Evidence for top quark production in nucleus-nucleus collisions with the CMS experiment

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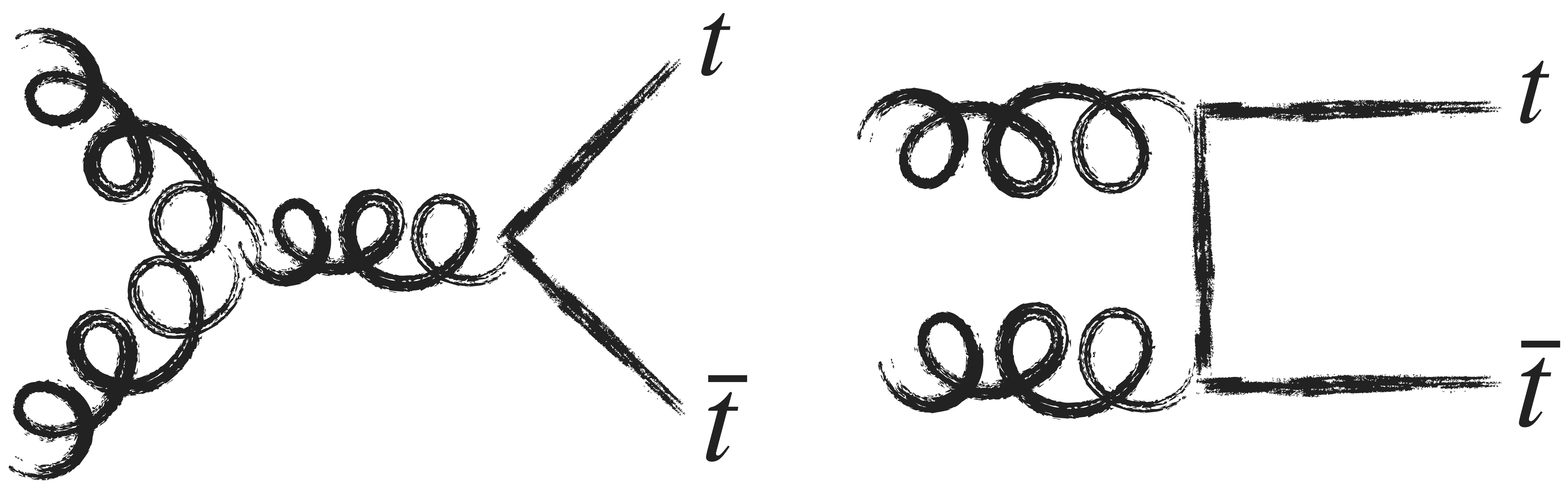
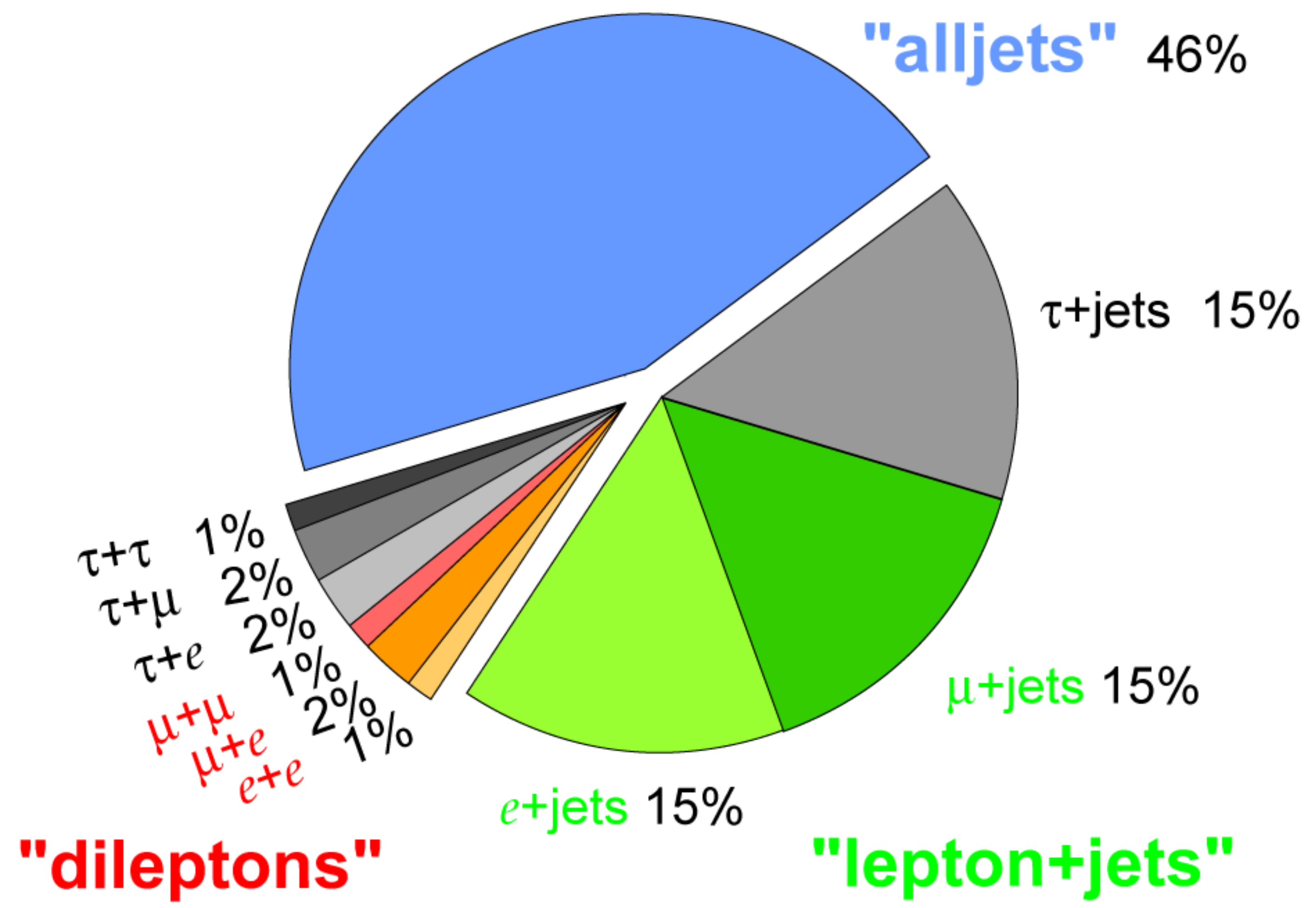
Introduction

Top quark:

- Discovered in 1995 in Tevatron
- Heaviest particle in the SM: $m_t \sim 173$ GeV
- Decay modes:
  - $t \rightarrow bW \rightarrow b + \ell\nu\,(\sim 33\,\%)$
  - $t \rightarrow bW \rightarrow b + q\bar{q}\,(\sim 66\,\%)$
- Primarily produced in $t\bar{t}$ pairs by gluon fusion at LHC

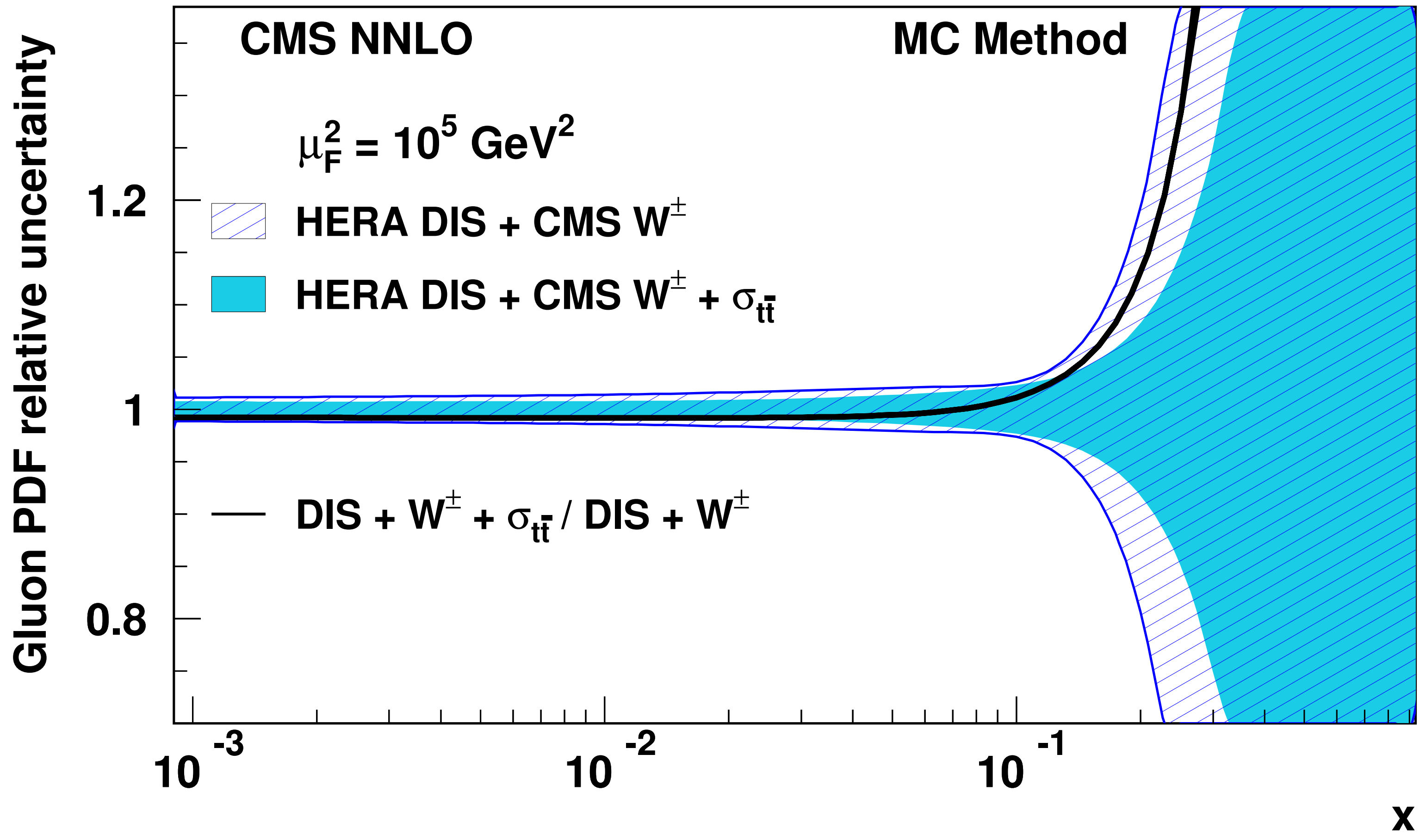


- Channels:
  - $\ell + jets$ (semileptonic):
    $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow q\overline{q'})$ High BR
  - Dilepton (leptonic):
    $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow \ell'\nu')$ Cleanest
  - All jets (hadronic):
    $t\bar{t} \rightarrow bb'W(\rightarrow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



Introduction

- Since its discovery, $t\bar{t}$ observed in:
  - $t\bar{t}$ 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
- Relevance:
  - pp:
    - pA and AA profit from pp measurements.
    - Constrain to proton PDF ($x \sim 1/\sqrt{s}$).
    - Different $\sqrt{s}$ test different Bjorken -x → gluon distribution functions.



