Top quark and vector meson production in heavy ion collisions at CMS

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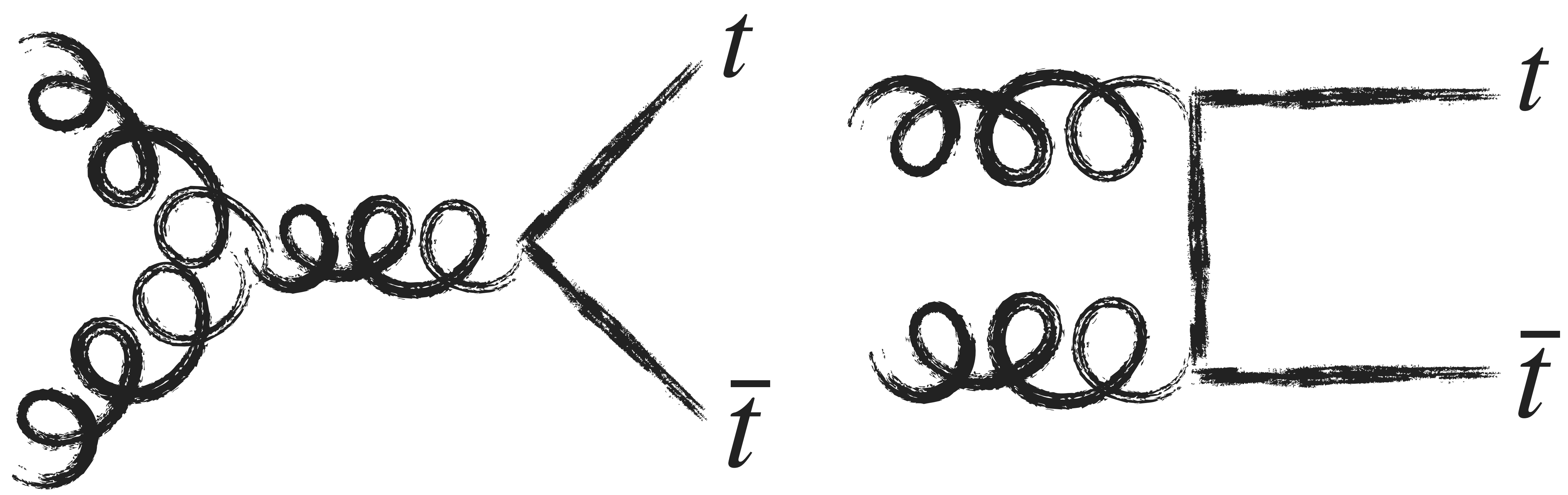
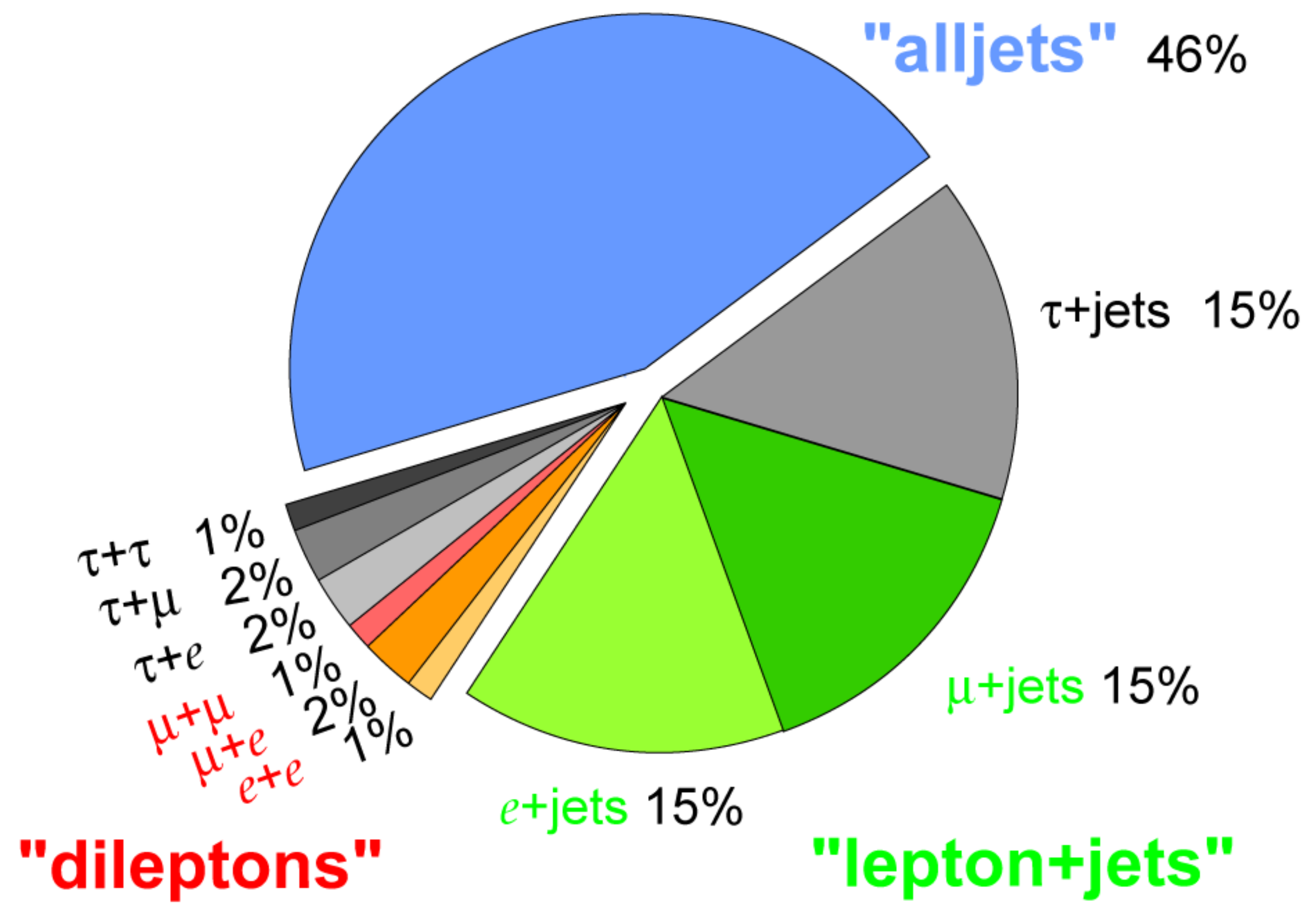
Top quark

Top quark:

- Discovered in 1995 in Tevatron
- Heaviest particle in the SM: $m_t \sim 173$ GeV
- Yukawa coupling $y_t = \sqrt{2}m/v \sim 1$
- Decay time : $\sim 10^{-24}s$
- Decay modes:
  - $t \rightarrow bW \rightarrow b + \ell\nu$ ($\sim 33\,\%$)
  - $t \rightarrow bW \rightarrow b + q\bar{q}$ ($\sim 66\,\%$)
- High production rate at the LHC
- Primarily produced in $t\bar{t}$ pairs by gluon fusion

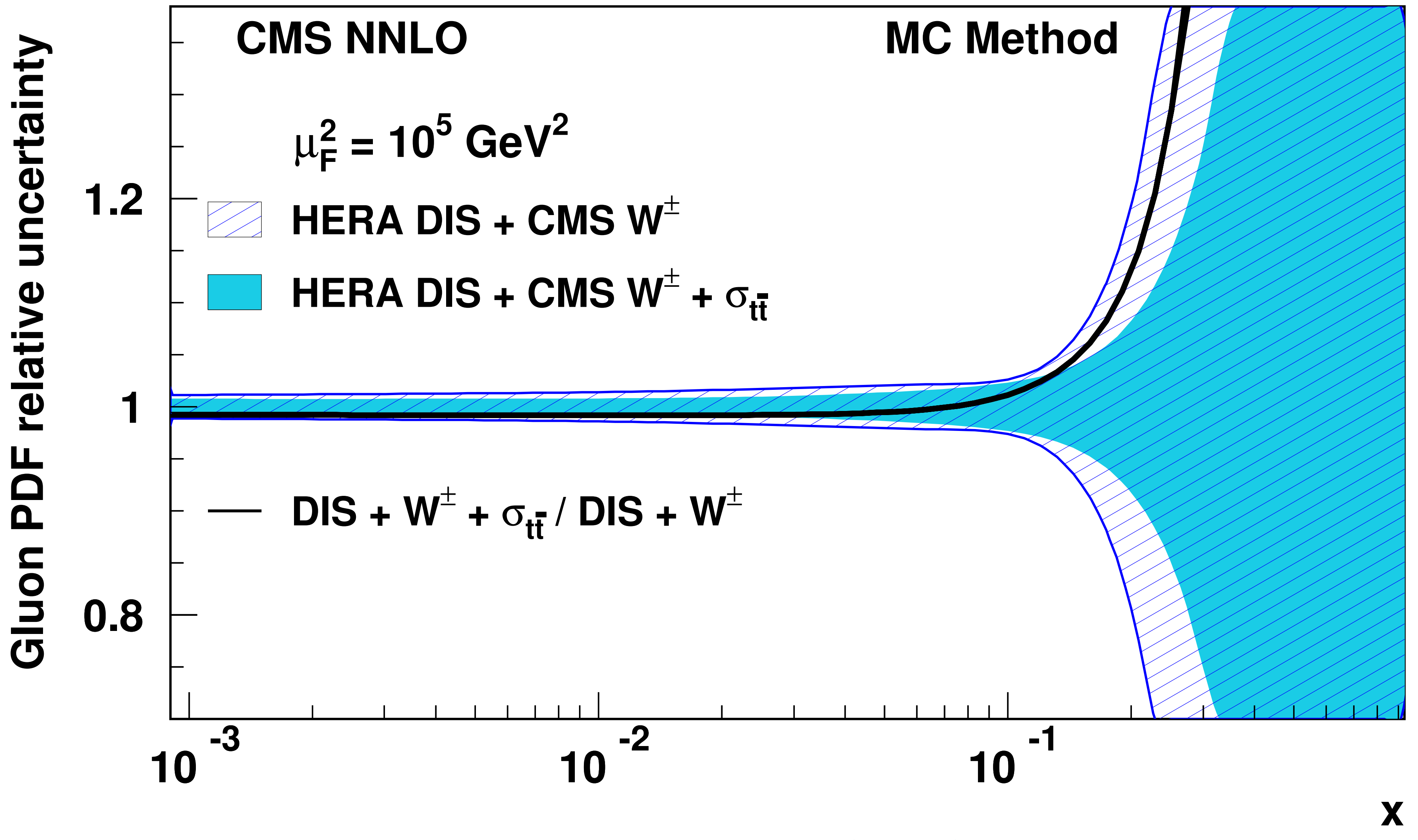


- Channels:
  - $\ell + jets$ (semileptonic):
    $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow q\overline{q'})$ High BR
  - Dilepton (leptonic):
    $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow \ell'\nu')$ Cleanest
  - All jets (hadronic):
    $t\bar{t} \rightarrow bb'W(\rightarrow q\overline{q'})W'(\rightarrow q''\overline{q'''})$ Dirtiest and more challenging.



Top quark

- Since its discovery, $t\bar{t}$ observed in CMS:
  - $t\bar{t}$ in pp: $\sqrt{s} = 5$ arXiv:2112.09114, 7, 8, JHEP 08 (2016) 029 Eur. Phys. J.C. 77, 15 (2017) 13 JHEP 09 (2017) 051 Eur. Phys. J.C. 77, 172 (2017) TeV
  - $t\bar{t}$ in pPb: $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 119, 242001
- Motivation:
  - pp:
    - pA and AA profit from pp measurements.
    - Constrain to proton PDF ($x \sim 1/\sqrt{s}$).



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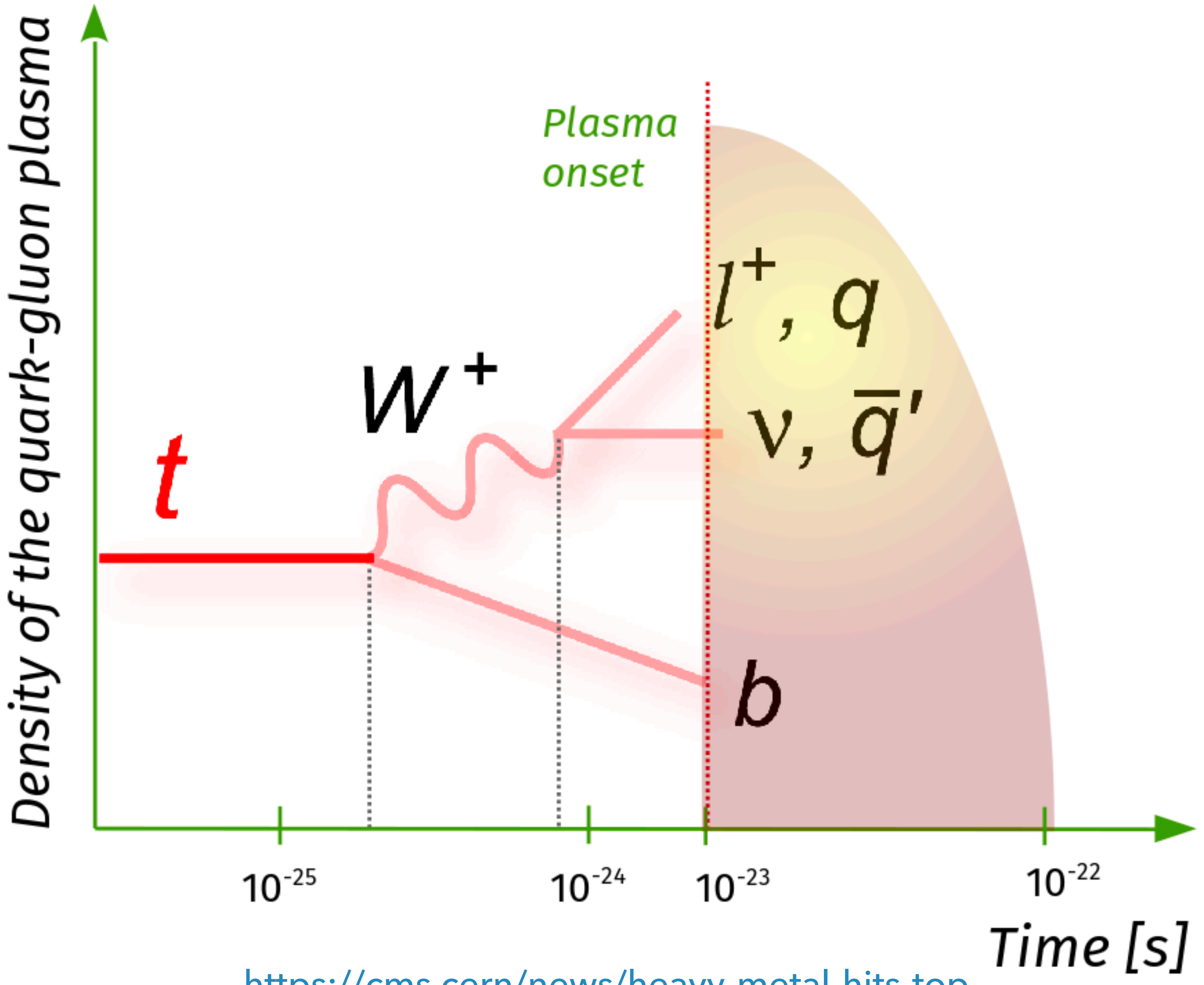
- pA and AA:
  - Probe for nuclear PDFs
  - Paves the way for using tops as a probe for QGP.



