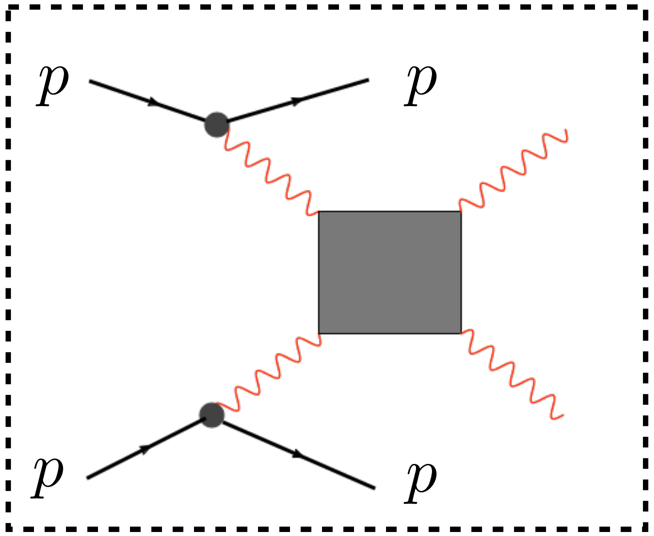
$\gamma\gamma \to \mu^+\mu^-$ System, experiment	measured $\sigma^{\rm data}$	gamma-UPC $\sigma^{\rm LO}$ ChFF (EDFF)	gamma-UPC $\sigma^{\rm NLO}$ ChFF (EDFF)	ratio $\sigma^{\rm data}/\sigma^{\rm NLO}$ ChFF (EDFF)
p-p at 7 TeV, CMS [54]	$3.38^{+0.62}_{-0.59}$ pb	3.62 (3.20) pb	3.50 (3.10) pb	$0.97^{+0.18}_{-0.17}$ $(1.09^{+0.20}_{-0.19})$
p-p at 7 TeV, ATLAS [37]	0.628 ± 0.038 pb	0.687 (0.59) pb	0.653 (0.56) pb	0.96 ± 0.06 (1.12 ± 0.07)
p-p at 13 TeV, ATLAS [55]	3.12 ± 0.16 pb	3.23 (2.88) pb	3.09 (2.76) pb	1.00 ± 0.05 (1.13 ± 0.06)
Pb-Pb at 5.02 TeV, ATLAS [58]	34.1 ± 0.8 μb	39.4 (31.5) μb	37.5 (30.0) μb	0.91 ± 0.02 (1.14 ± 0.03)



Importance of NLO and ChFF !

Light-by-Light Scattering





NLO see 2312.16956 & 2312.16966