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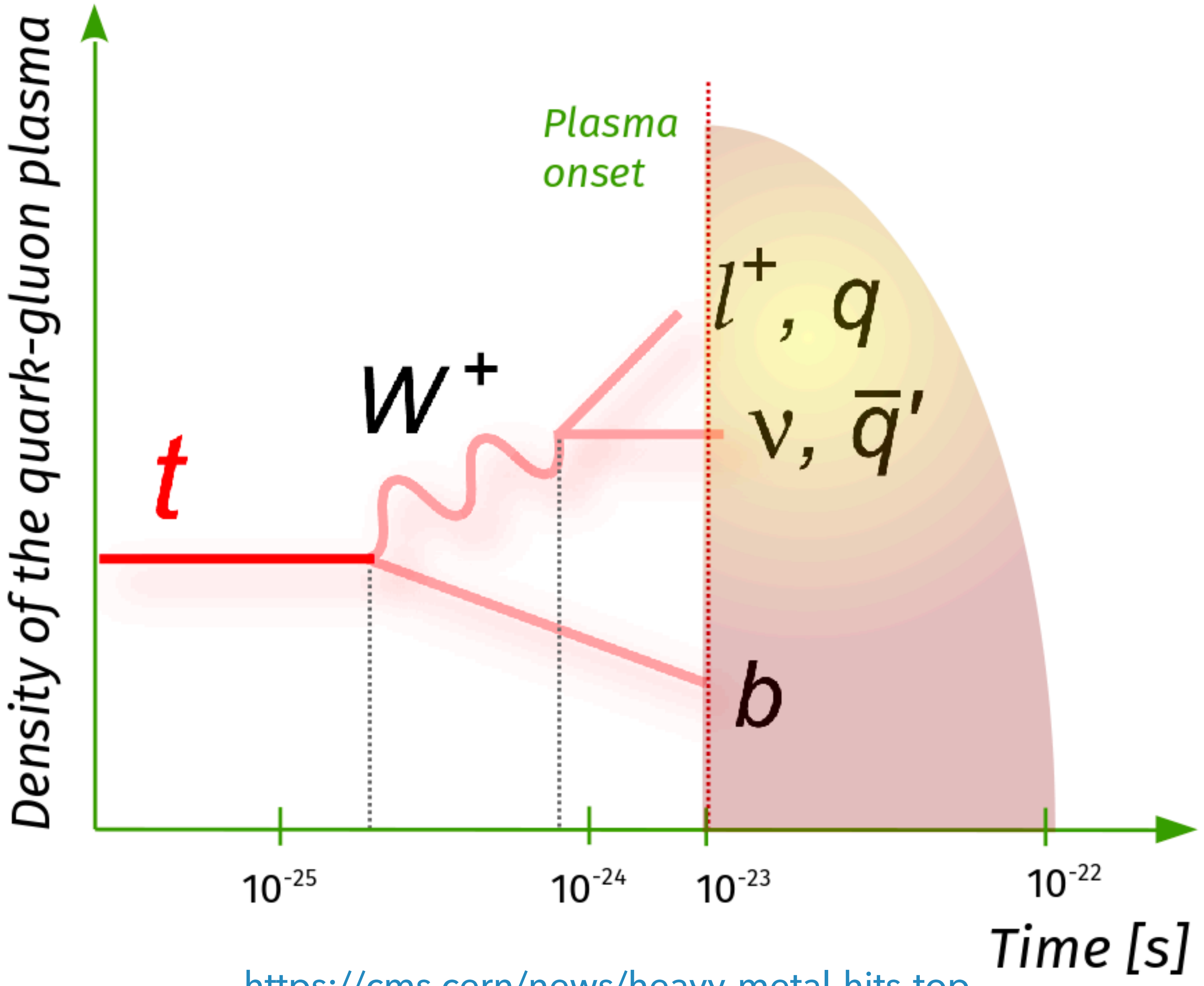
- pA and AA:
  - Probe for nuclear PDFs
  - Paves the way for using top to probe QGP.



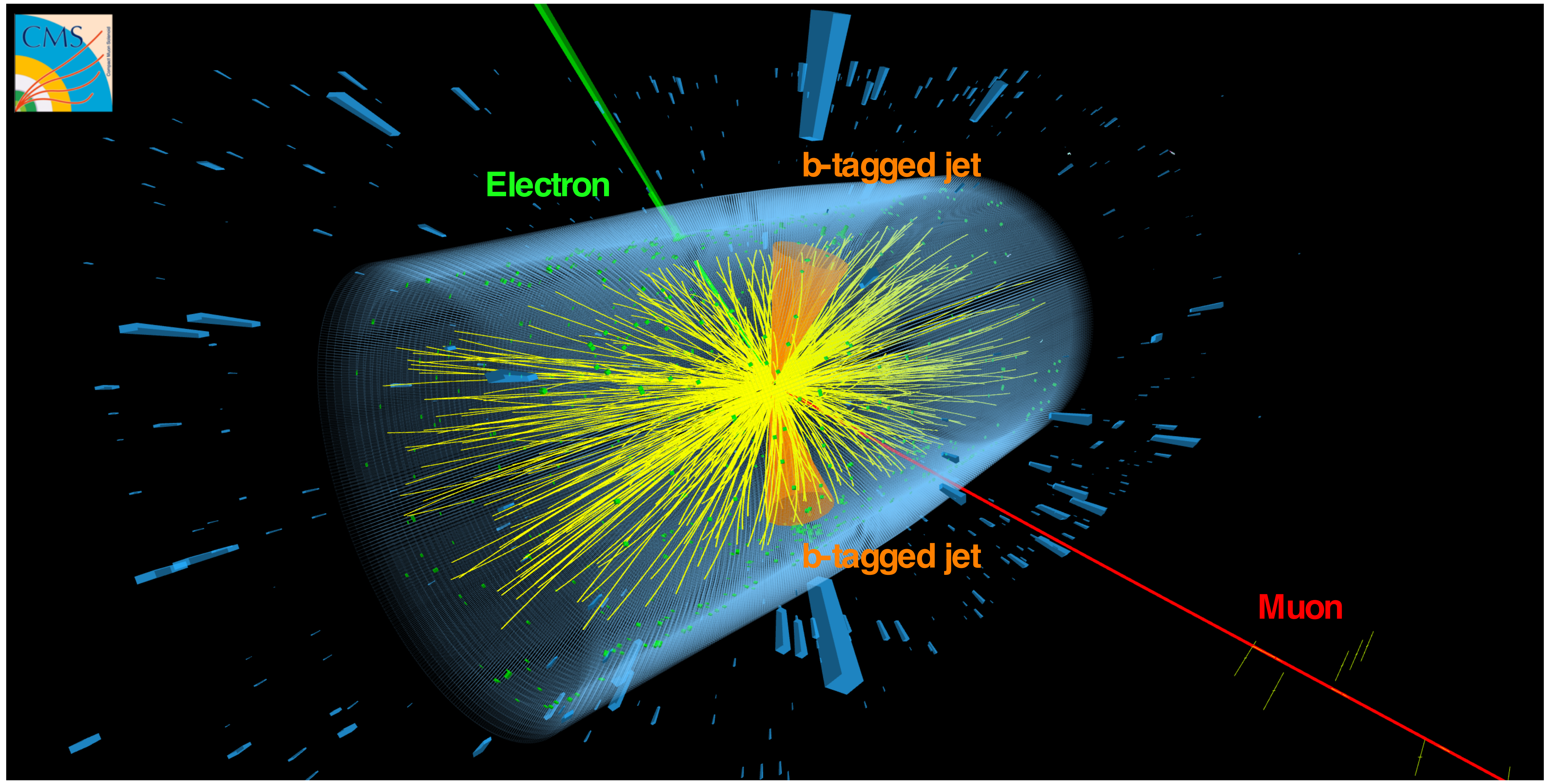
https://cms.cern/news/heavy-metal-hits-top

Methods

- 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:

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



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Methods

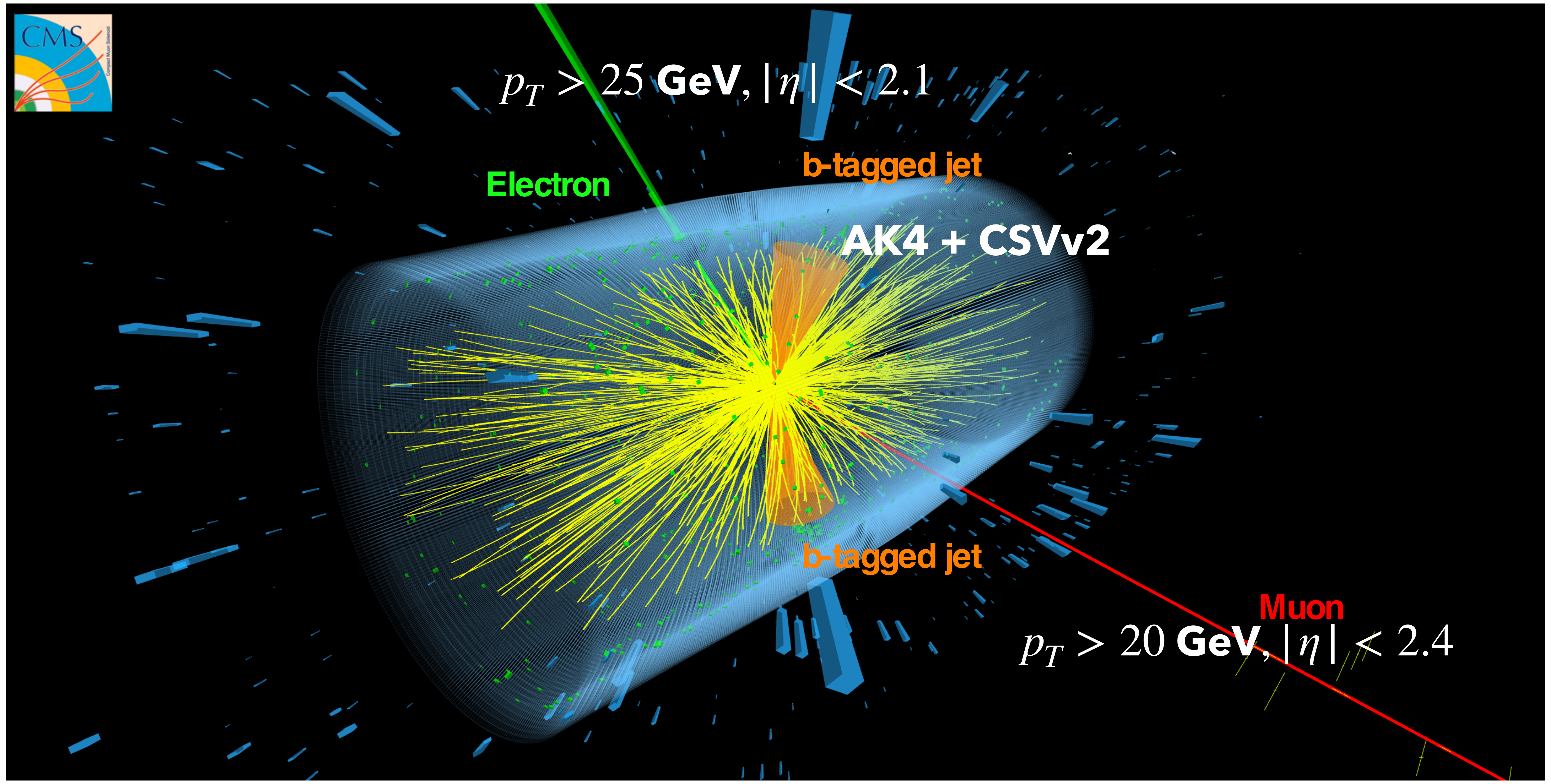
Signal extraction

- Boosted decision trees (BDT): based on kinematics of the leading and sub-leading p_T leptons.
- Simultaneous (three final states) likelihood fits to binned BDT distributions are performed separately for the two methods.
- Fits account to all sources of uncertainty
- Signal strength is extracted: $\mu = \sigma_{t\bar{t}}/\sigma_{theory}$

Simulation

- Signal NN (N=p,n) $\rightarrow t\bar{t}$: MadGraph5_aMC@NLO embedded to HYDJET
- Main background is DY ($Z/\gamma*$). Estimated from MC and data.
- Nonprompt (QCD multijet, W+jets) from control regions in data.