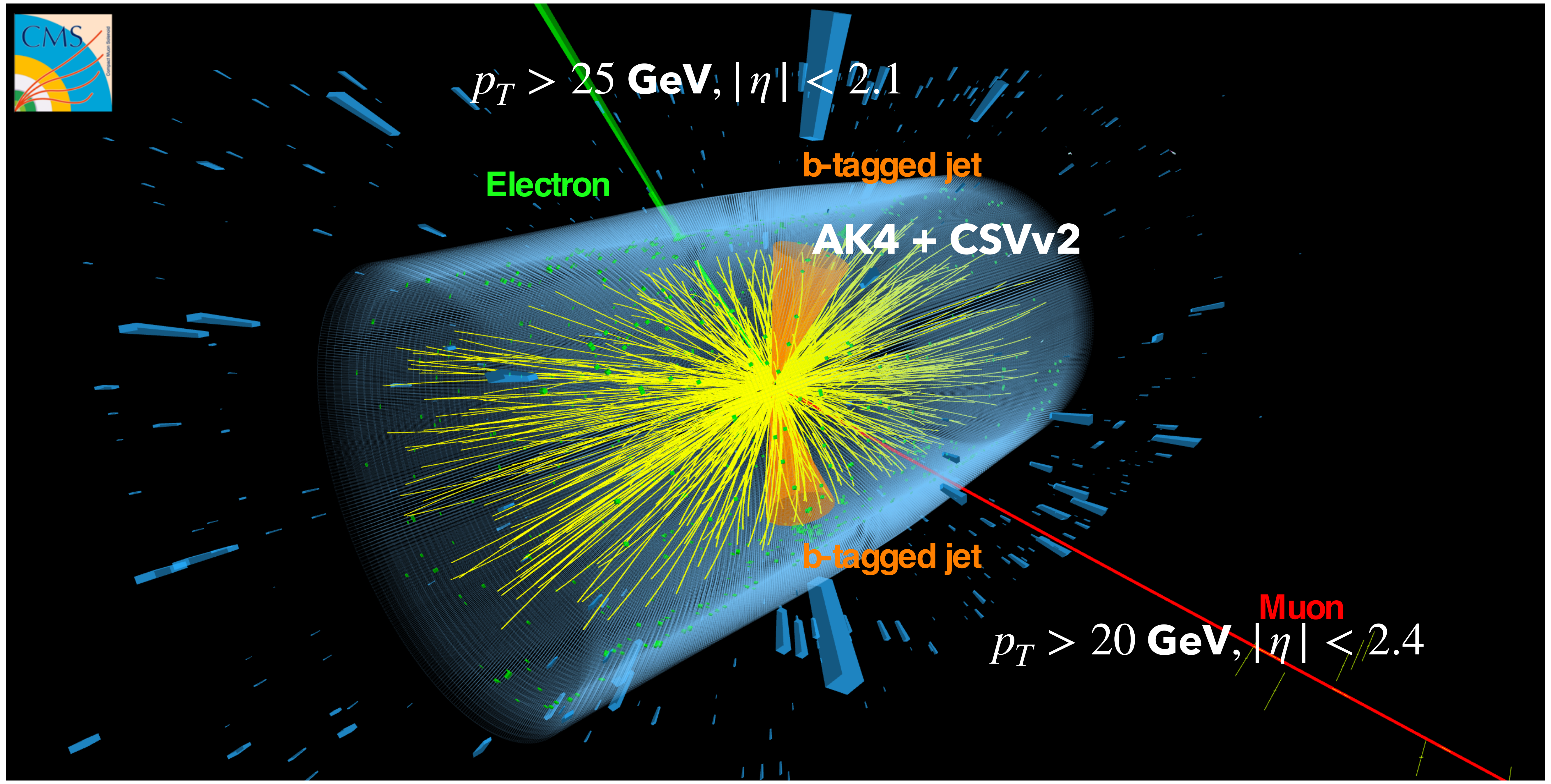
https://cms.cern/news/heavy-metal-hits-top

Top quark

- First evidence of $t\bar{t}$ in nucleus-nucleus using PbPb collision data recorded by CMS in 2018 at $\sqrt{s} = 5.02$ TeV Phys. Rev. Lett. 125, 222001
- Data sample corresponds to $\mathscr{L} = 1.7 \pm 0.1\ nb^{-1}$
- Dilepton ($t\bar{t} \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$) final states were analyzed.
  - BR($t\bar{t} \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$) $\sim 5\,\%$
- Two methods to extract $\sigma_{t\bar{t}}$:
  - Dilepton only: Final state kinematic properties alone
  - Dilepton + b-jets: Imposing extra requirements on the number of b-tagged jets

Theoretical prediction (CT14 NLO + EPPS16 NLO) J. Comp. Phys. Com. Vol. 185. , Phys. Rev. Lett. 110, 252004:

$$\sigma^{th}_{t\bar{t}} = 3.22^{+0.38}_{-0.35}\,(nPDF \oplus PDF)^{+0.09}_{-0.10}\,(scale)\ \mu b$$



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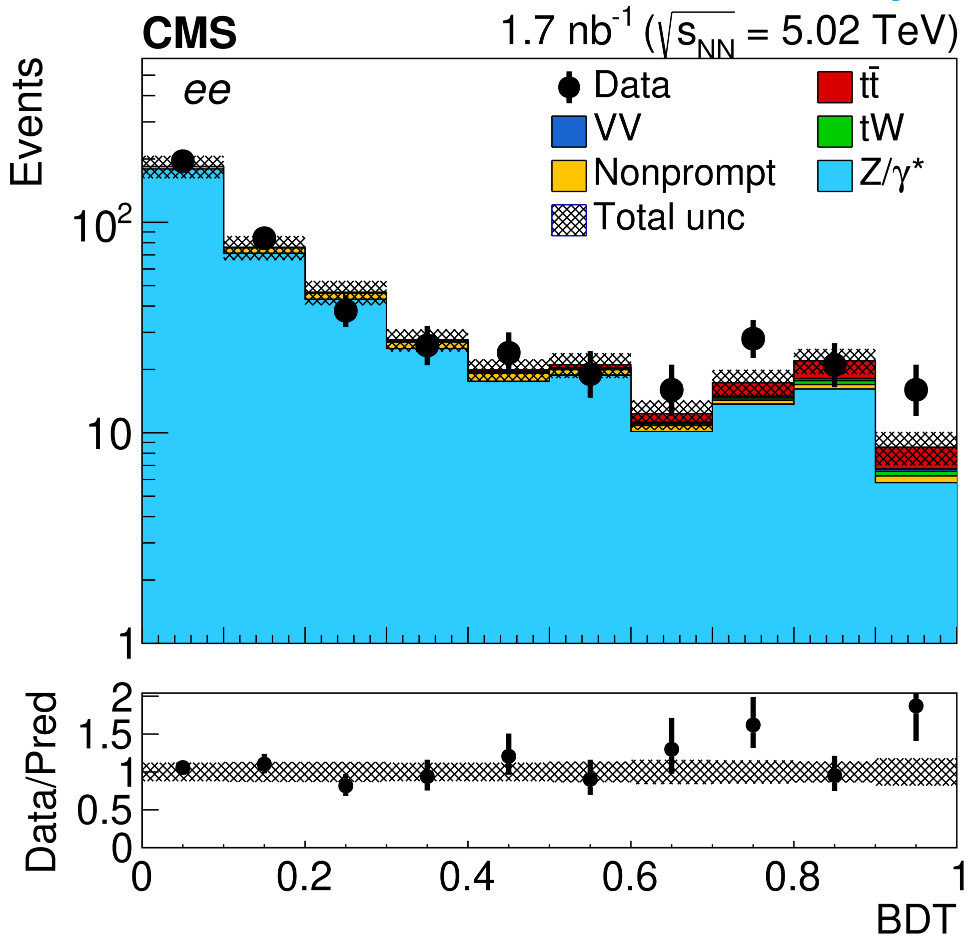
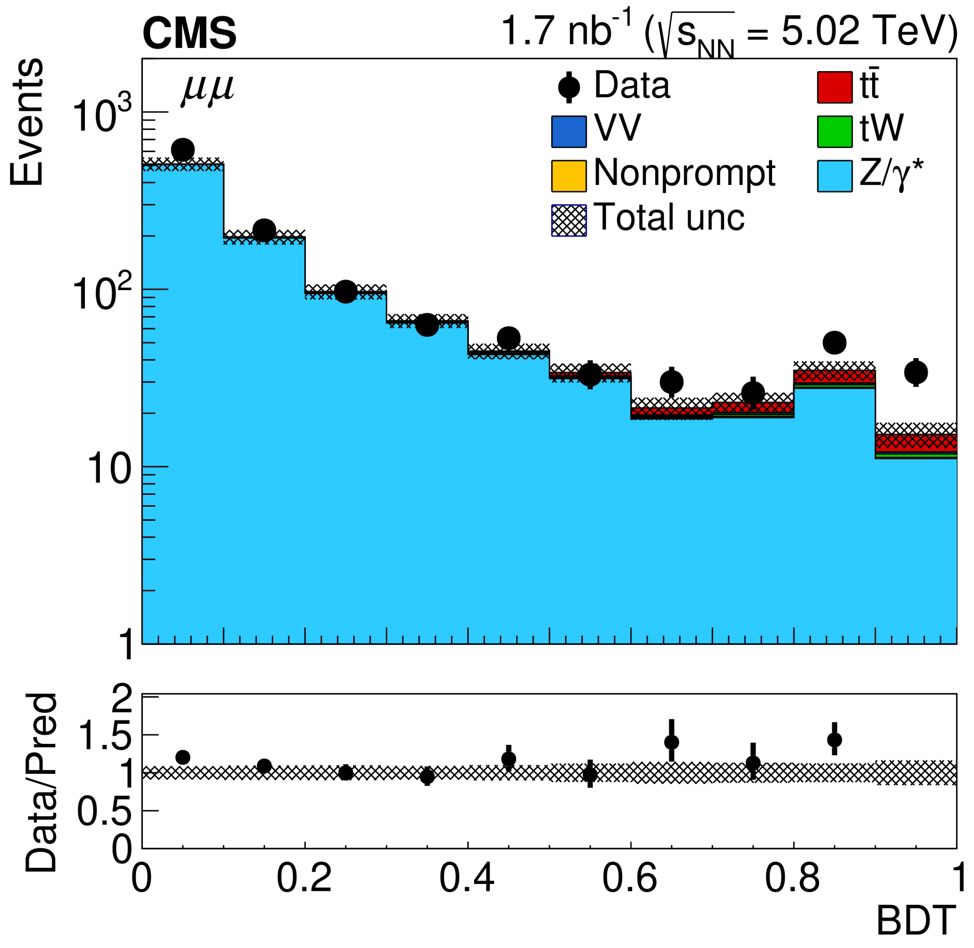
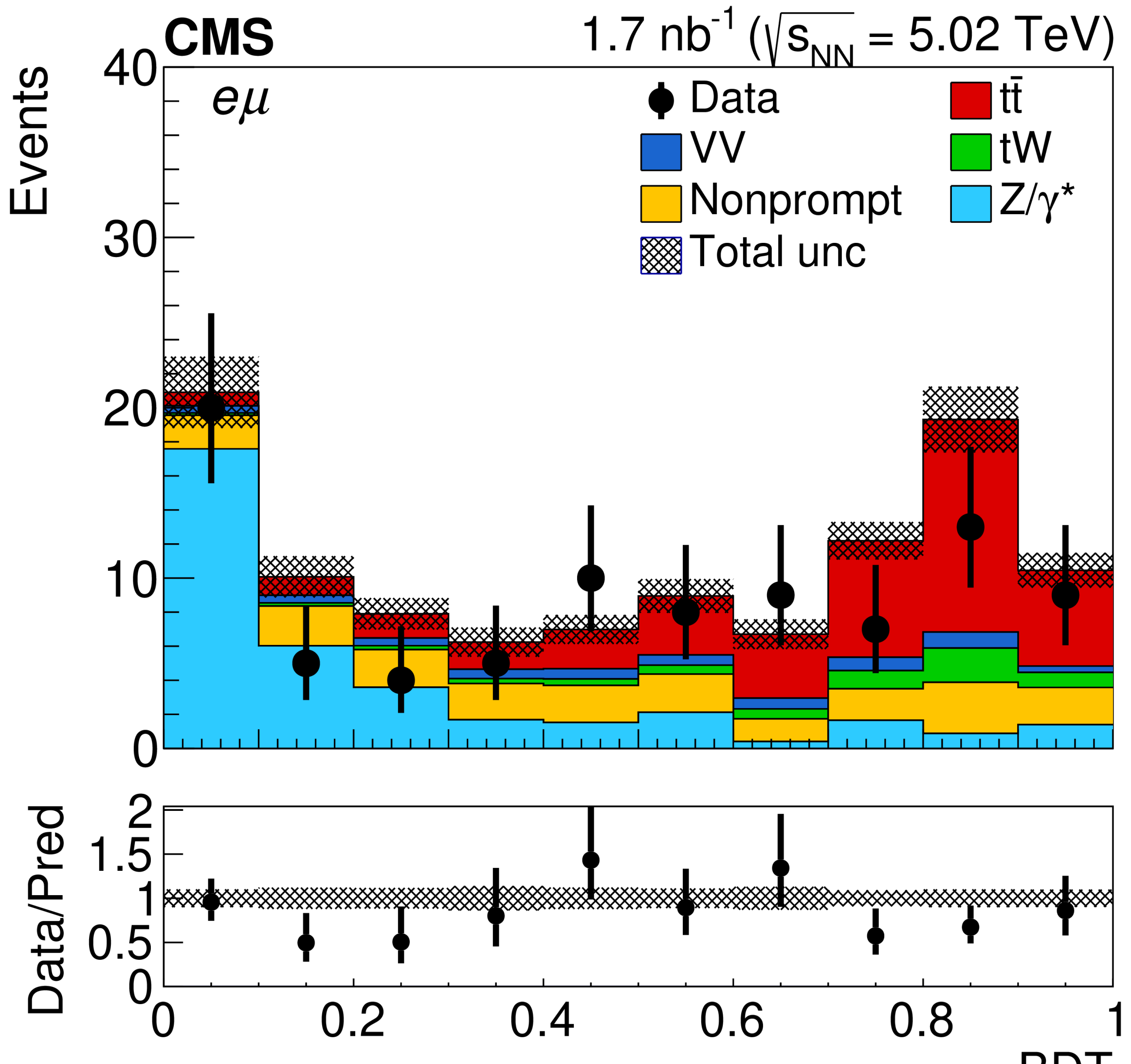
Top quark

Dilepton

Phys. Rev. Lett. 125, 222001







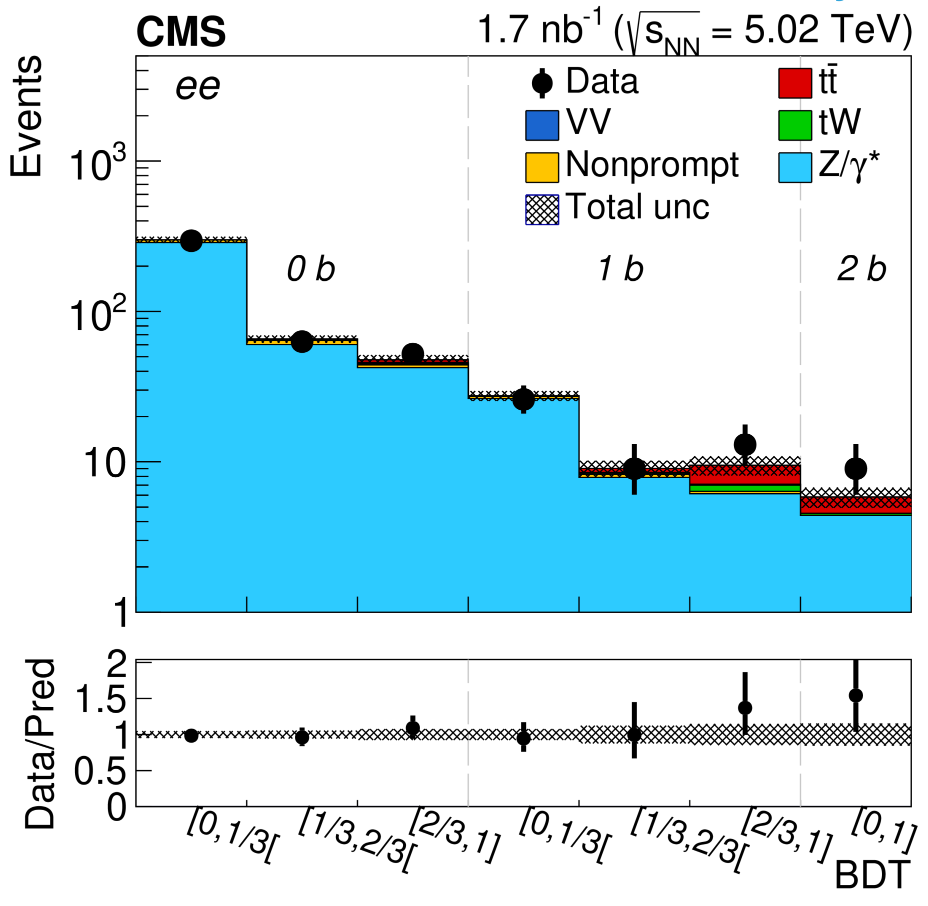
Phys. Rev. Lett. 125, 222001

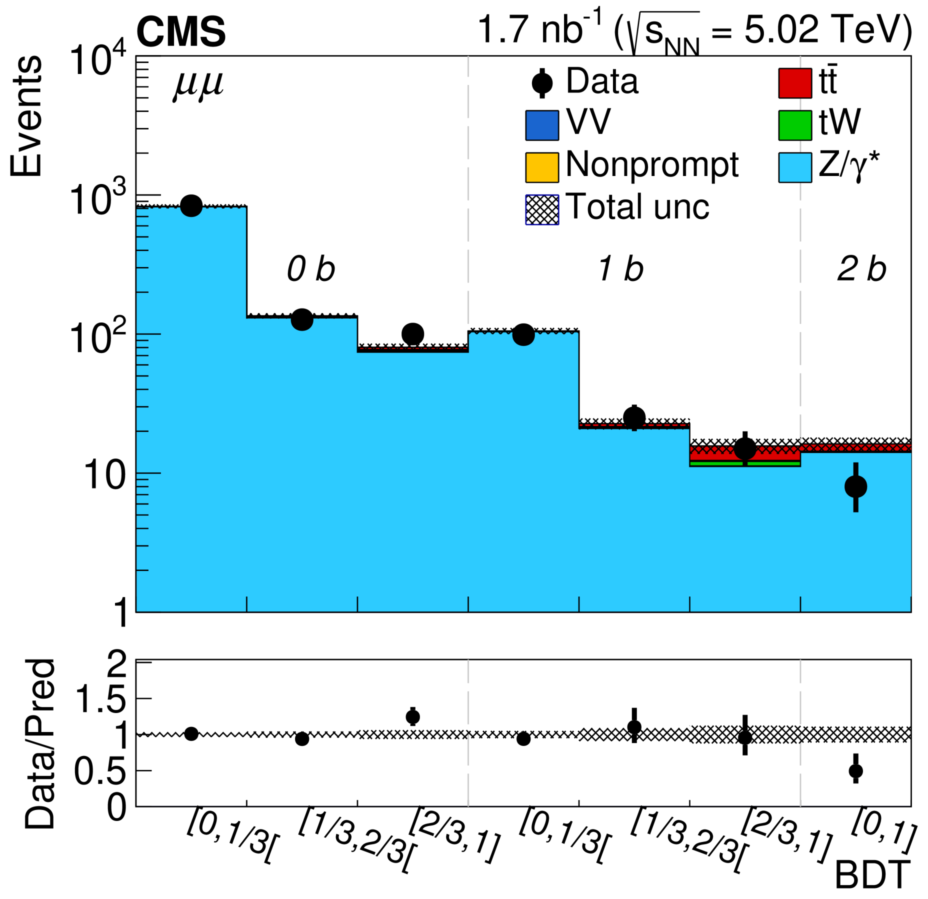
$e^{\pm}\mu^{\mp}$ is the highest sensitivity final state