Event selection



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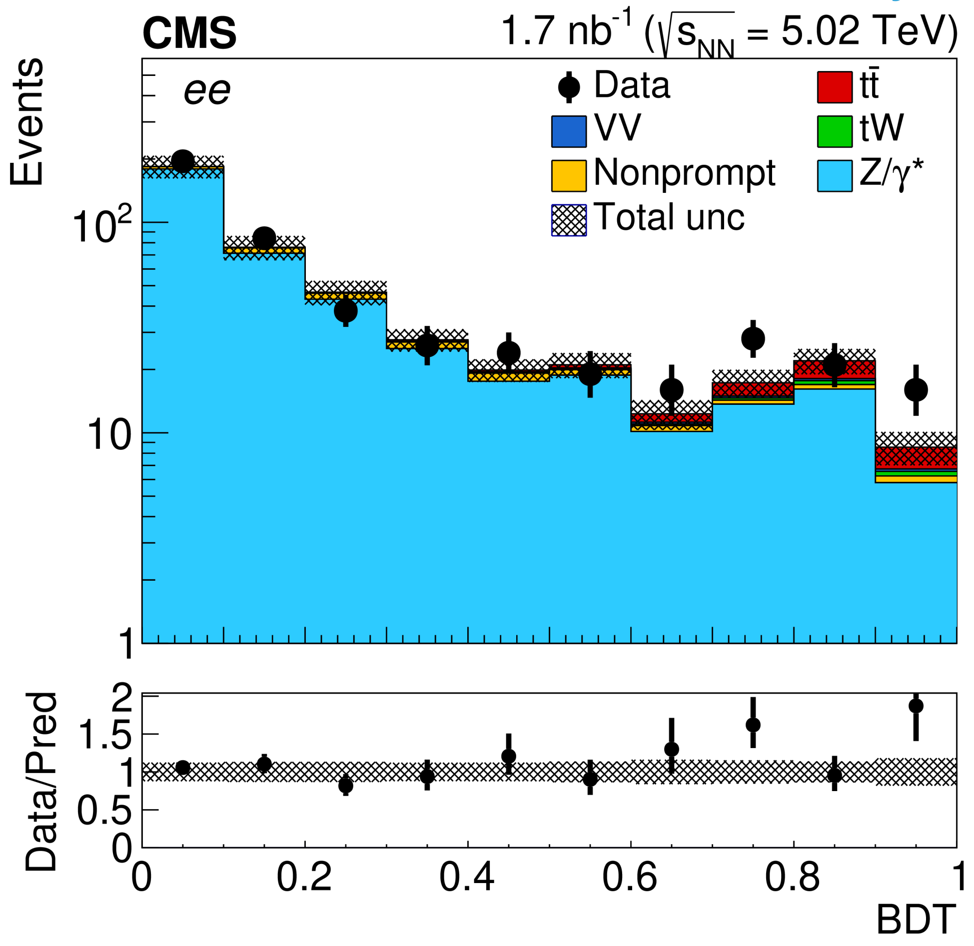
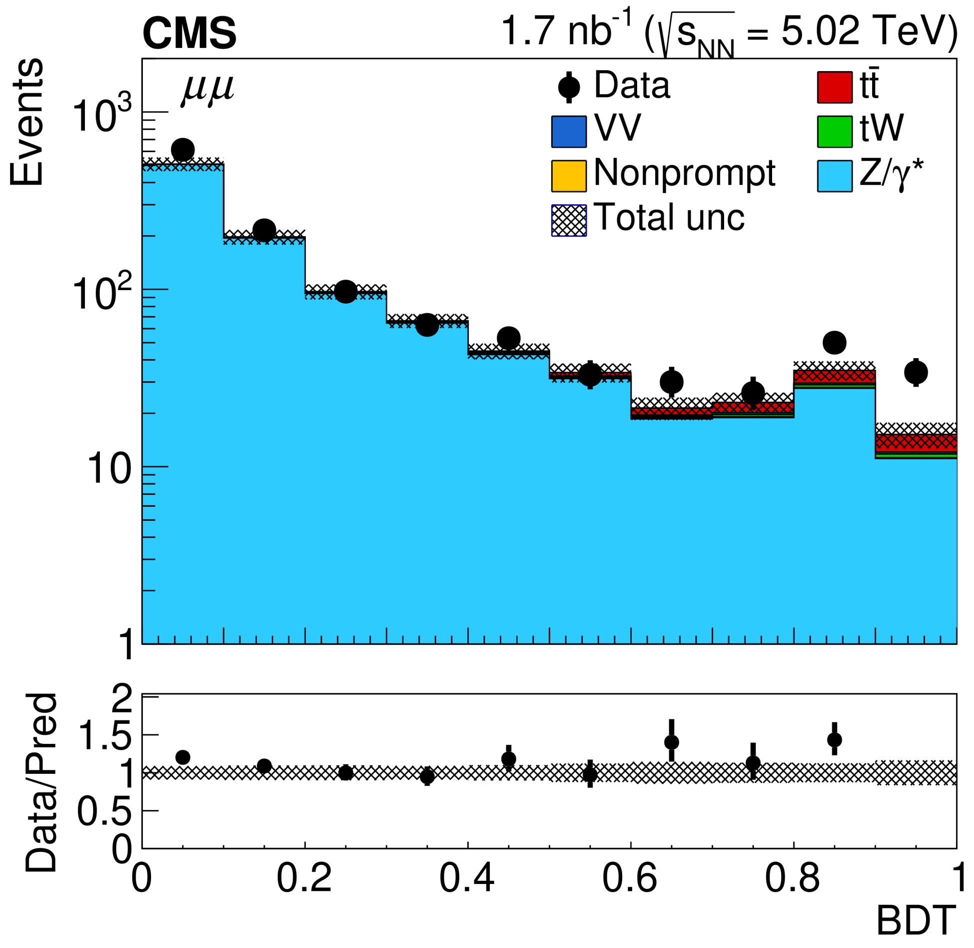
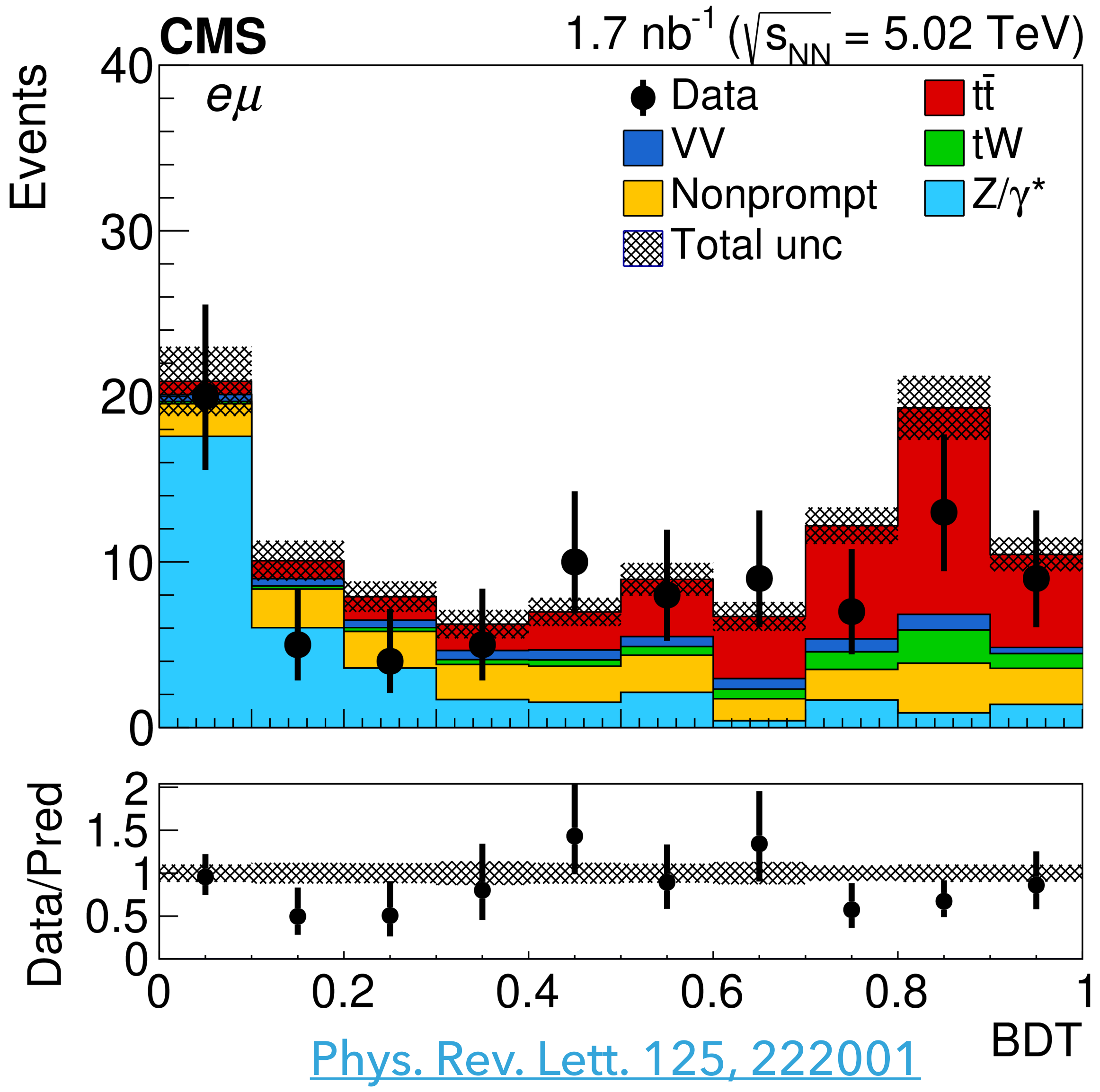
Results

Dilepton

Phys. Rev. Lett. 125, 222001







Phys. Rev. Lett. 125, 222001

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

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

Dilepton + b-jets

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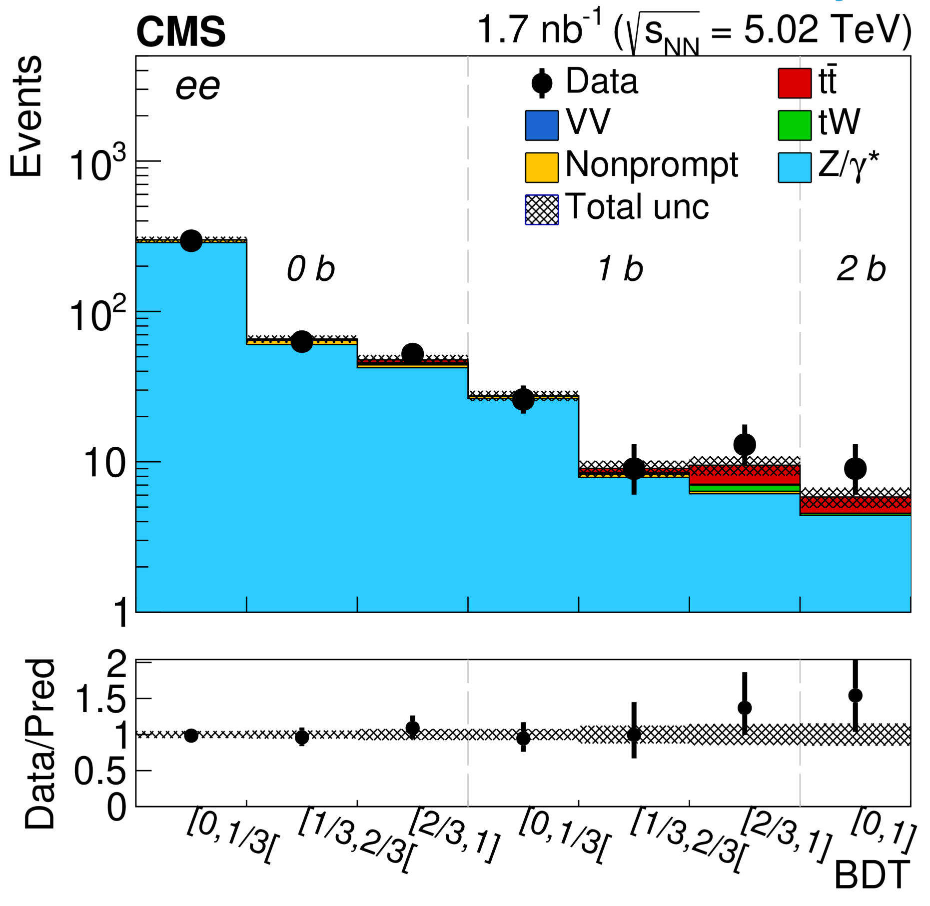
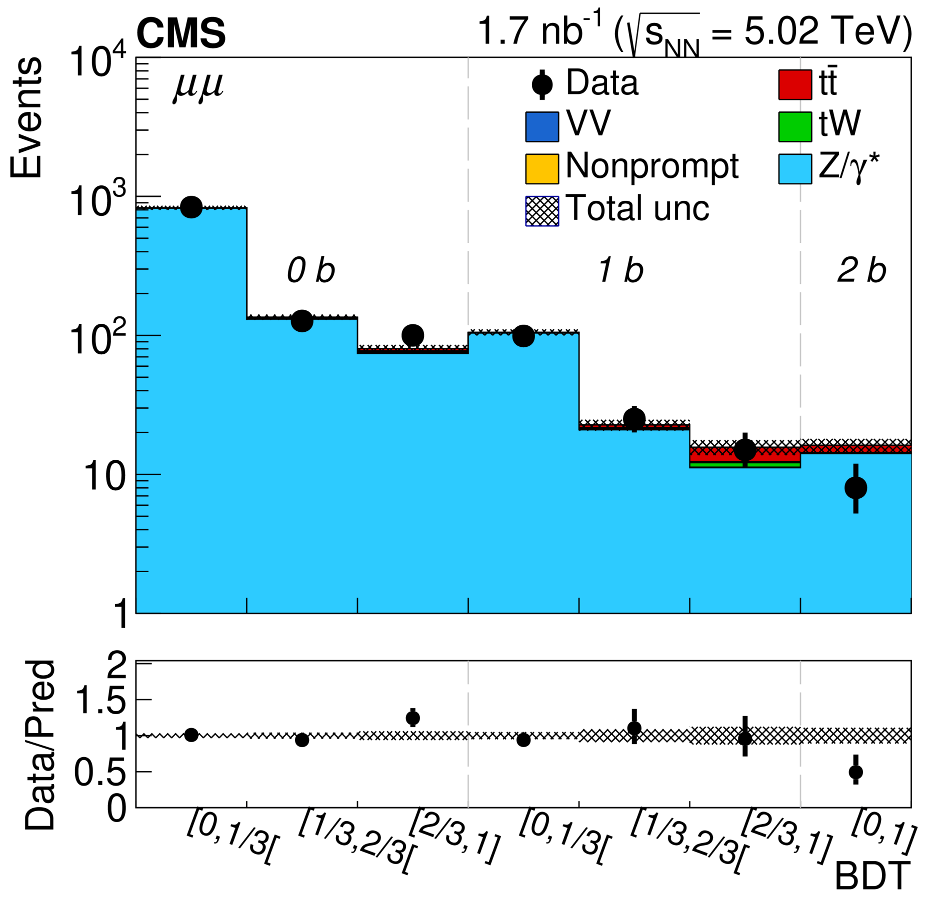
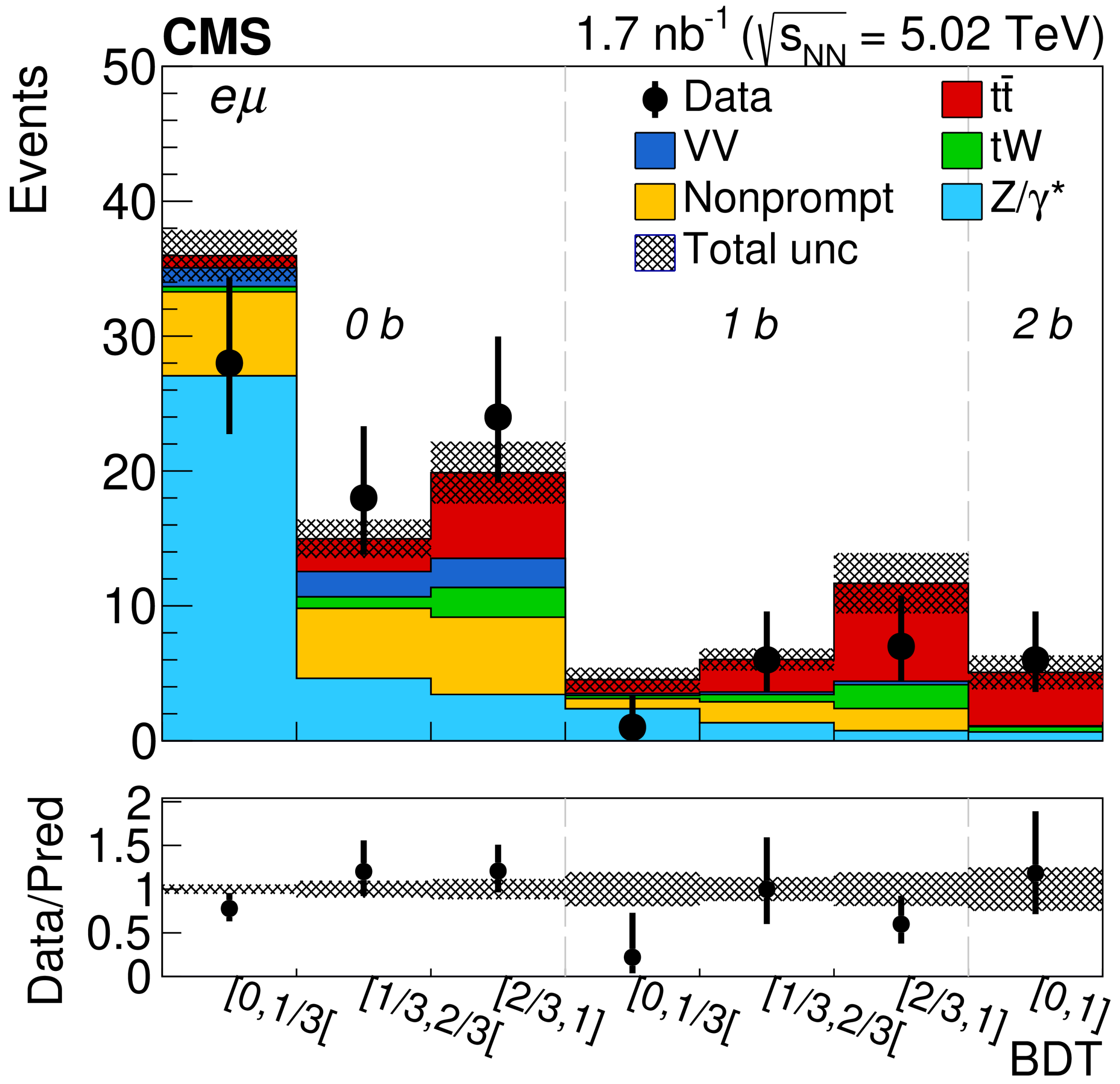