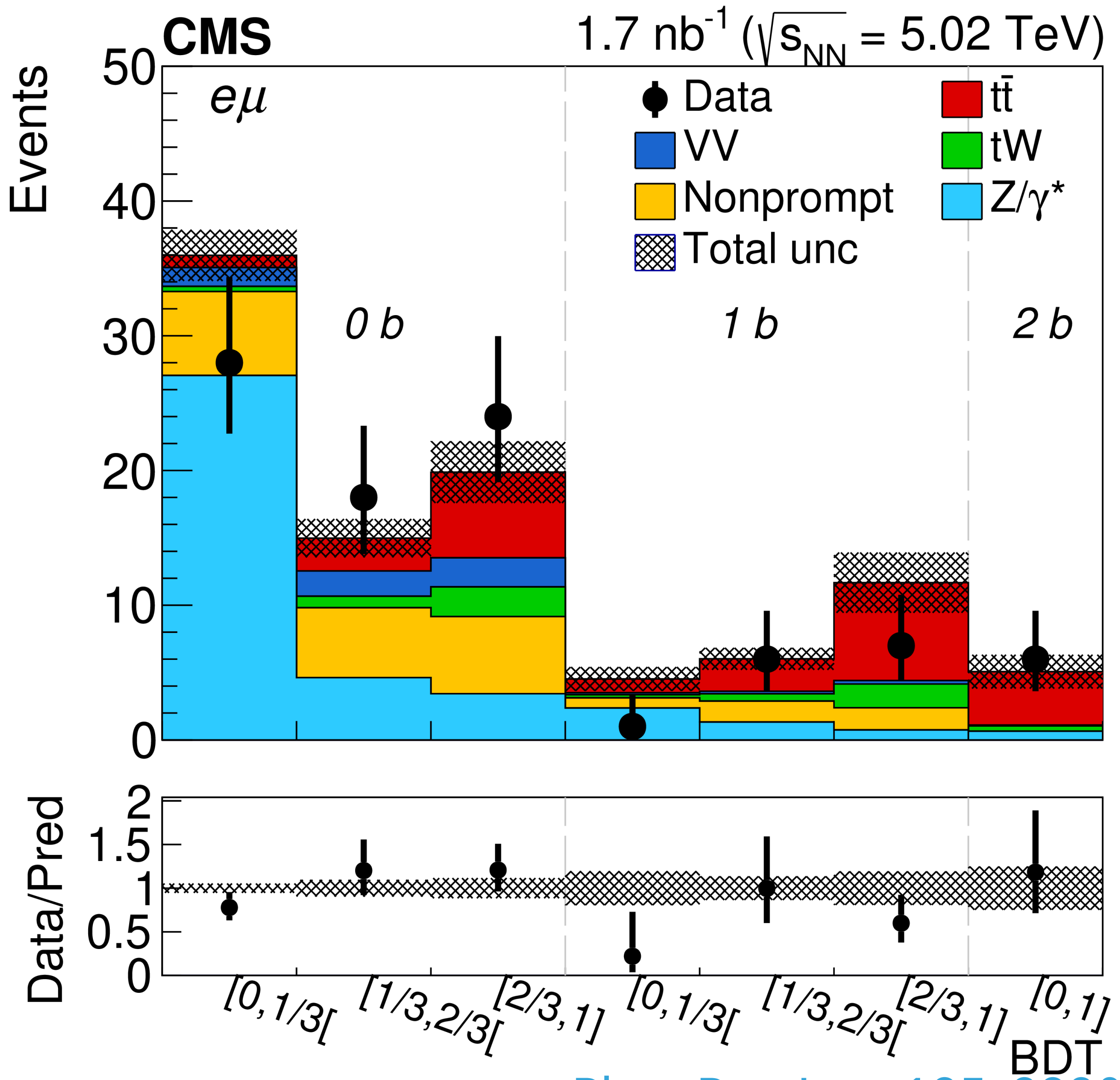
$\mu = 0.79^{+0.26}_{-0.23}$ (3.8 s.d.)

Dilepton + b-jets

Phys. Rev. Lett. 125, 222001







Phys. Rev. Lett. 125, 222001

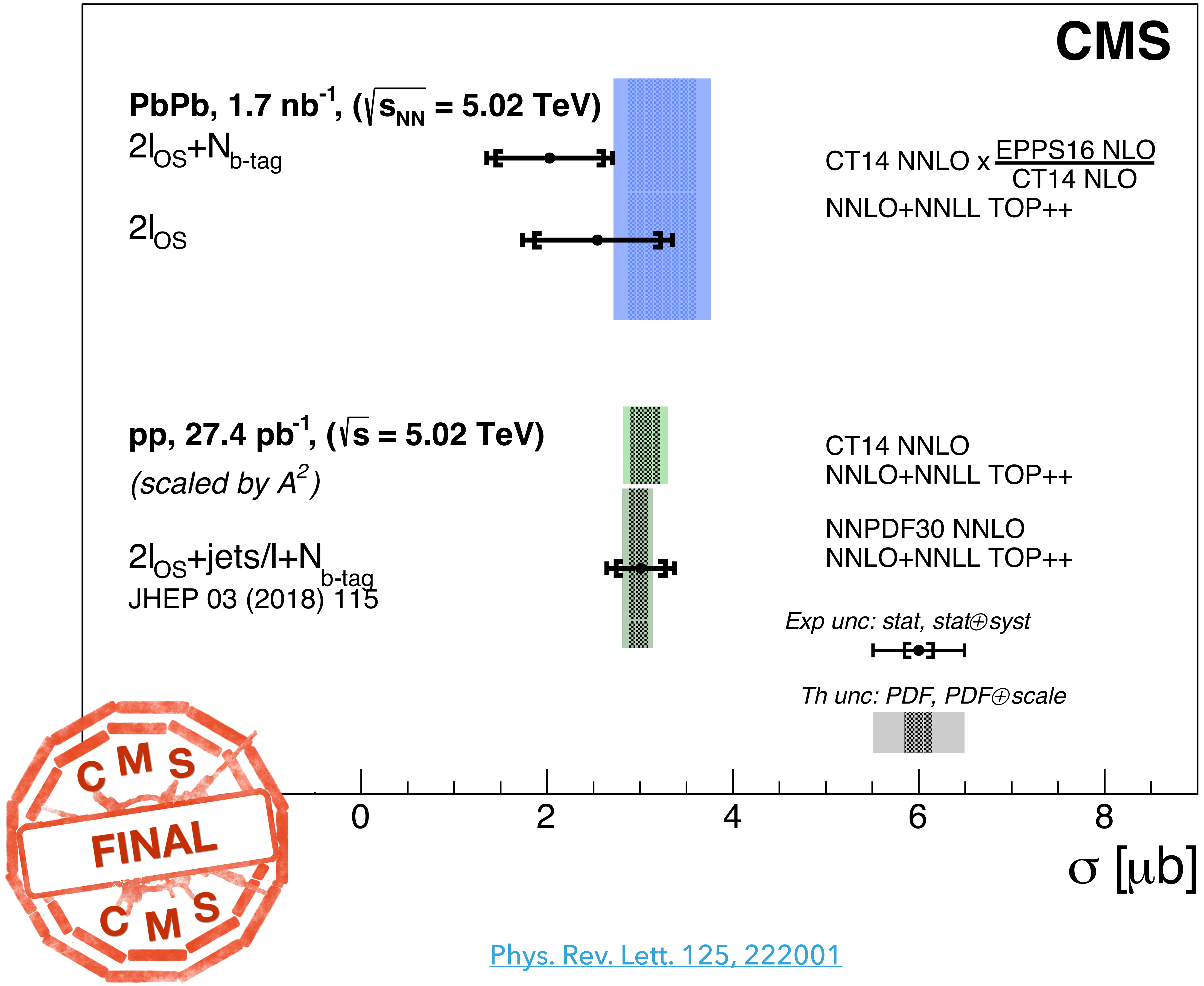
Notice only 1 bin: we need more stats!

$\mu = 0.63^{+0.22}_{-0.20}$ (4.0 s.d.)

Top quark

Dilepton + b-jets → $\sigma_{t\bar{t}} = 2.03^{+0.71}_{-0.64}\ \mu b$

Dilepton → $\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}\ \mu b$



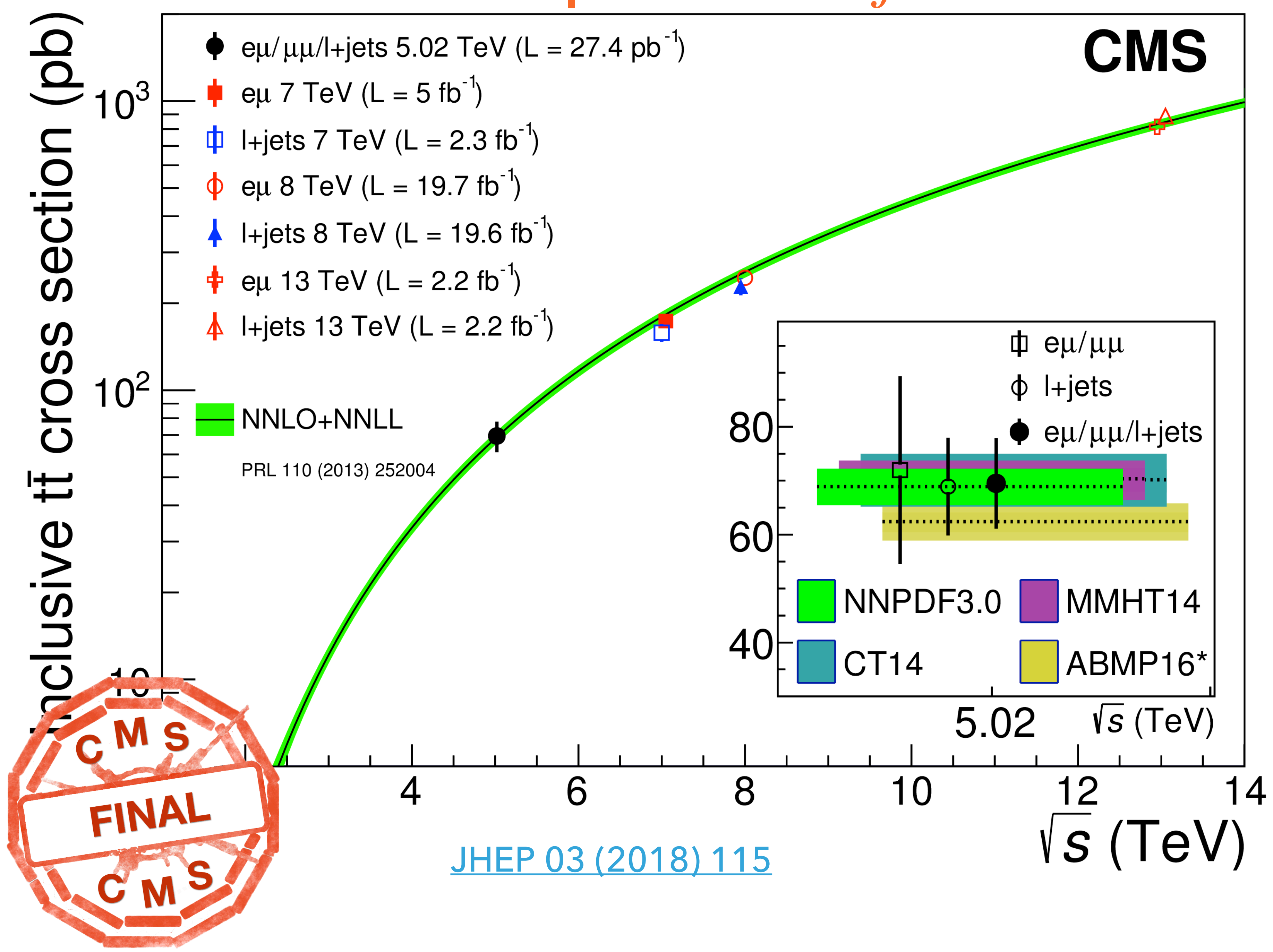
Phys. Rev. Lett. 125, 222001

- Compatible with pp scaled data and QCD calculations.
- Statistical uncertainties dominate by far.
- Evidence of top production in PbPb

Going further dileptons...

- $t\bar{t}$ in pp: baseline reference for AA
  - $t\bar{t}$ in pp at 5.02 TeV update in dilepton channel with 2017 data. arXiv:2112.09114
  - Dilepton & $\ell + jets$ channel accessible
  - Reaching higher precision

2015: dilepton & $\ell + jets$



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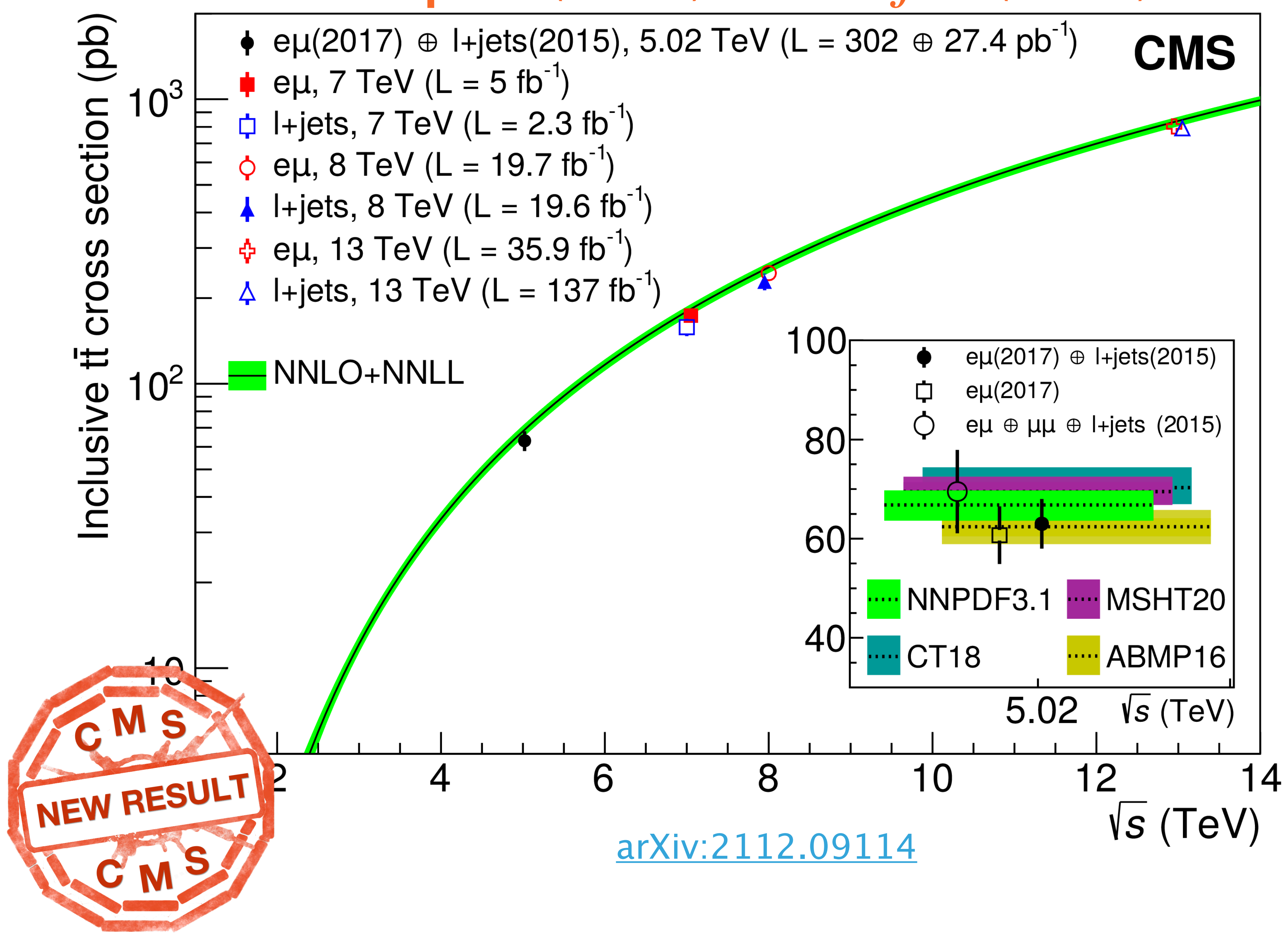
$\sigma_{t\bar{t}} = 69.5 \pm 6.1\ (stat) \pm 5.6\ (syst) \pm 1.6\ (lumi)$ pb