Phys. Rev. Lett. 125, 222001

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

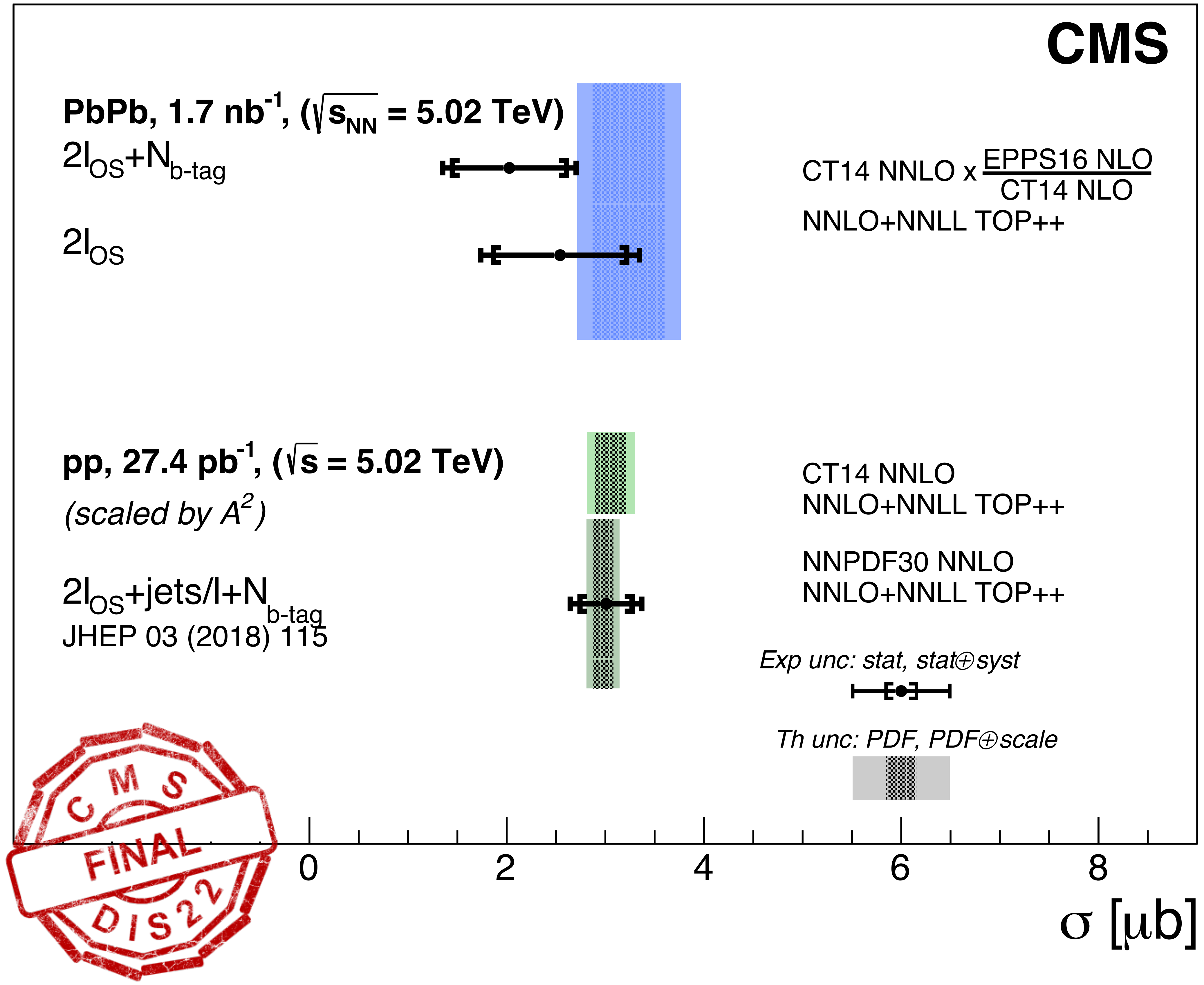
Results

Dilepton + b-jets

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

Dilepton

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



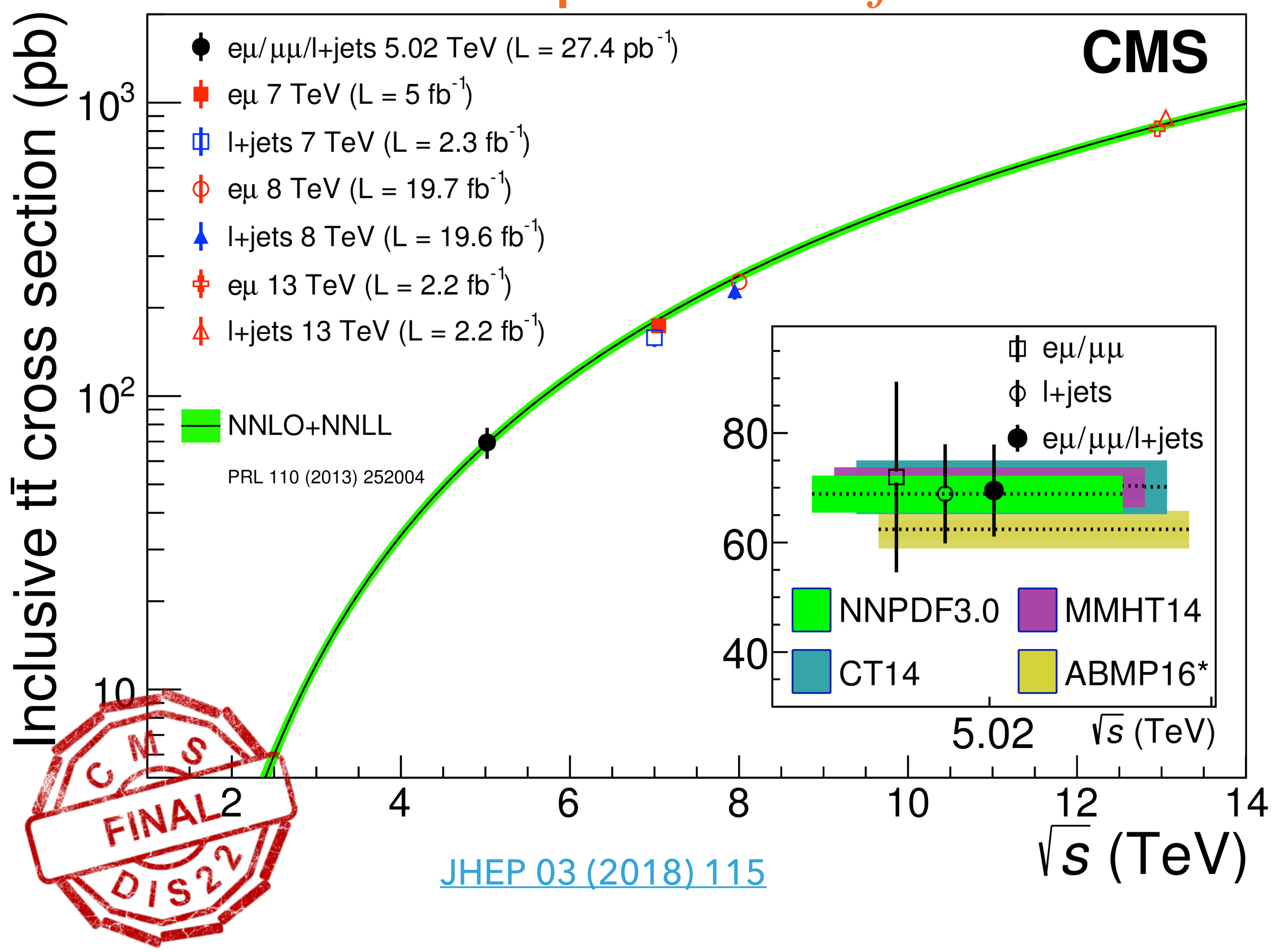
Phys. Rev. Lett. 125, 222001

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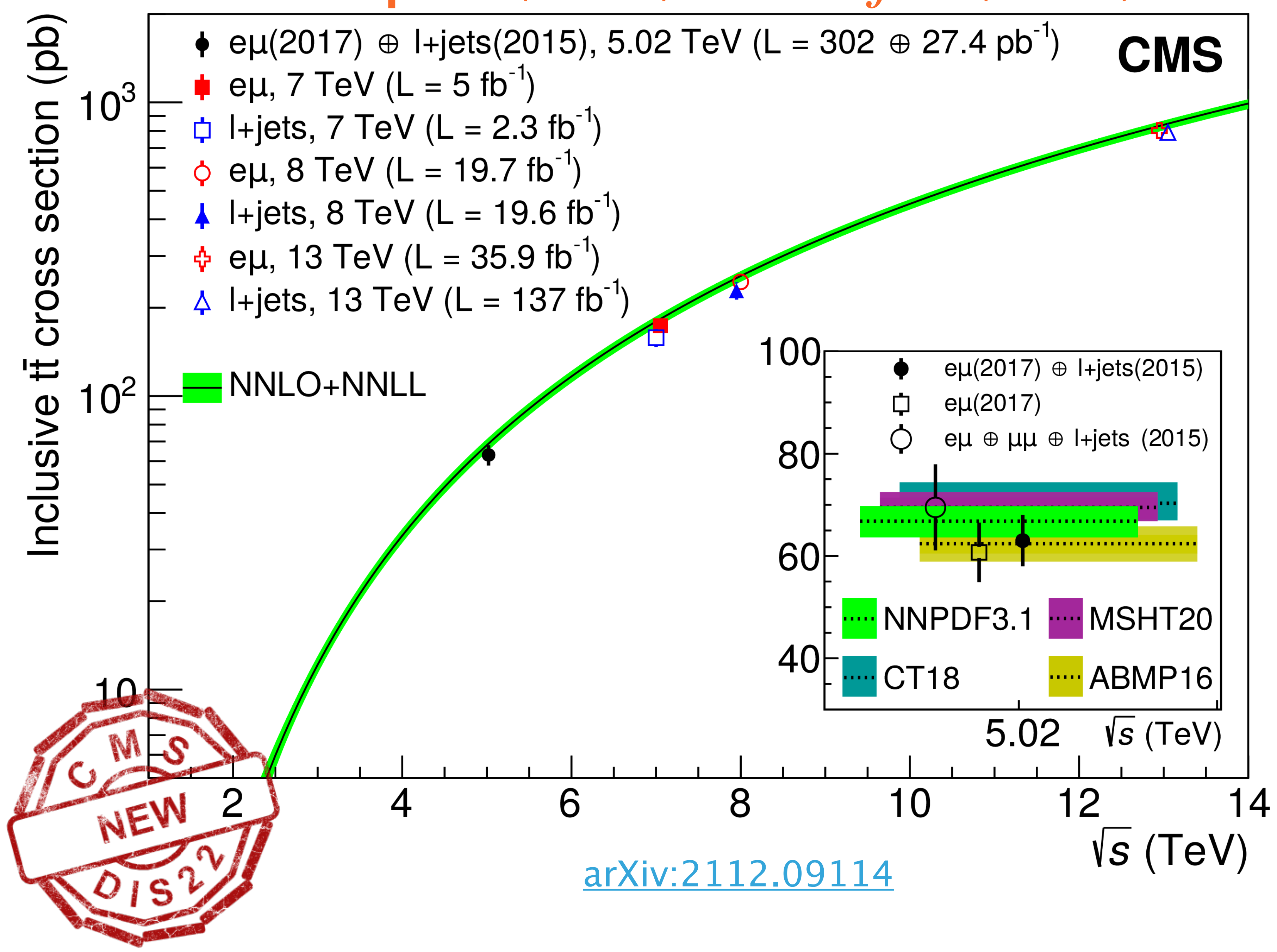
$$\sigma_{t\bar{t}} = 69.5 \pm 6.1\ (stat) \pm 5.6\ (syst) \pm 1.6\ (lumi)\ \text{pb}$$