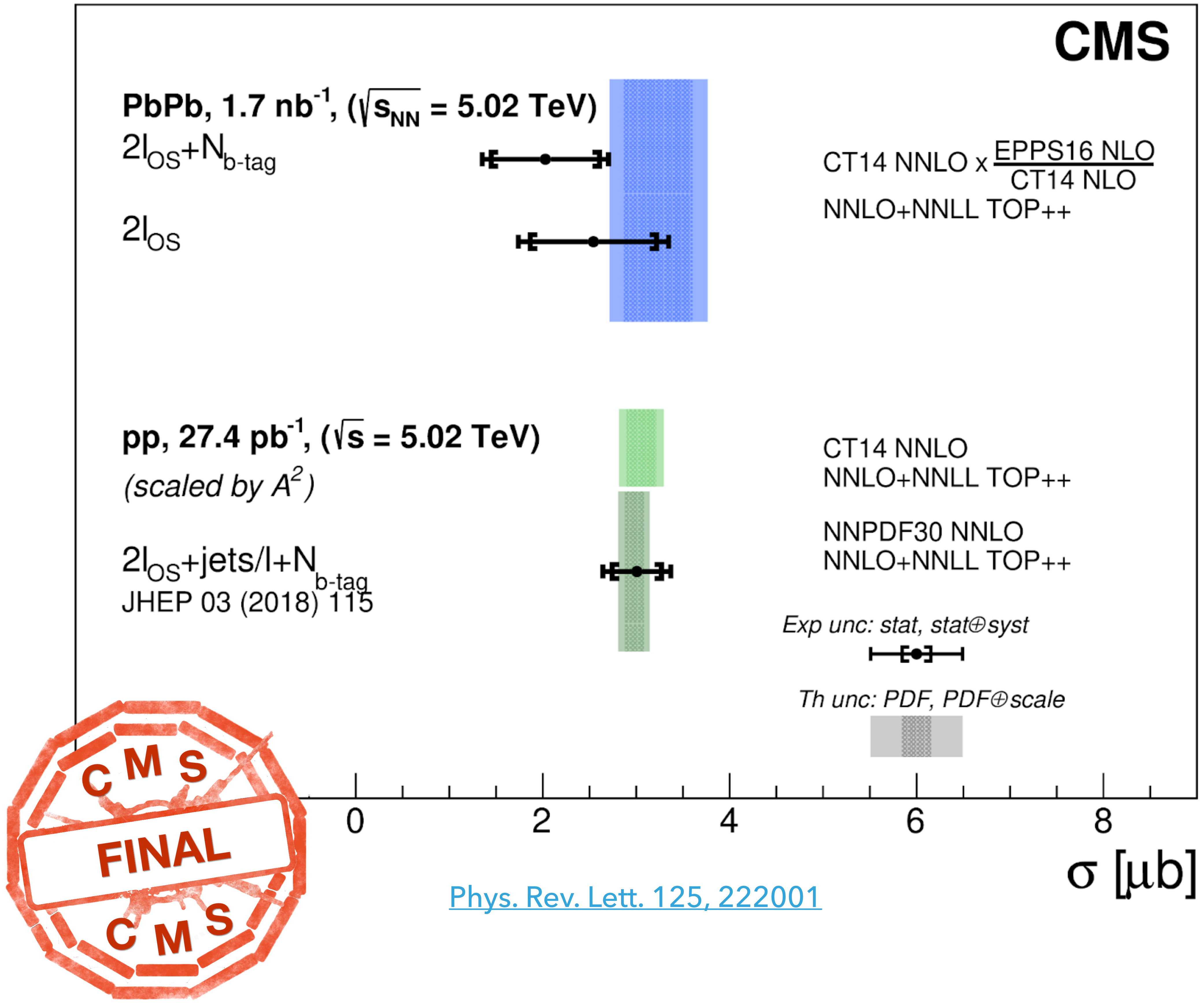
dilepton(2017) & $\ell + jets$(2015)



arXiv:2112.09114

$\sigma_{t\bar{t}} = 63.0 \pm 4.1\ (stat) \pm 3.0\ (syst + lumi)$ pb

Projections for $t\bar{t}$ in PbPb at HL-LHC



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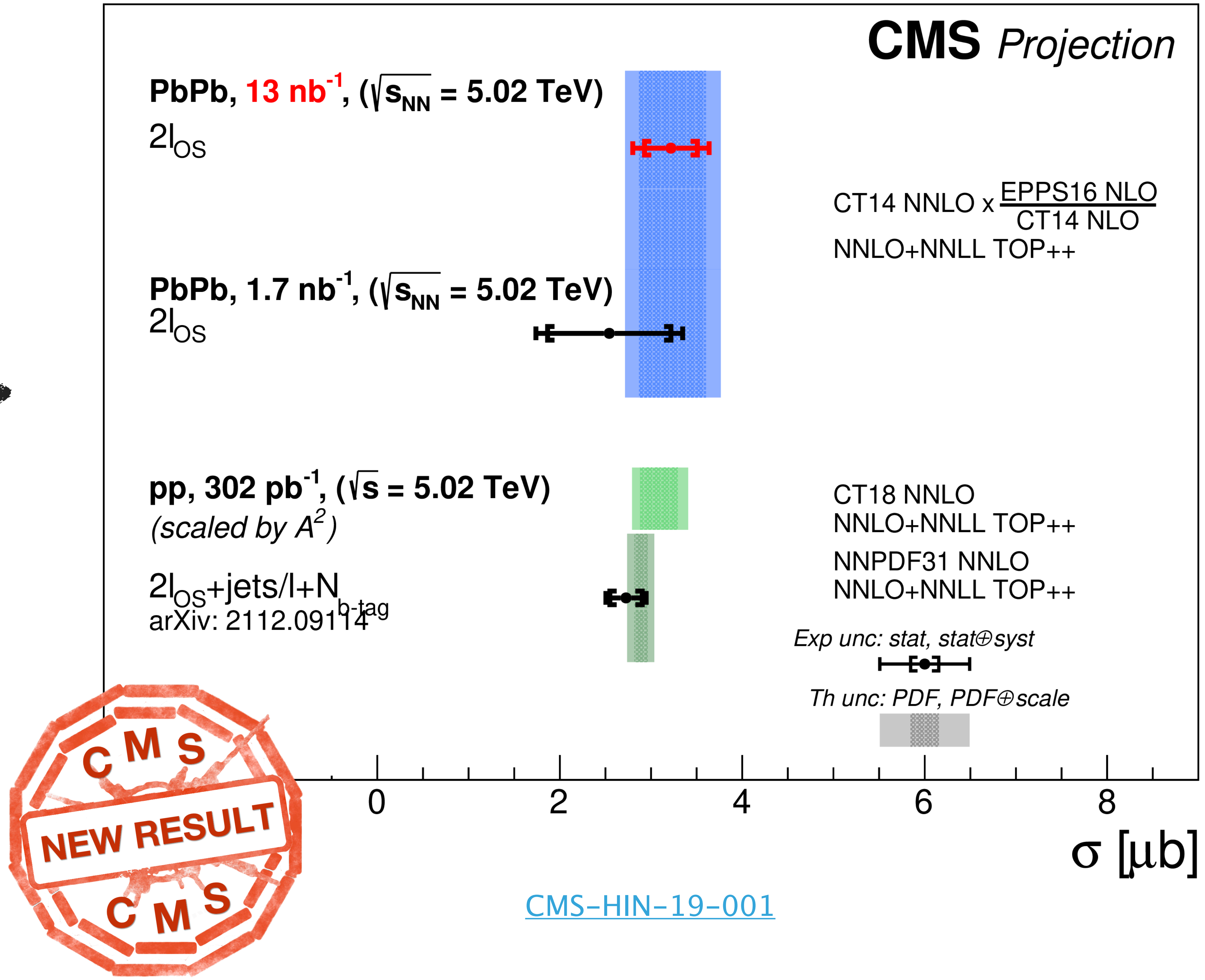

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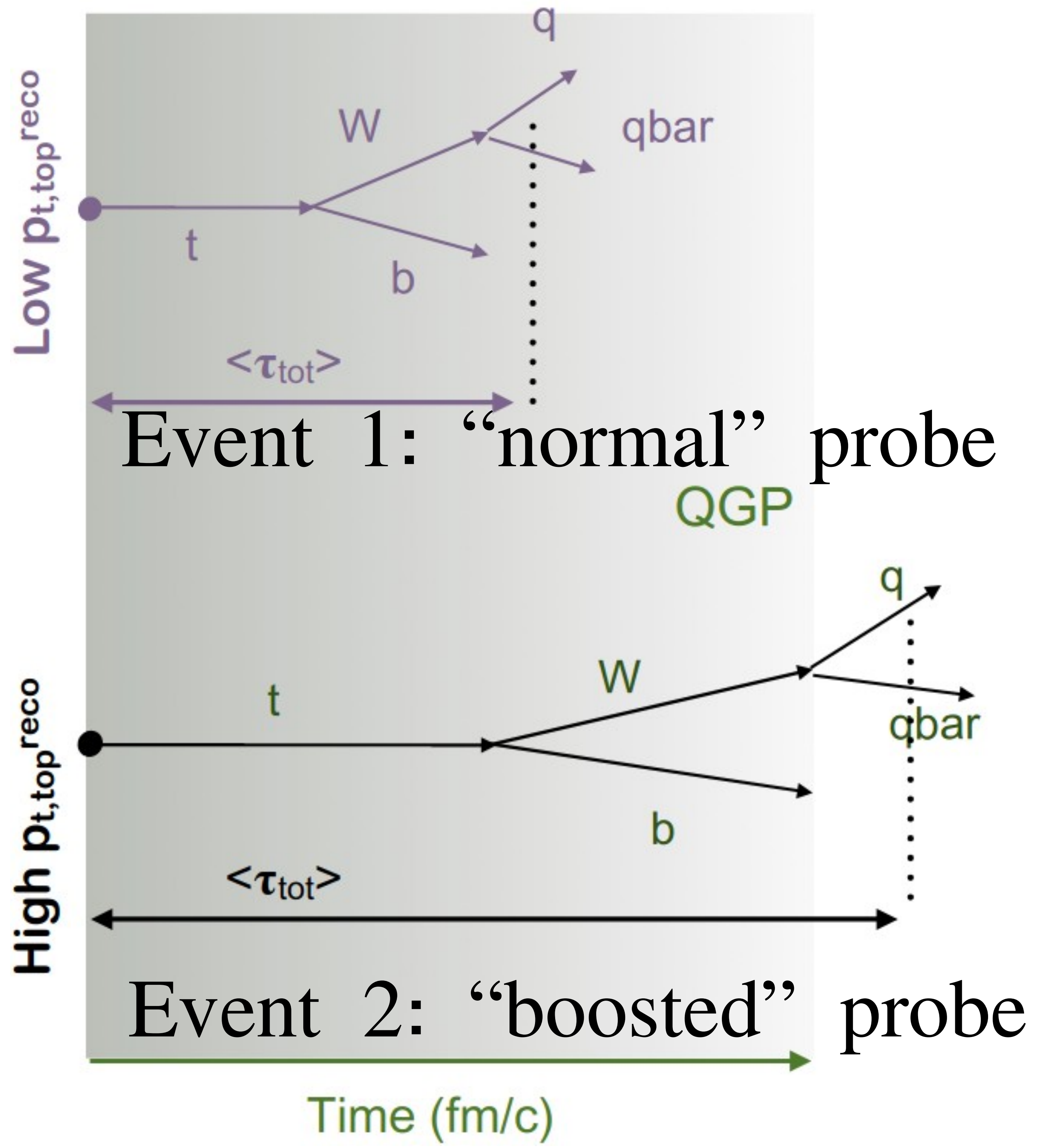
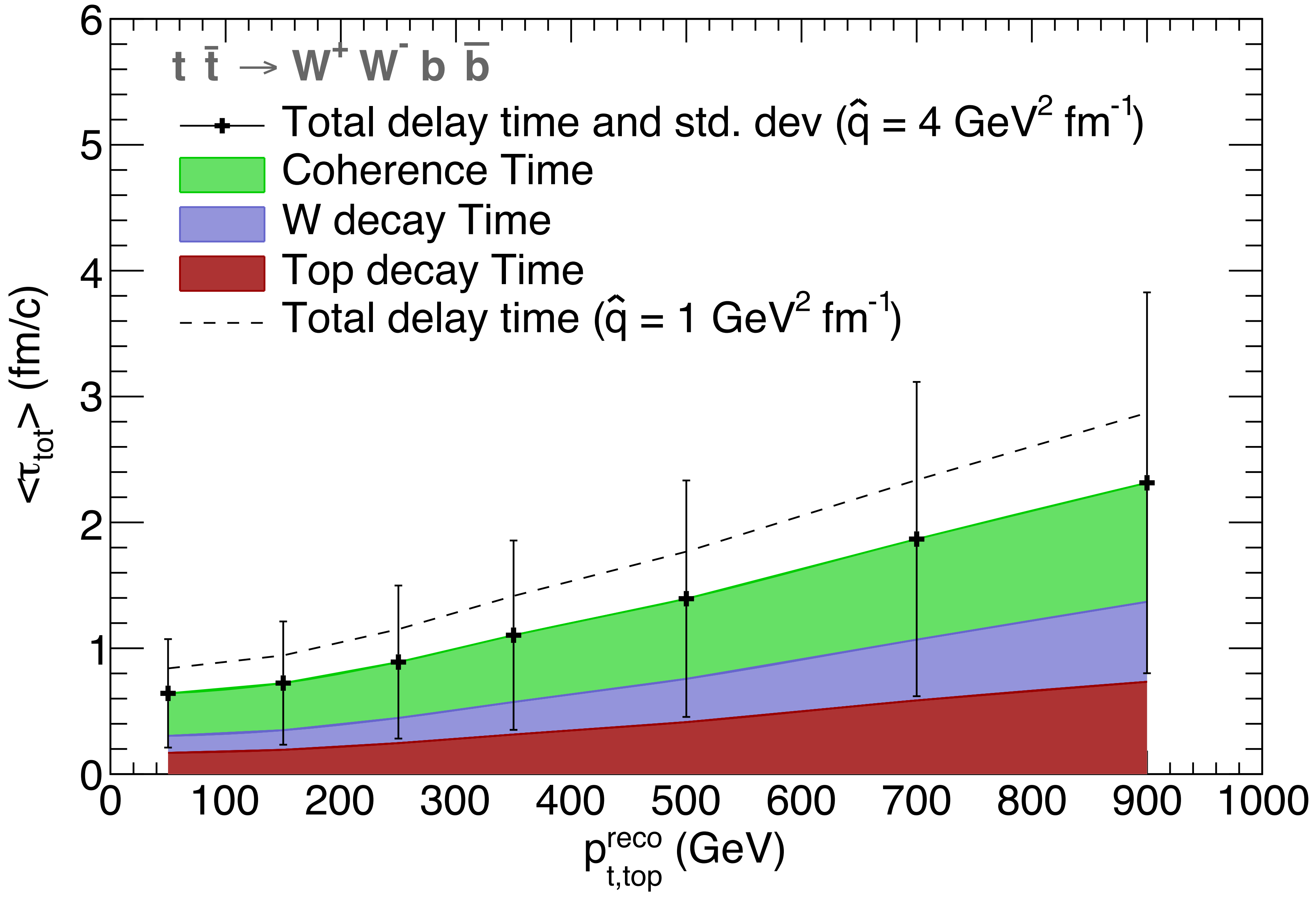
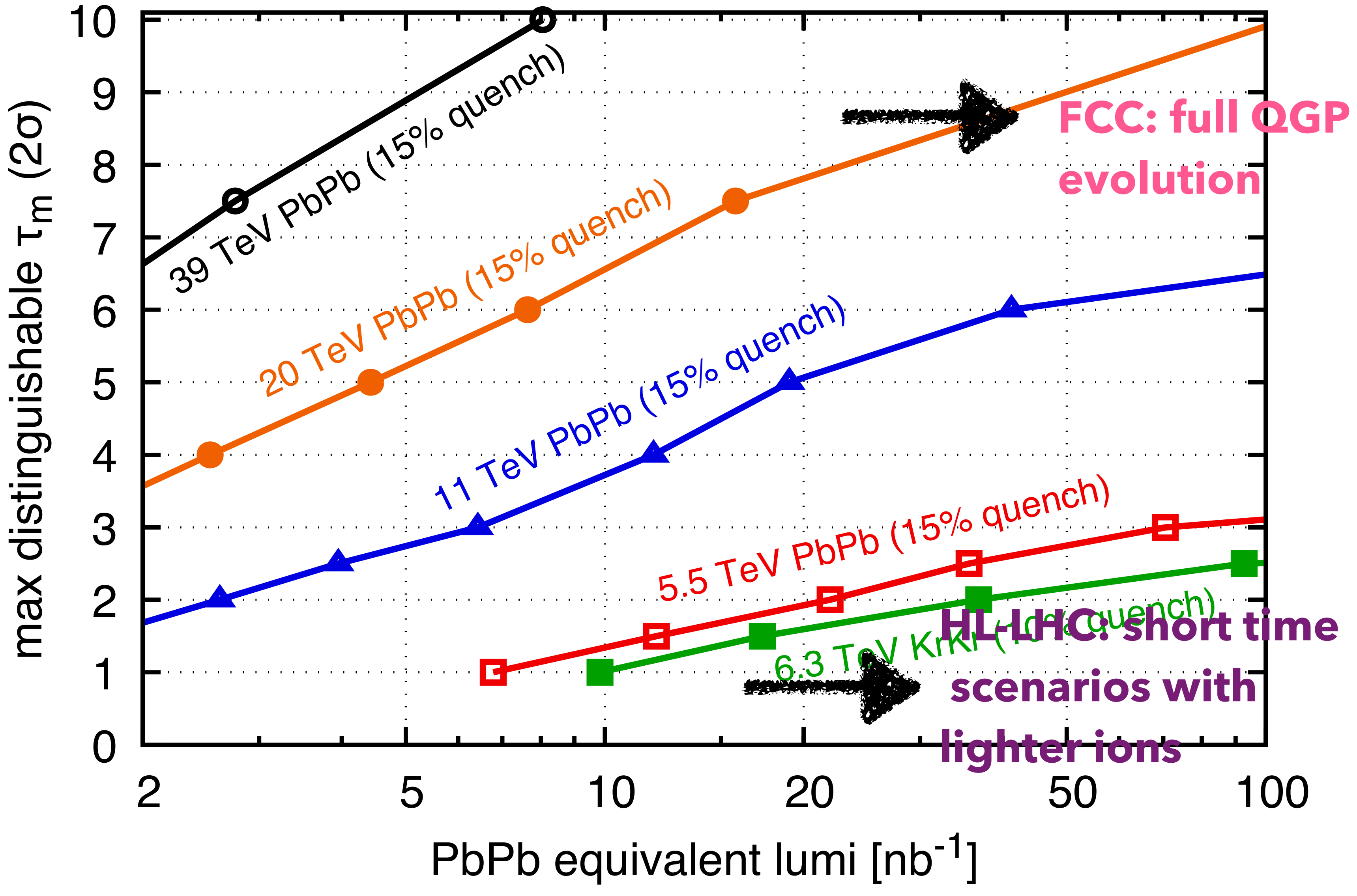
- Focusing on dilepton only method (no b-jets).
- Total uncert. expected to be halved w.r.t. Run 2.

Top quark as a probe for QGP

- $\tau_t \sim 10^{-24}$ sec. Does not hadronize and decays before QCD mechanisms start acting.
- Unlike other jet quenching probes (dijets, $Z/\gamma + jets$) which are produced simultaneously with the collision, tops can resolve the time evolution of QGP:
- Depending p_t tops can decay before or within QGP.
- Taking "snapshots" at different times (p_t), one could resolve the QGP time evolution.
- Semileptonic $t\bar{t}$ represents a "golden channel":
  - High BR
  - Good S/B





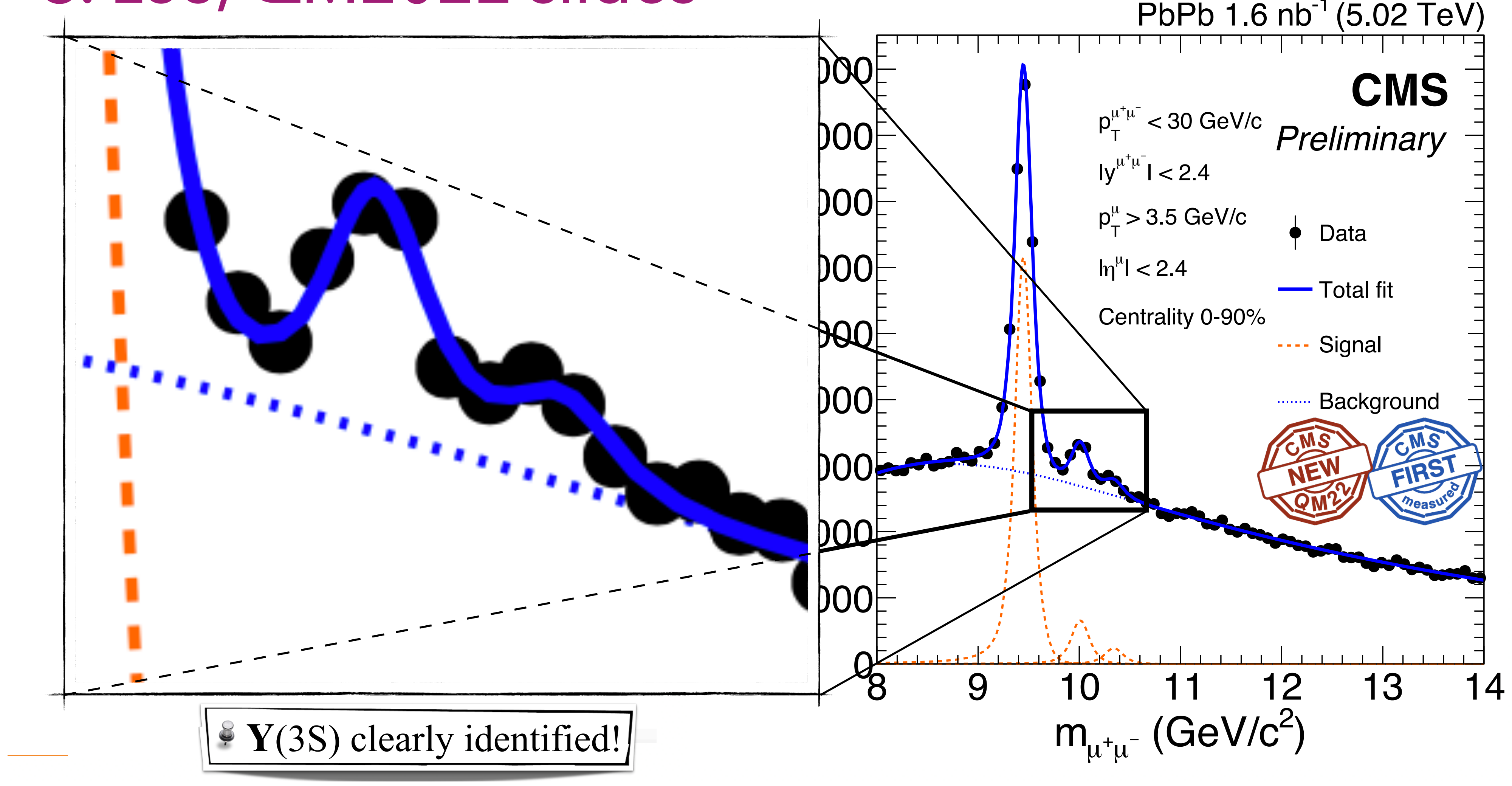


PRL 120 (2018) 232301

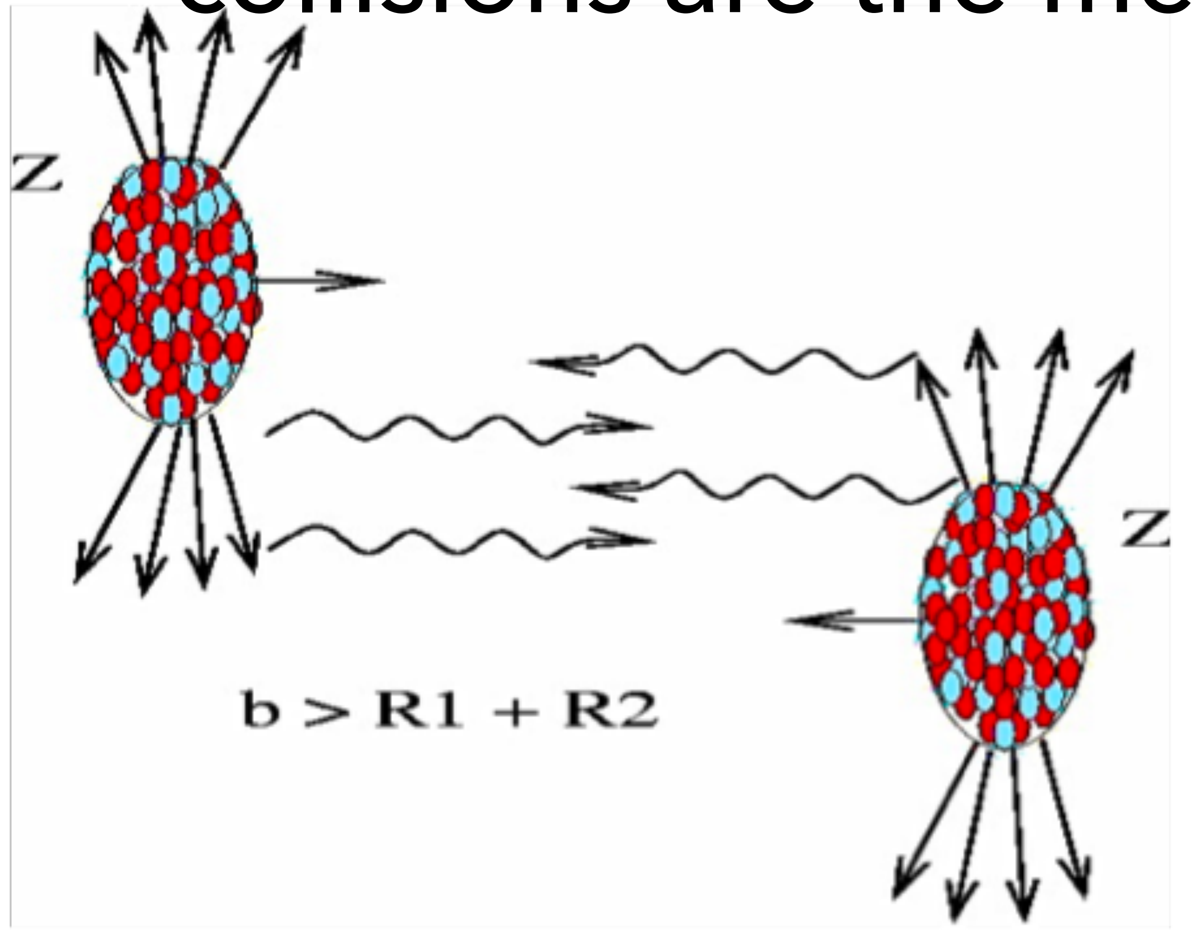
Vector mesons in UPC

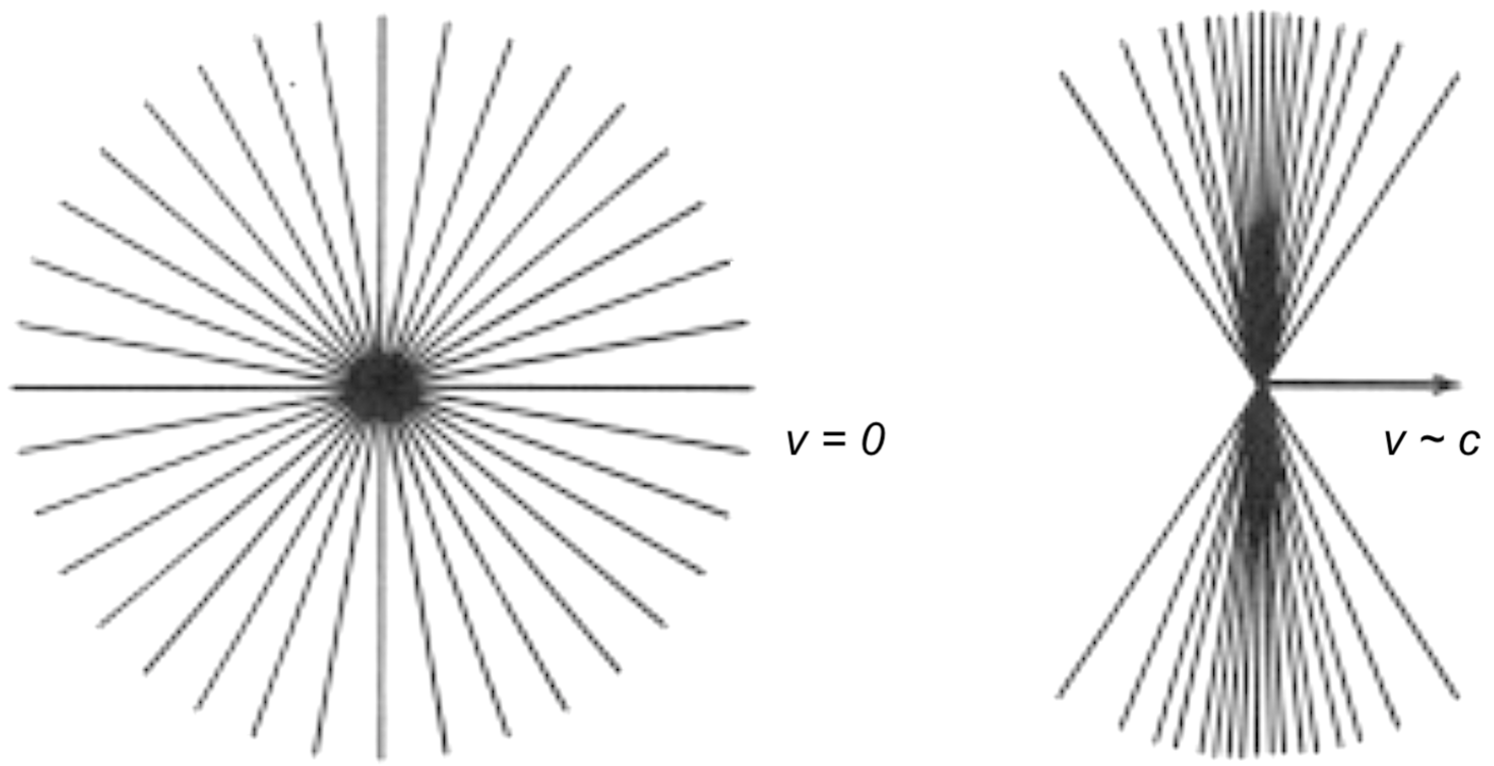
- **Central** HI collisions mainly devoted to study quark matter properties:

S. Lee, QM2022 slides

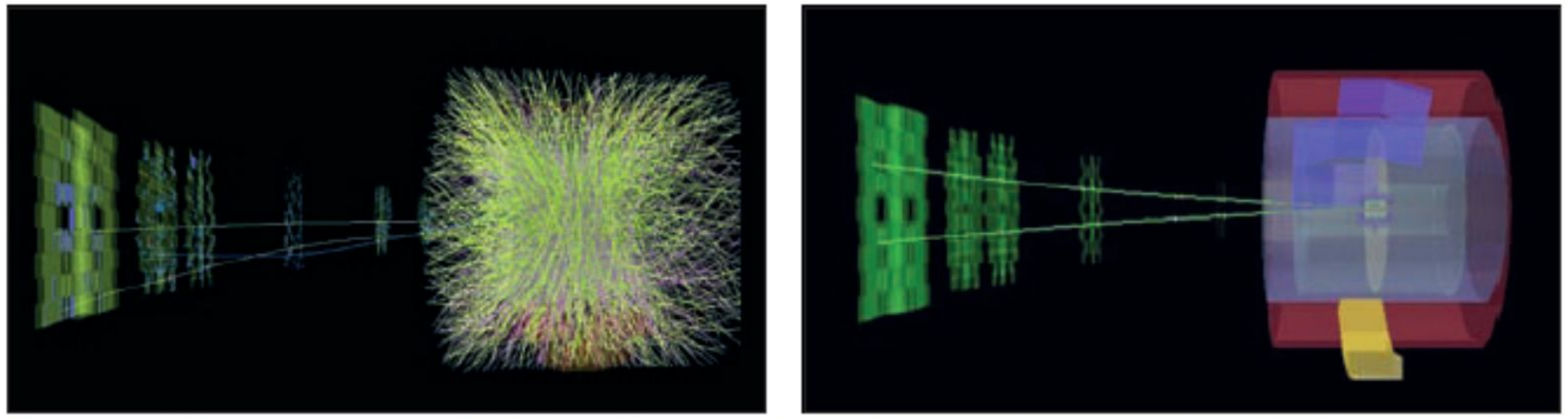


- Large photon flux $\sim Z^2$ (Fermi/Weizsacker-Williams see Mariola's talk).
- Experimentally clean. (Paradoxically HI collisions are the messiest and cleanest!).