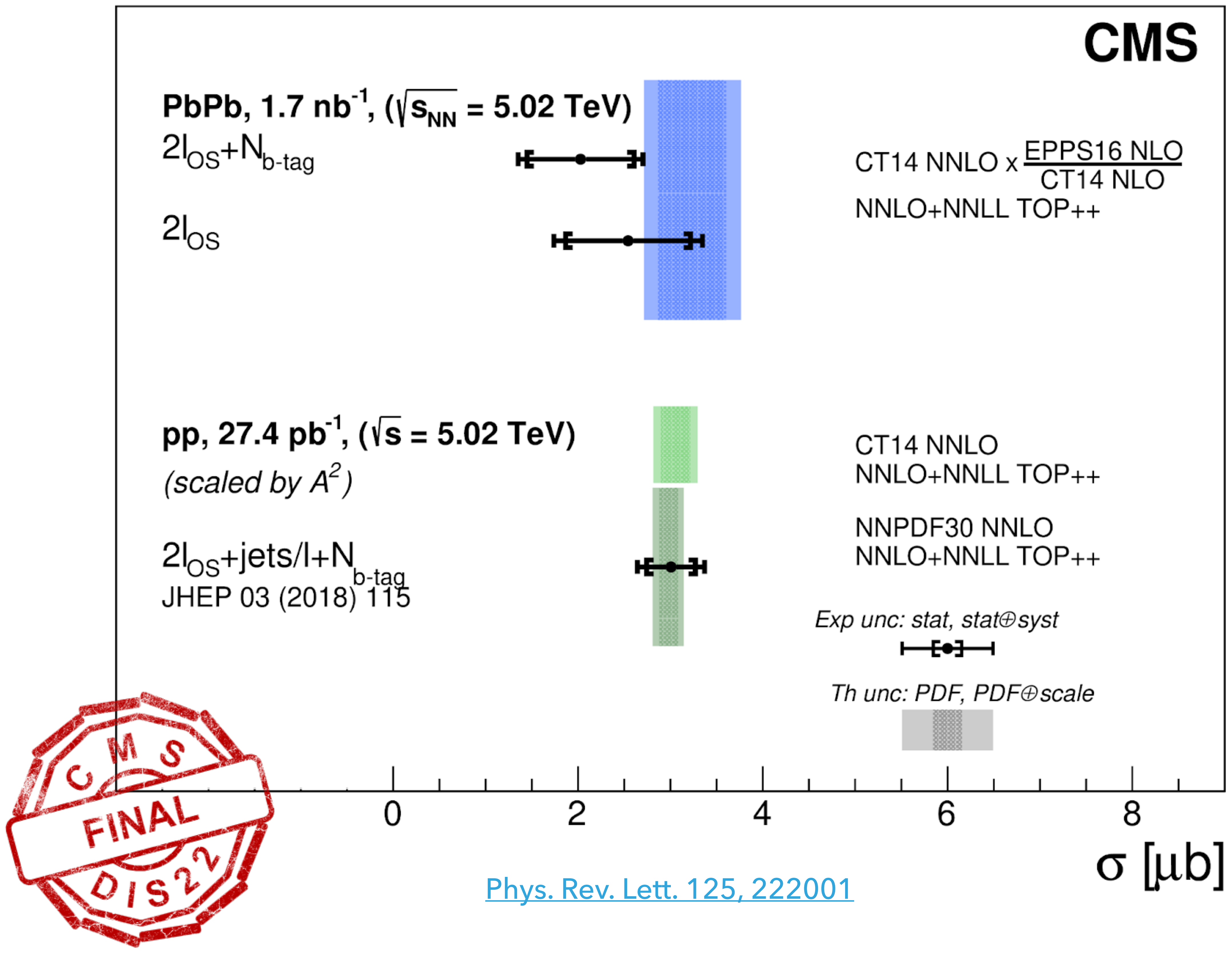
dilepton(2017) & $\ell + jets$(2015)



arXiv:2112.09114

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

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



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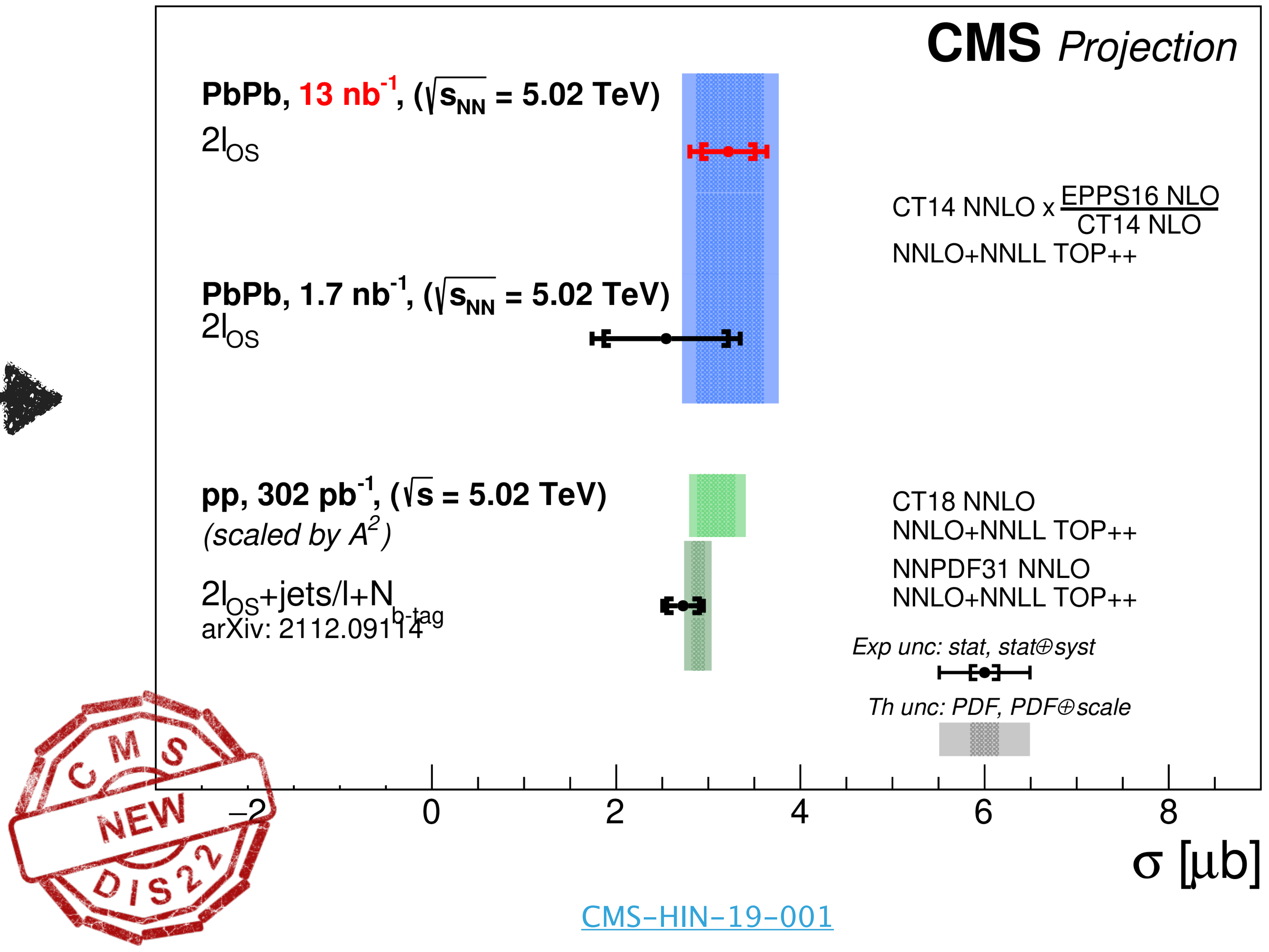

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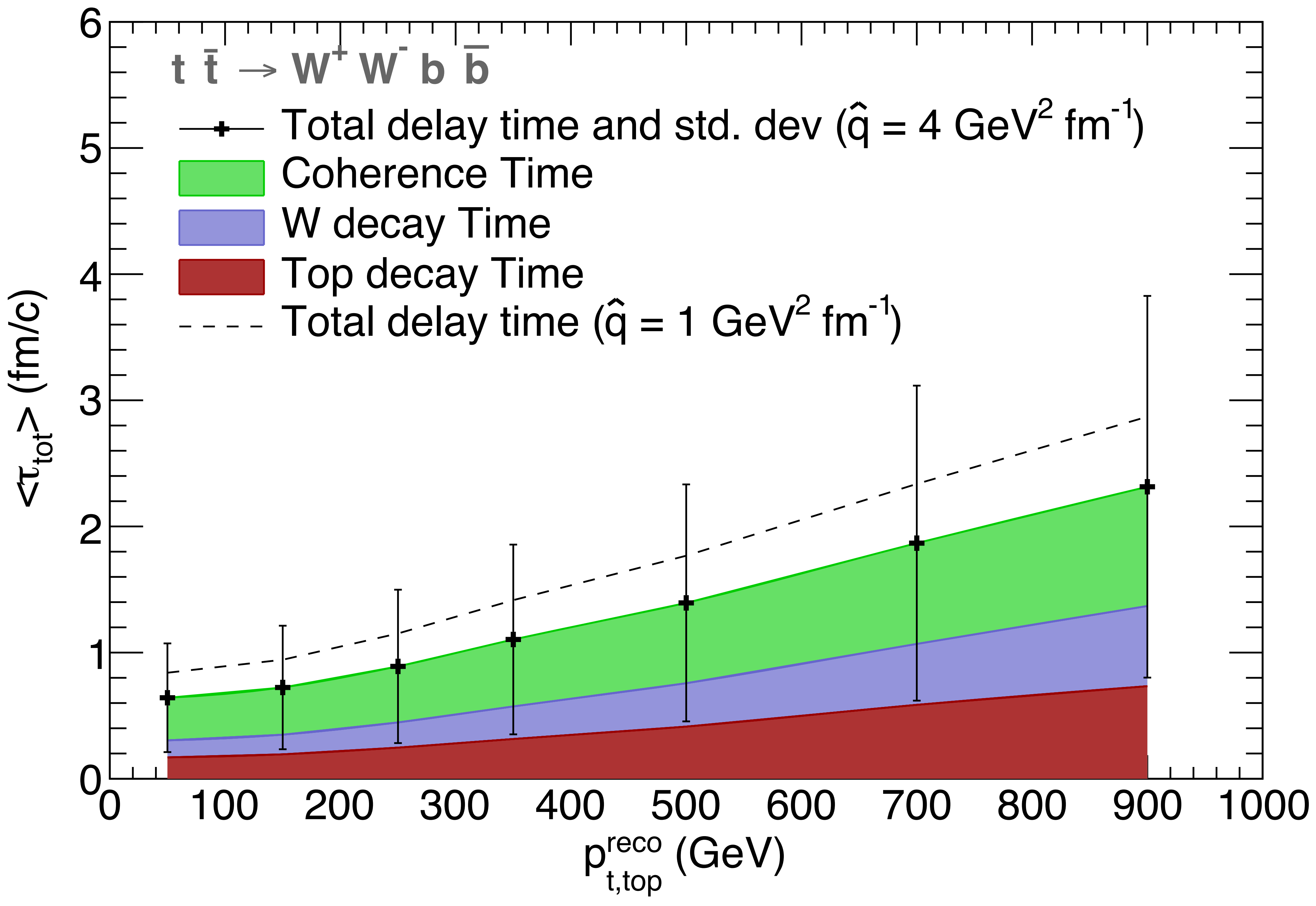
- Focusing on dilepton only method (no b-jets).
- Total uncert. expected to be halved w.r.t. Run 2.