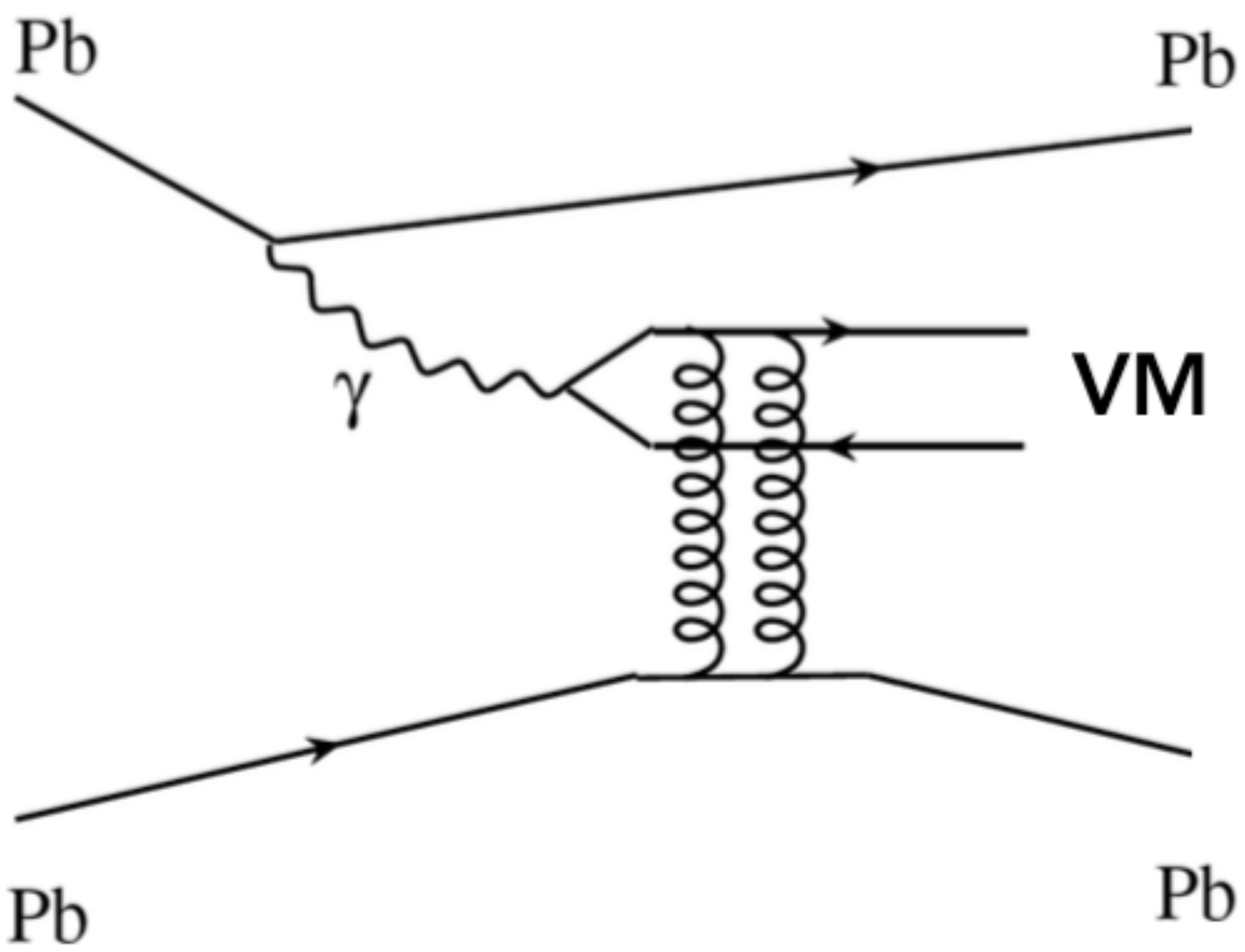
- **Ultra-Peripheral HI Collisions (UPC):**
- Interplay between QED, QCD and BSM.
- Impact parameter $b > R_1 + R_2$ (nuclei don't "touch" each other.



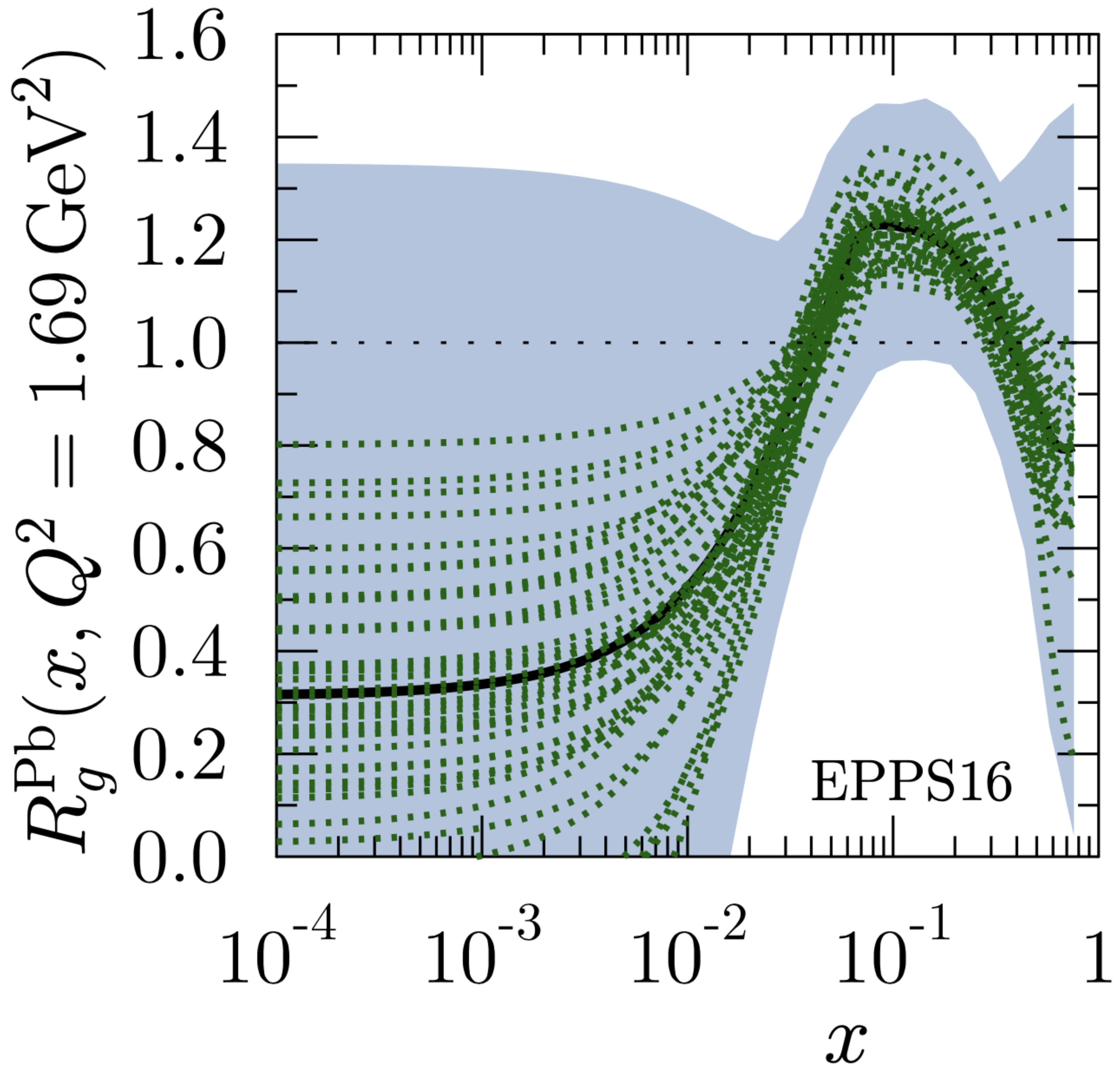
J/ψ candidates in a central PbPb collision (left) and in an ultra-peripheral collision (right).

Upsilon production in HI UPC

- **How do we produce Υ in UPC ?**
  - Photon produced from one ion fluctuates to a quark-antiquark pair which interacts with the other nucleus via two gluon color singlet.
  - Pb+Pb → Pb + V + Pb



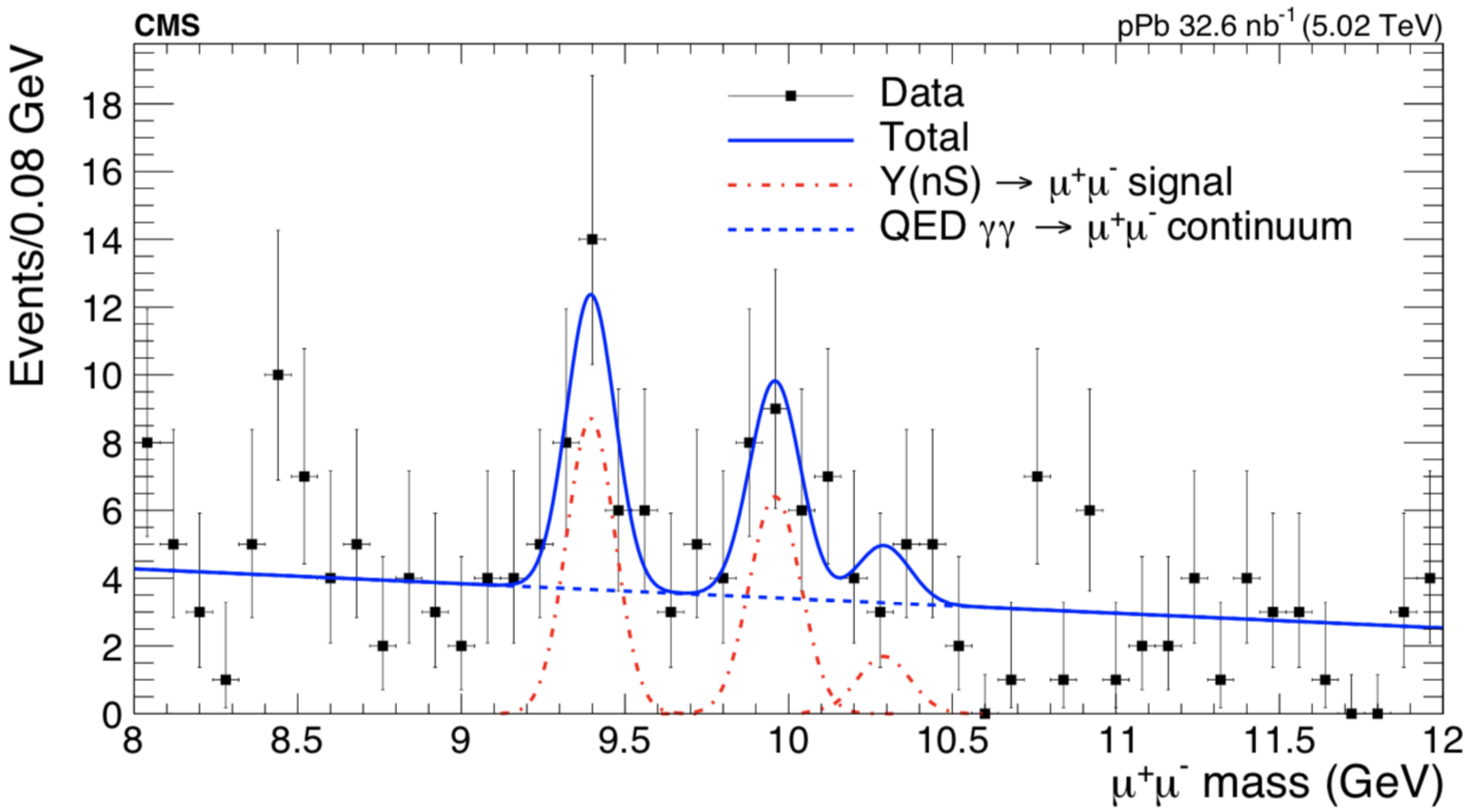
- Relevance:
  - Understand nuclear structure: nuclear PDFs, specially at lox x. (Nucleus is not just a simple superposition of protons and neutrons).

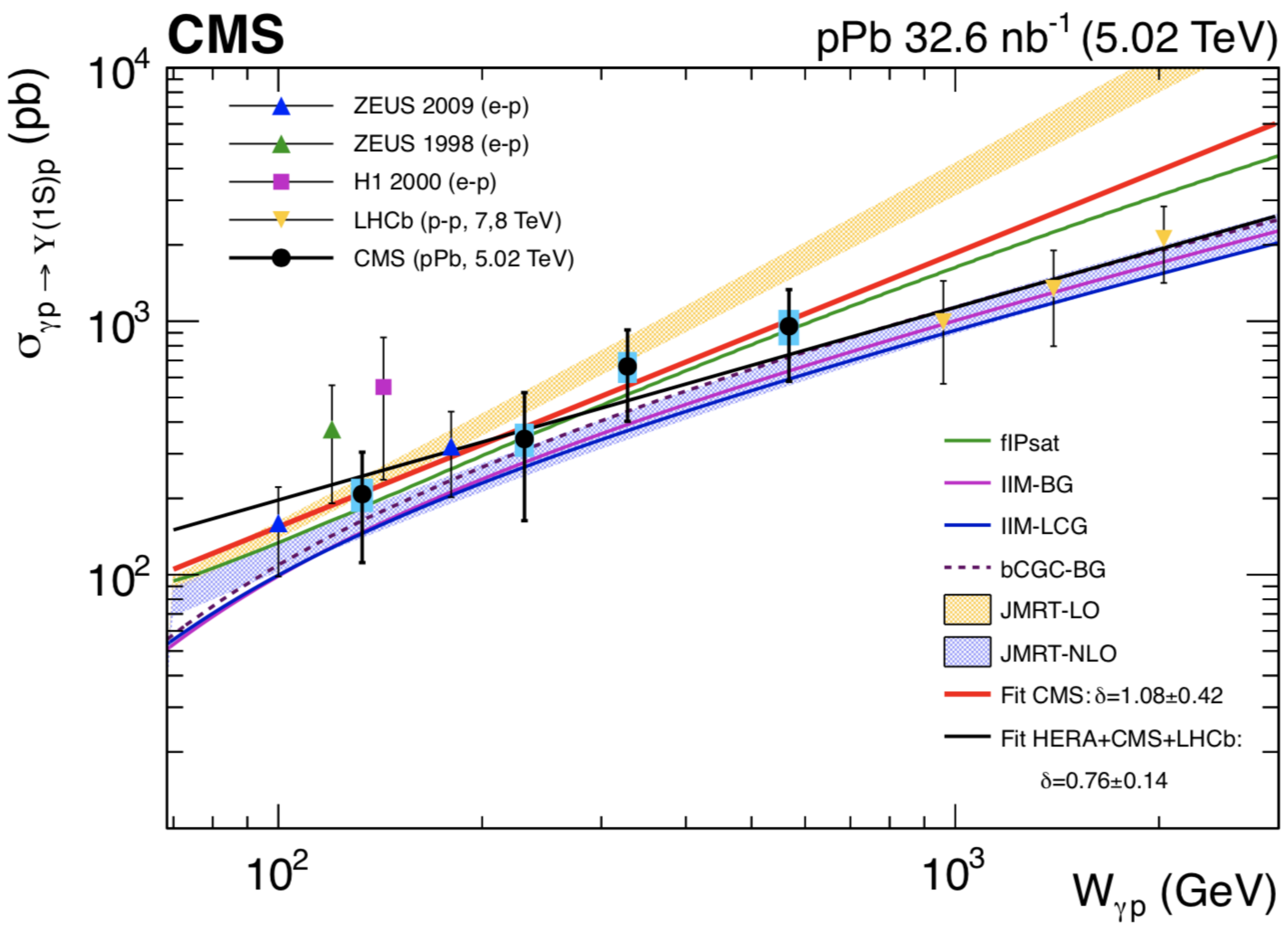


  - Constrains theoretical models of nuclei.

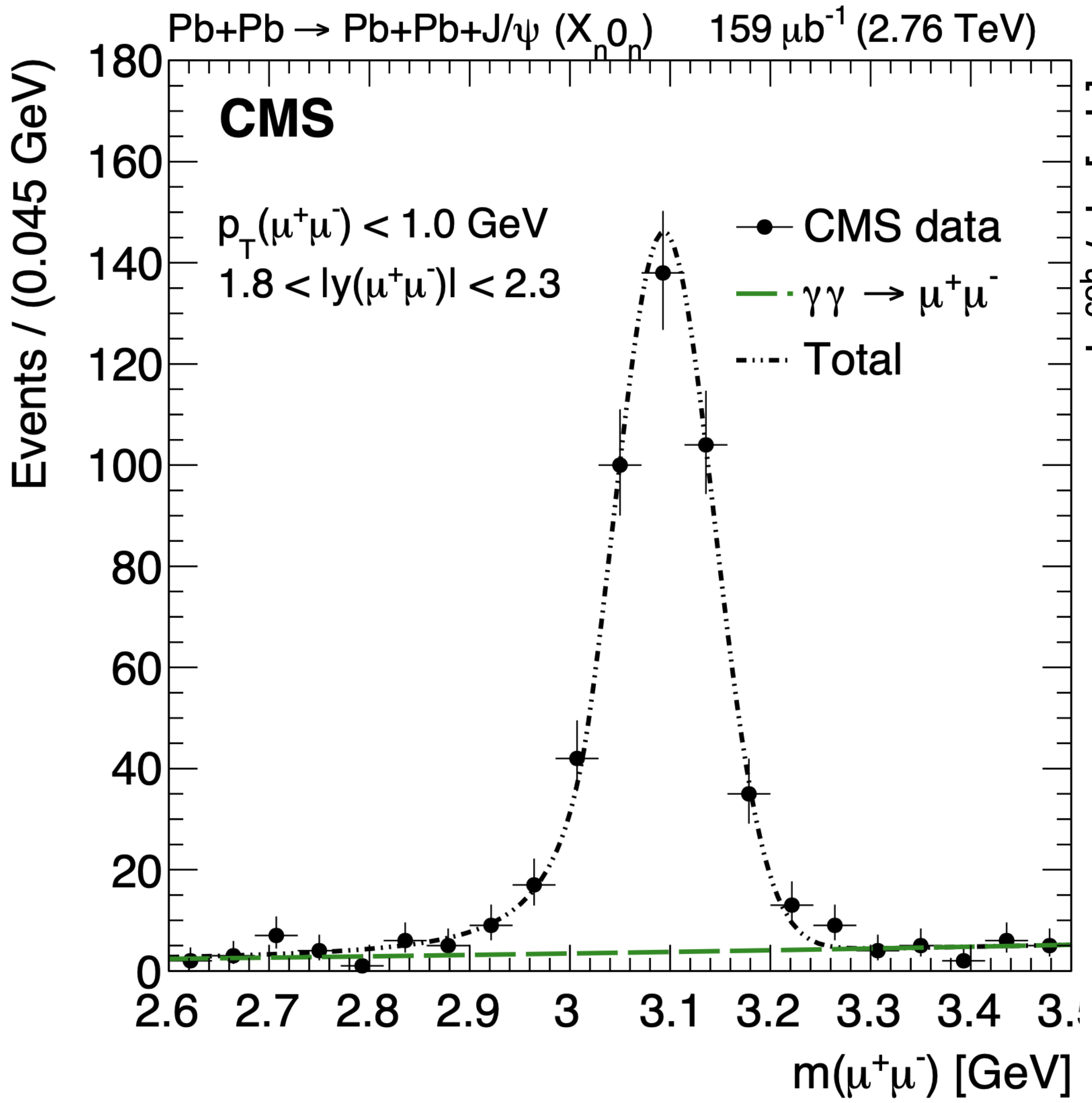
Upsilon production in HI UPC

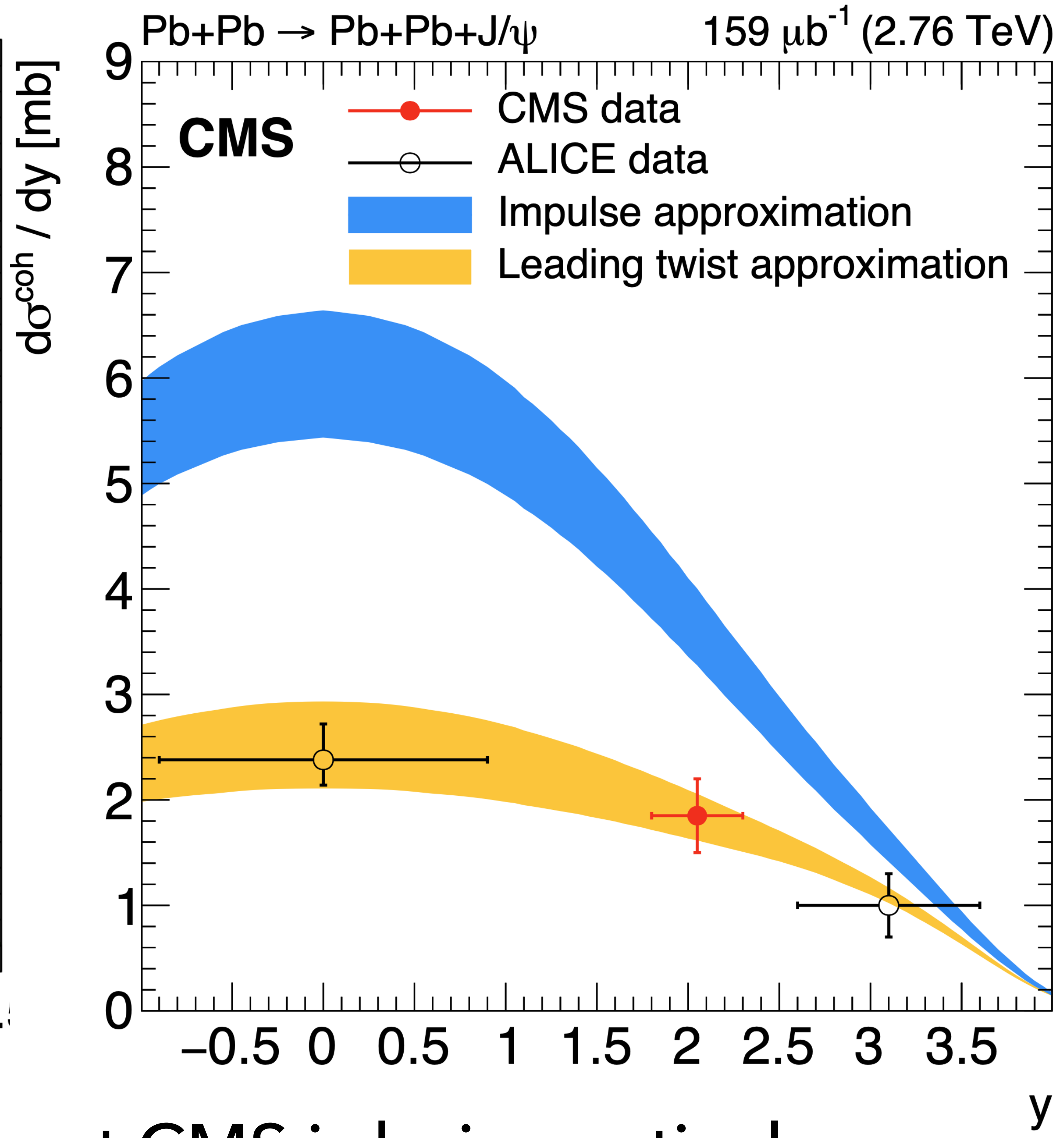
- **Relevant related analyses by CMS:**
  - Υ photo-production in pPb arXiv:1809.11080 at 5.02 TeV





- **Relevant related analyses by CMS:**
  - J/ψ photoproduction in PbPb at 2.76 TeV arXiv:1605.06966

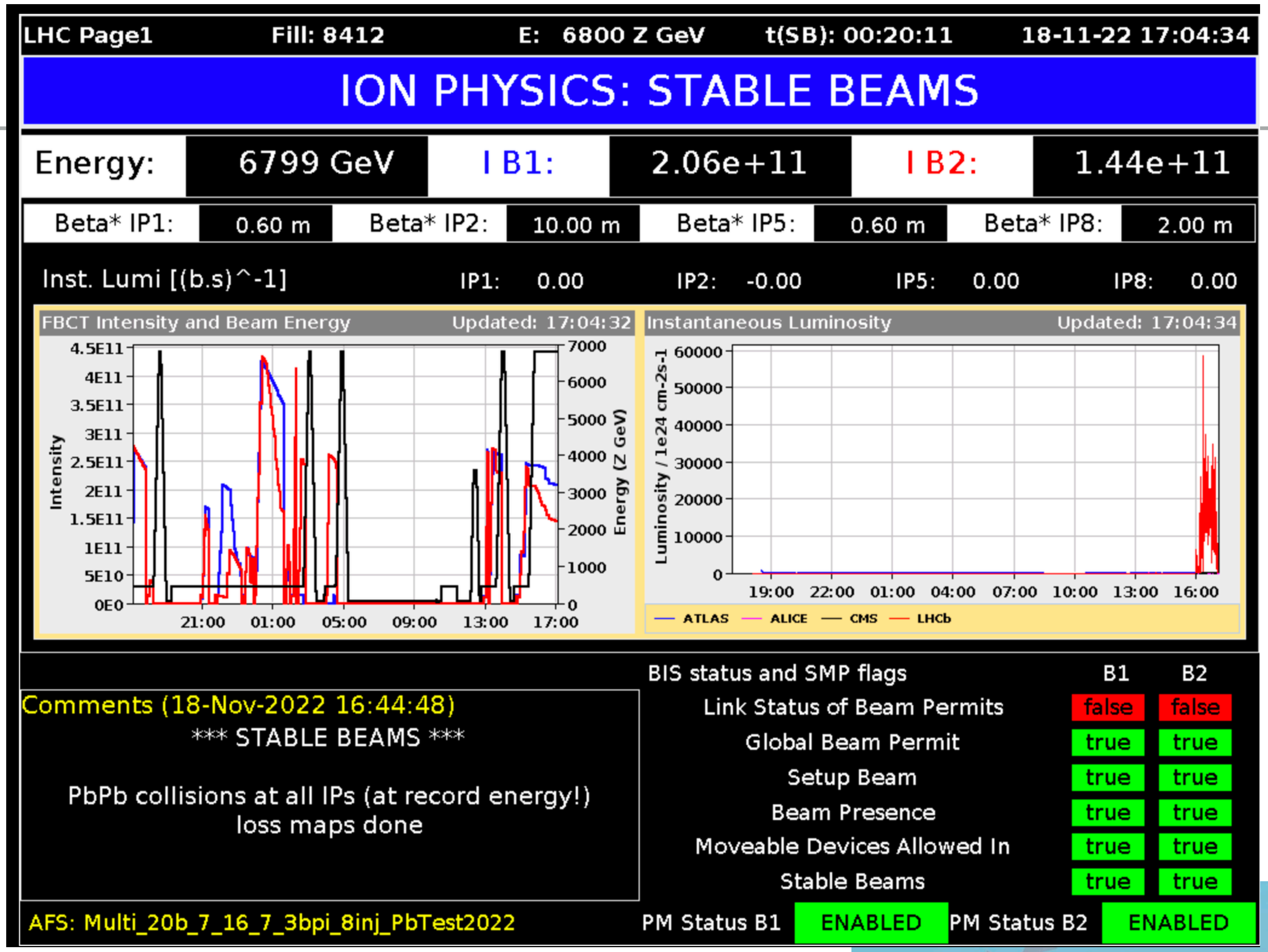


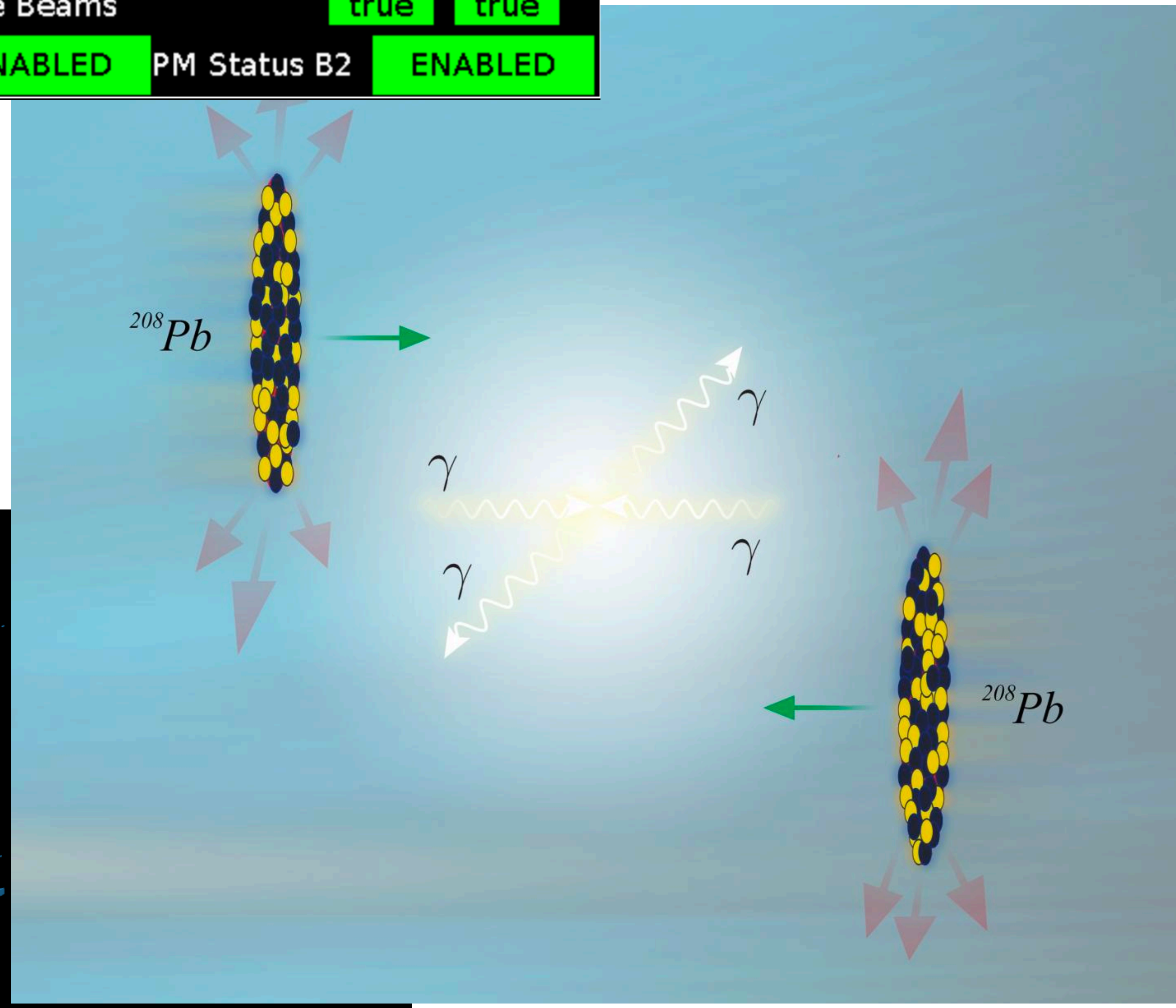


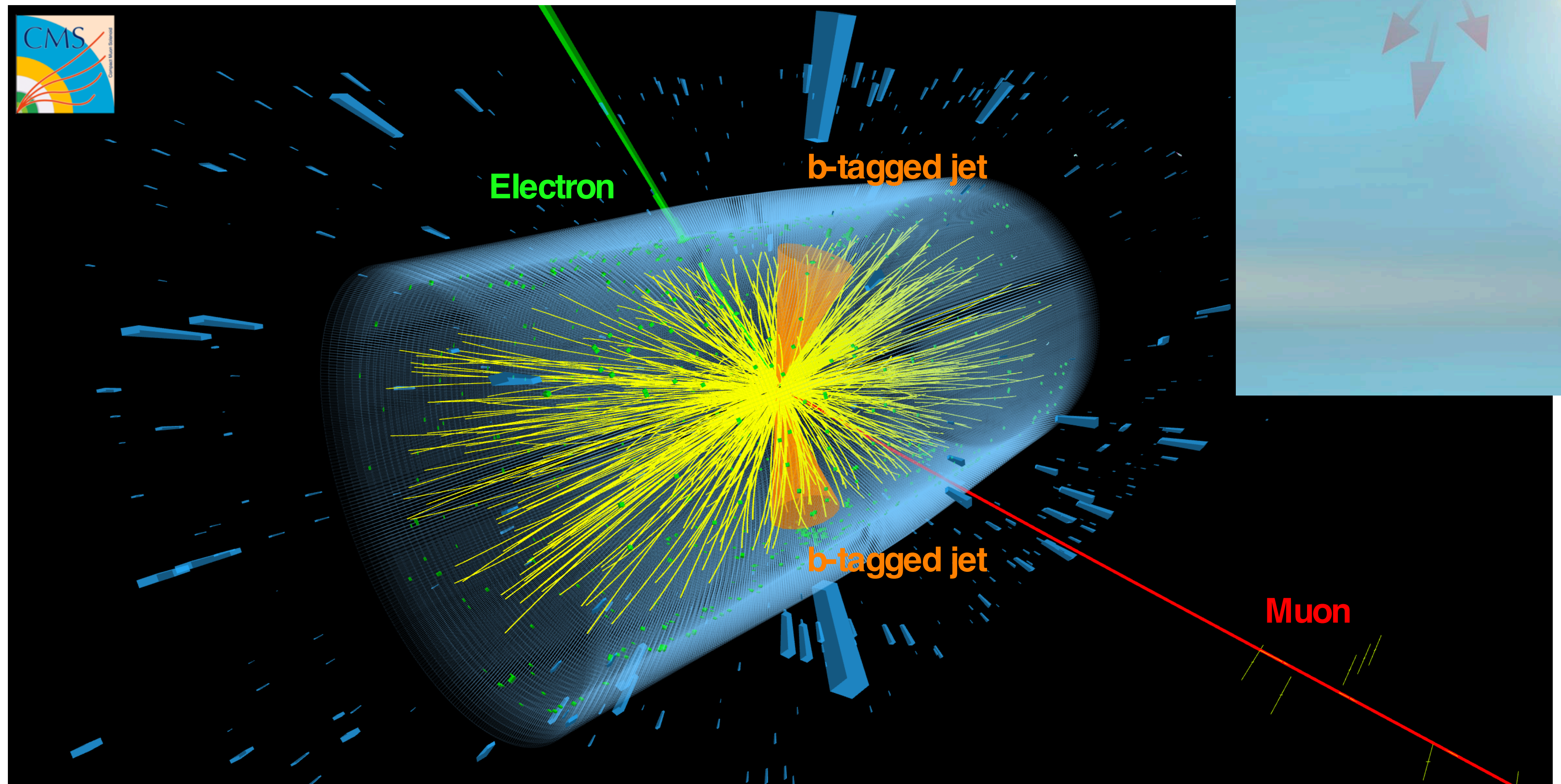
- Vector meson photoproduction at CMS is being actively studied.
- Ongoing analyses e.g. J/ψ, Υ in PbPb at 5.02 TeV which might bring new hints about saturation and nuclear behavior.