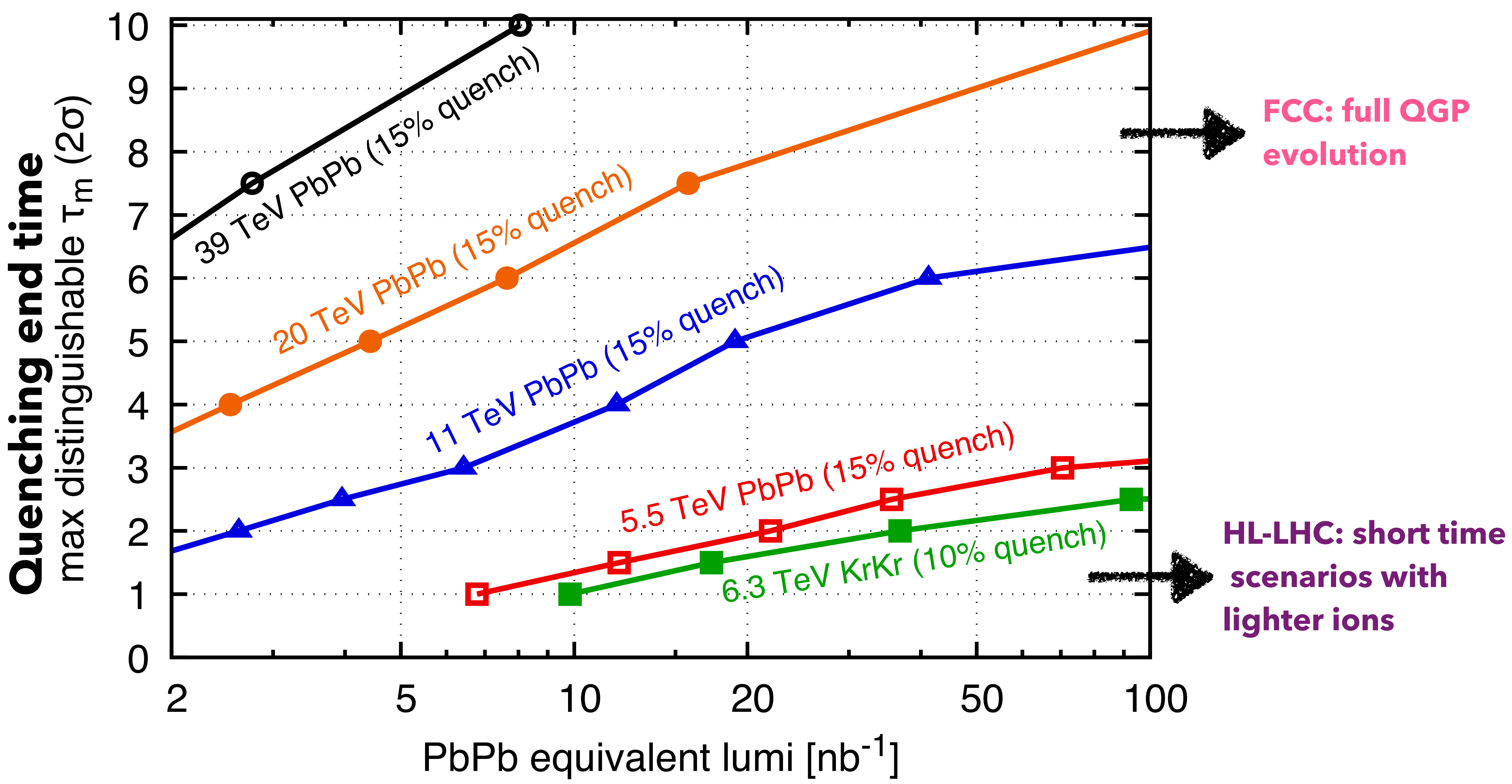
Going further dileptons…

- 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.



PRL 120 (2018) 232301



PRL 120 (2018) 232301

Summary

- $t\bar{t}$ at $\sqrt{s} = 5,7,8,13$ TeV.
- $t\bar{t}$ in pp, pPb and and evidence in $PbPb$.
- $\sigma_{t\bar{t}}$ in all systems consistent with theory.
- $t\bar{t}$ in AA collisions has the potential to resolve the time structure of the QGP in the context of HL-LHC and future colliders.

https://www.symmetrymagazine.org/article/top-quark-couture

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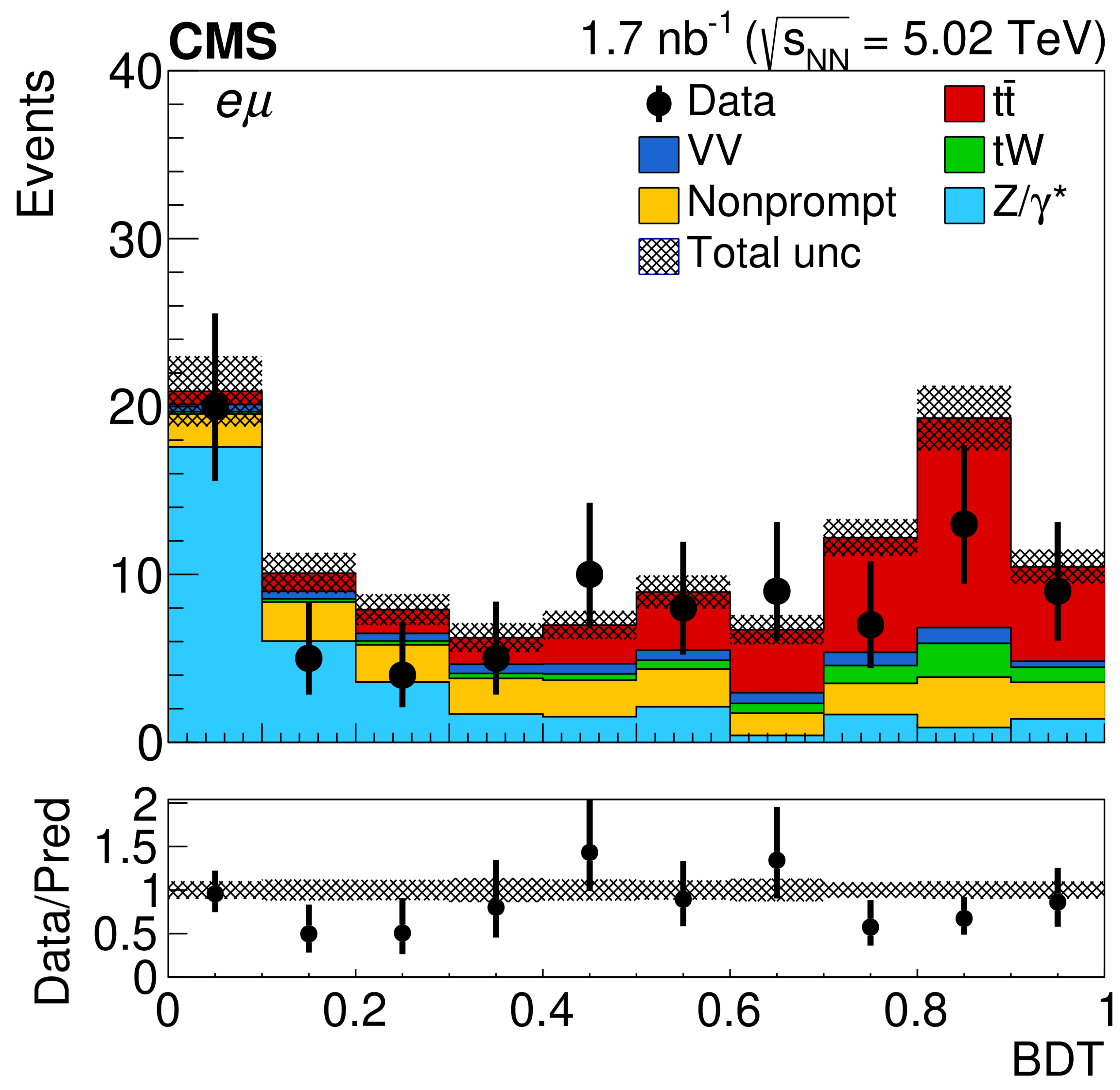

Backup slides

Uncertainties

Source	$\Delta\mu/\mu$ Dilepton only	$\Delta\mu/\mu$ Dilepton plus b-tagged jets
Total statistical uncertainty	0.27	0.28
Total systematic experimental uncertainty	0.17	0.19
Background normalization	0.12	0.12
Background and $t\bar{t}$ signal distribution	0.07	0.08
Lepton selection efficiency	0.06	0.06
Jet energy scale and resolution	—	0.02
b jet identification (ε_b)	—	0.06
Integrated luminosity	0.05	0.05
Total theoretical uncertainty	0.05	0.05
nPDF, μ_R, μ_F scales, and $\alpha_S(m_Z)$	$<$0.01	$<$0.01
Top quark and Zboson p_T modelling	0.05	0.05
Top quark mass	$<$0.01	$<$0.01
Total uncertainty	0.32	0.34

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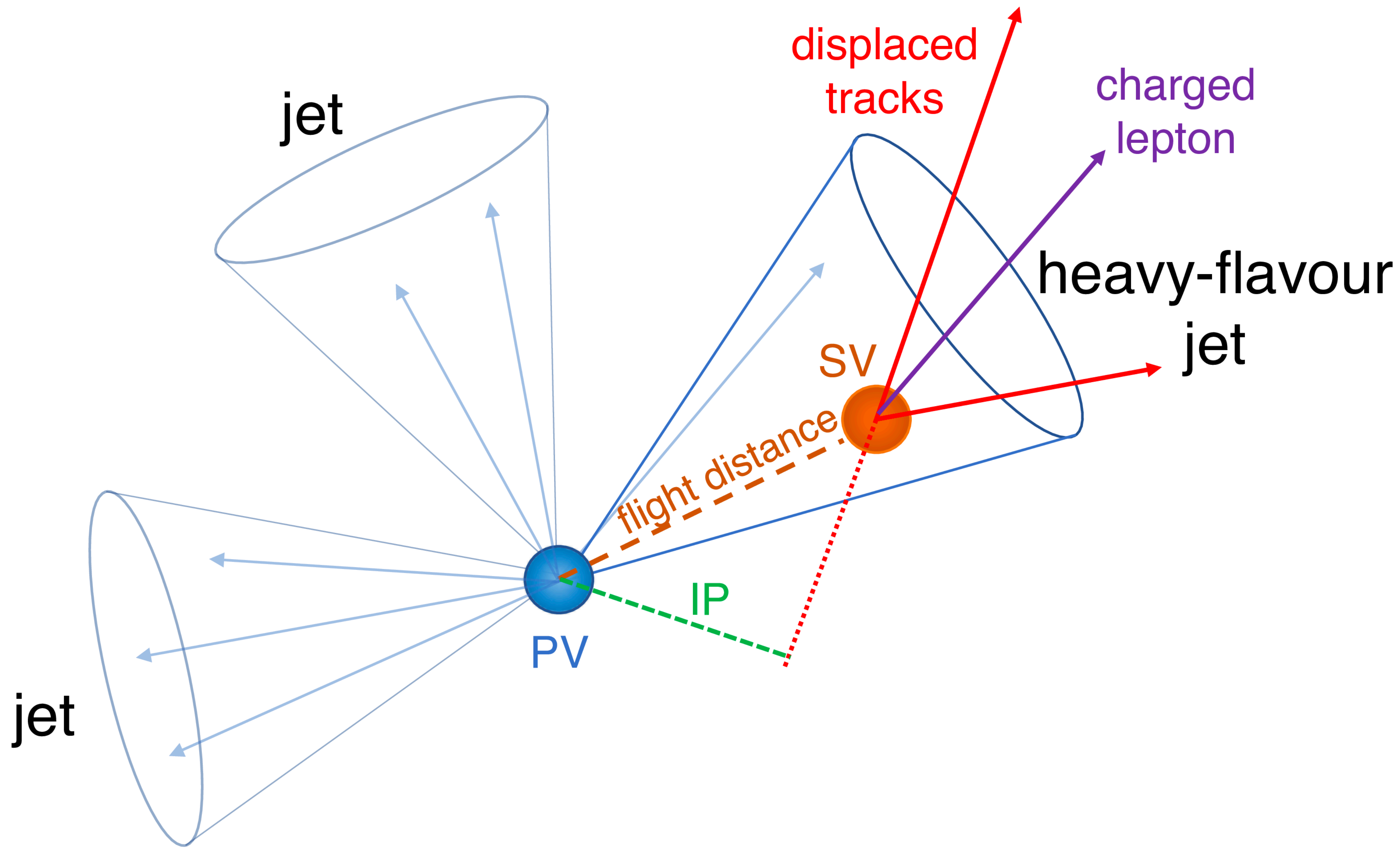
Backup