Summary

- **Top quark:**
- $t\bar{t}$ at $\sqrt{s} = 5,7,8,13$ TeV.
- $t\bar{t}$ in pp, pPb and and evidence in PbPb.
- Looking forward for observation with Run 3 data.
- Top quark in HI is unique probe to resolve the time evolution of QGP.
- **Vector meson in UPC:**
- Important for nPDF determination.
- Relevant to understand saturation.
- Quarkonium photoproduction analyses ongoing (J/ψ to be approved soon…).





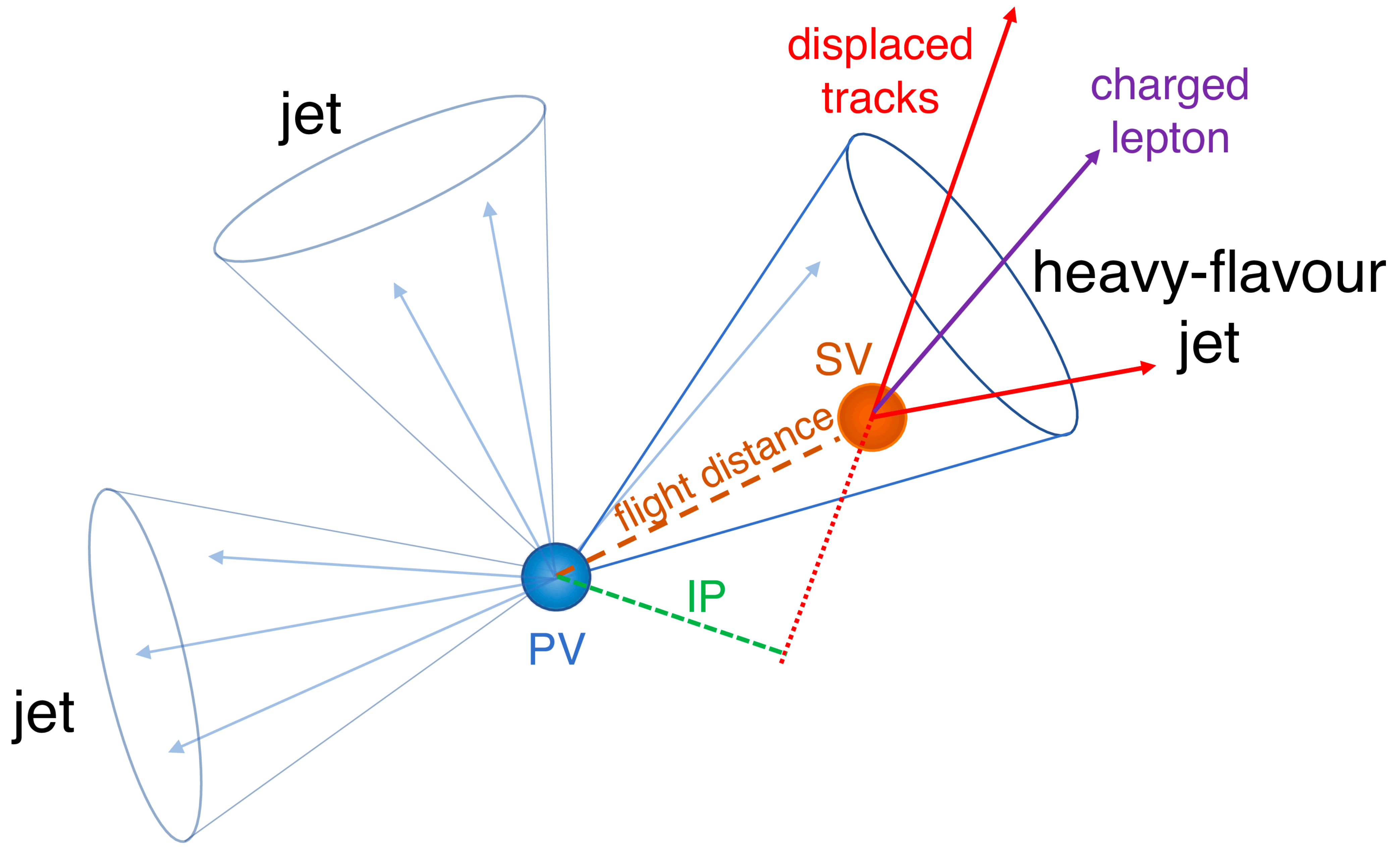


Backup slides

Backup

Identification of b-jets

- Combined Secondary Vertex Algorithm (CSV Run I, CSv2V Run II): combines the info. of displaced tracks and secondary vertices associated with the jet using MVA.



JINST 13 (2018) P05011

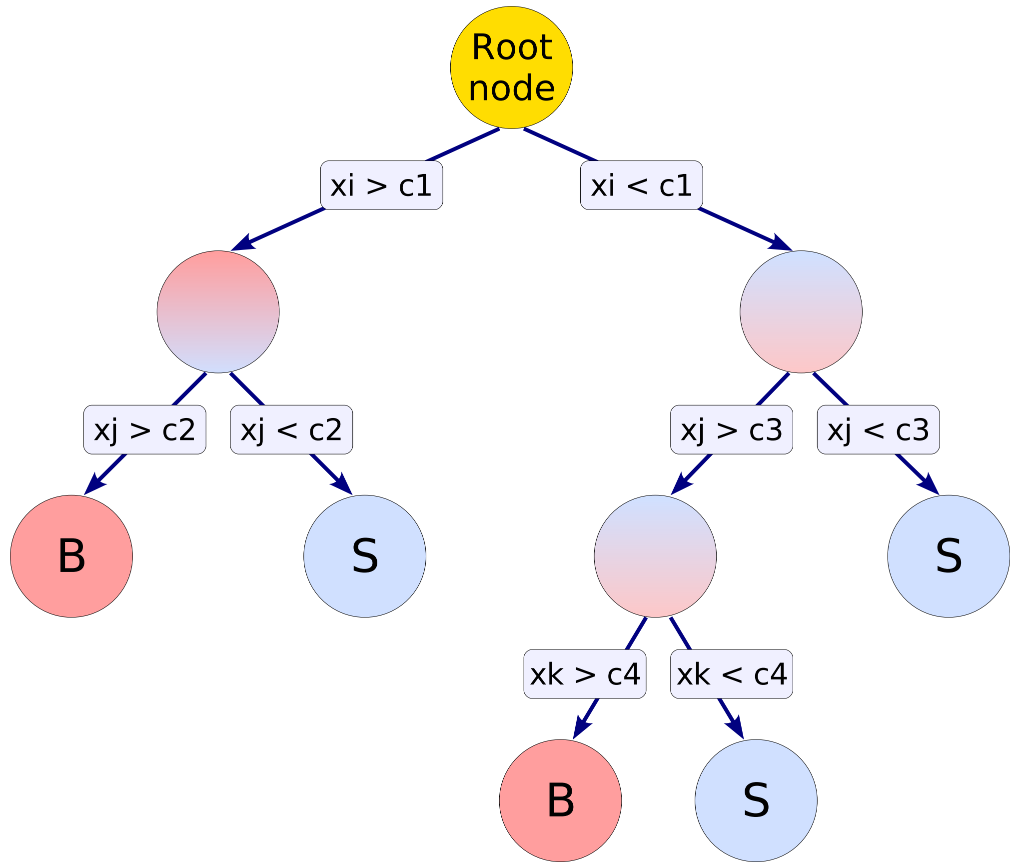
Table 1: Input variables used for the Run 1 version of the CSV algorithm and for the CSVv2 algorithm. The symbol "x" ("—") means that the variable is (not) used in the algorithm

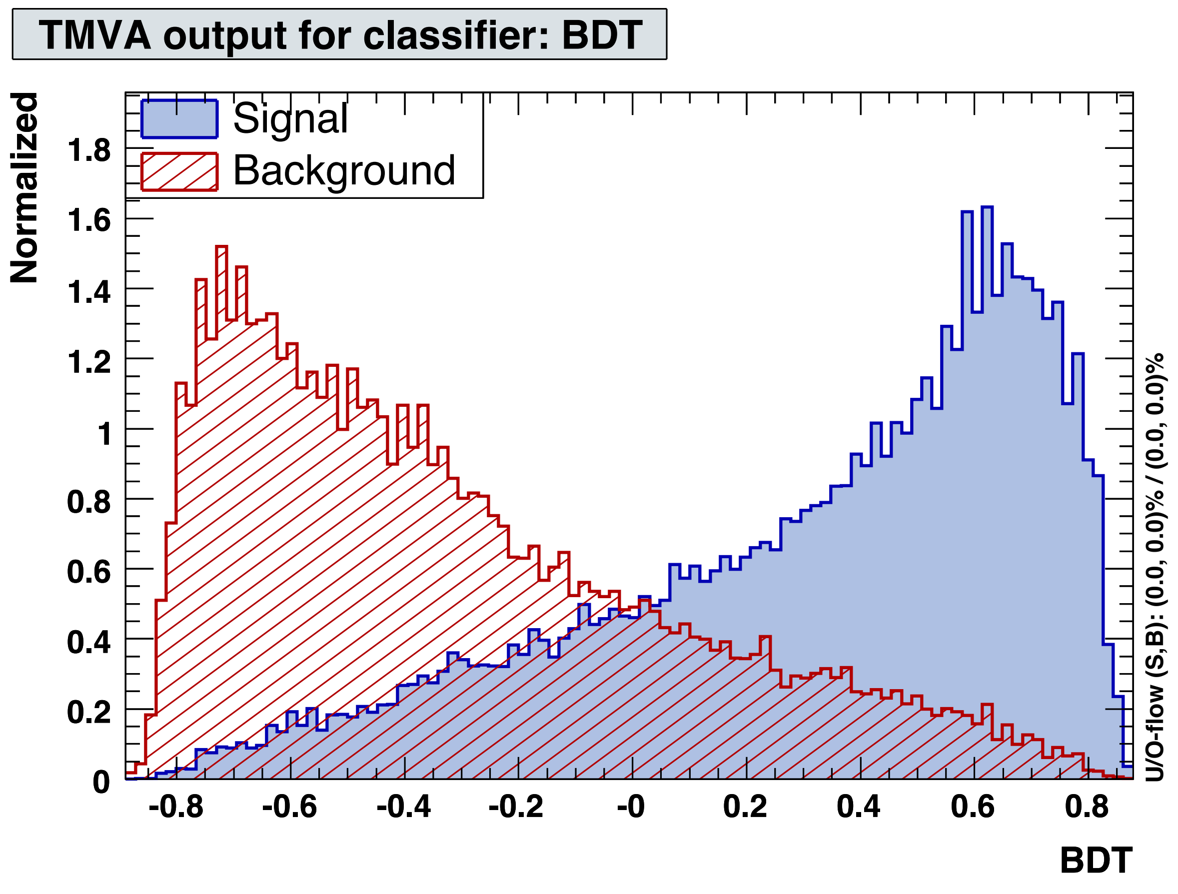
Input variable	Run 1 CSV	CSVv2
SV 2D flight distance significance	x	x
Number of SV	—	x
Track η_{rel}	x	x
Corrected SV mass	x	x
Number of tracks from SV	x	x
SV energy ratio	x	x
ΔR(SV, jet)	—	x
3D IP significance of the first four tracks	x	x
Track $p_{T,rel}$	—	x
ΔR(track, jet)	—	x
Track $p_{T,rel}$ ratio	—	x
Track distance	—	x
Track decay length	—	x
Summed tracks E_T ratio	—	x
ΔR(summed tracks, jet)	—	x
First track 2D IP significance above c threshold	—	x
Number of selected tracks	—	x
Jet p_T	—	x
Jet η	—	x

Backup

Boosted Decision Trees (BDT)

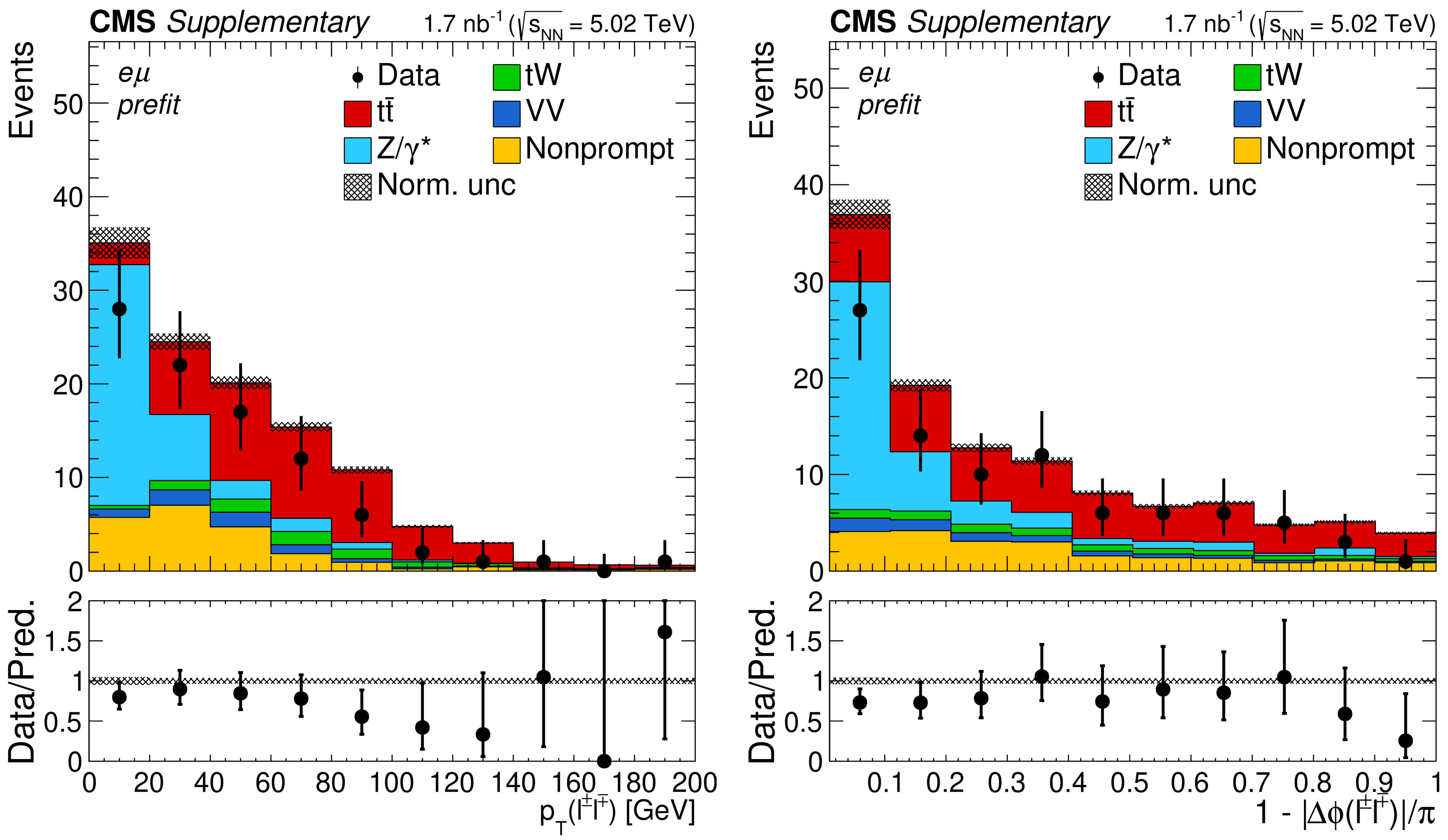
- Decision Tree (DT): binary classifier in which repeated decisions are taken until a stop criterion is reached.
- Boosted DT (BDT): extends the idea from one tree (weak classifier) to several trees (forest)
  - Better performance classifier
- By convention, signal (background) events accumulate at large (small) BDT score.





CERN-OPEN-2007-007

- $t\bar{t}$ in PbPb: BDT is trained with kinematics of the two leading-p_T leptons.
  - p_T of leading lepton, $p_T(\ell_1)$
  - Asymmetry in lepton-p_T's, $\frac{p_T(\ell_1) - p_T(\ell_2)}{p_T(\ell_1) + p_T(\ell_2)}$
  - Dilepton system p_T, $p_T(\ell\ell)$
  - Dilepton system pseudorapidity, $|\eta(\ell\ell)|$
  - Absolute azimuthal separation in ϕ of the two leptons, $|\Delta\phi(\ell\ell)|$
  - Sum of absolute η's of leptons, $\sum_i |\eta_i|$



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