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 $p_{\text{T,rel}}$	—	x
ΔR(track, jet)	—	x
Track $p_{\text{T,rel}}$ 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

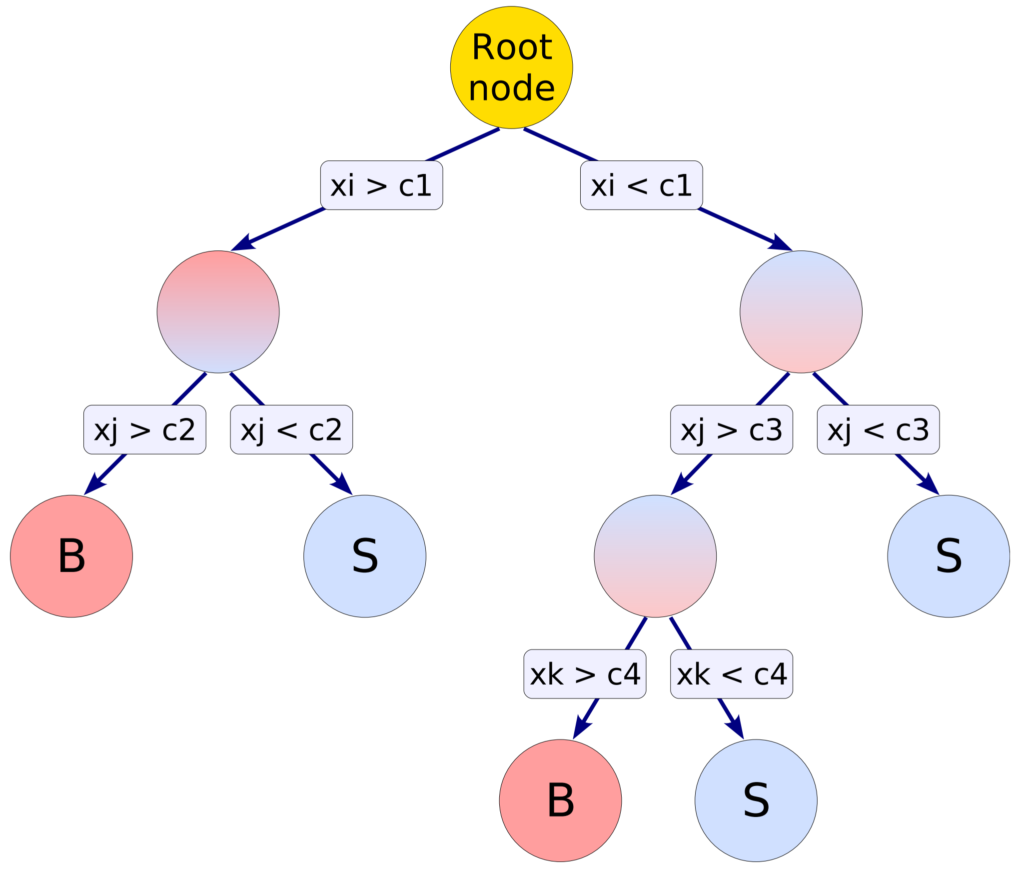
Boosted Decision Trees (BDT)

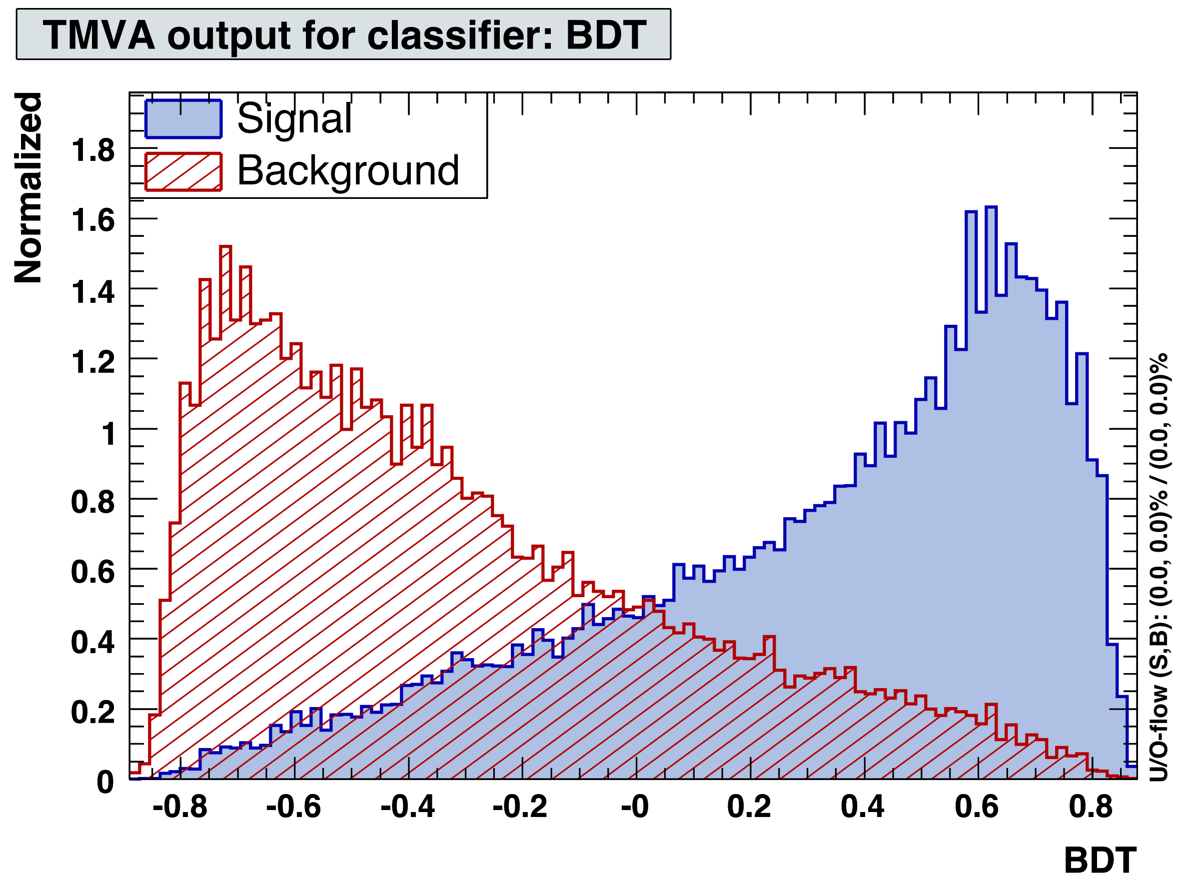
Decision Tree (DT): binary classifier in which repeated decisions are taken until a stop criterion is reached.

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.

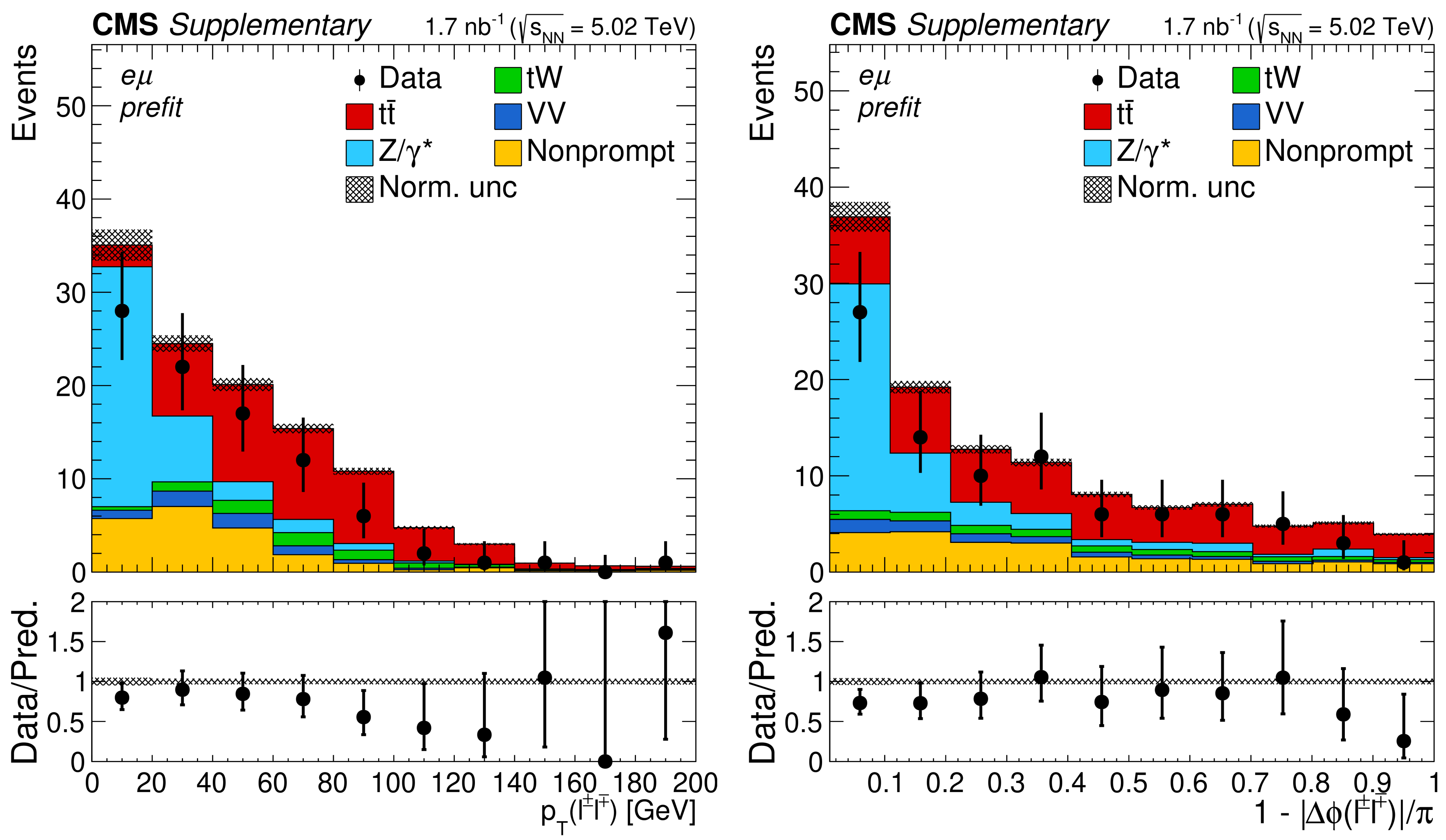




CERN-OPEN-2007-007

$t\bar{t}$ 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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