Top quark in heavy ions in CMS

Luis F. Alcerro
(On behalf of the CMS Collaboration)
l.alcerro@cern.ch
Collaborators: C. Royon (Ph.D. advisor), G. Krintiras

Department of Physics & Astronomy
University of Kansas

Low-x Meeting
Elba, Italy
Sept. 30, 2021

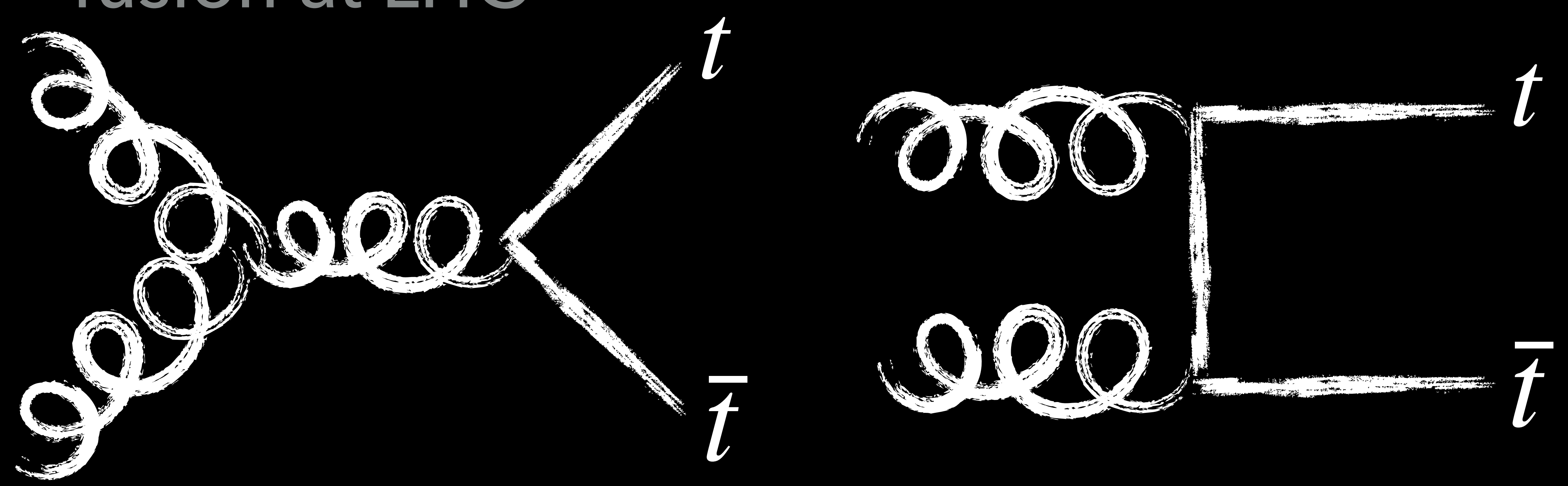
OUTLINE

- Introduction
- $t\bar{t}$ production in pp
- $t\bar{t}$ production in pPb
- $t\bar{t}$ production in PbPb
- $t\bar{t}$ as a probe for QGP
- Summary

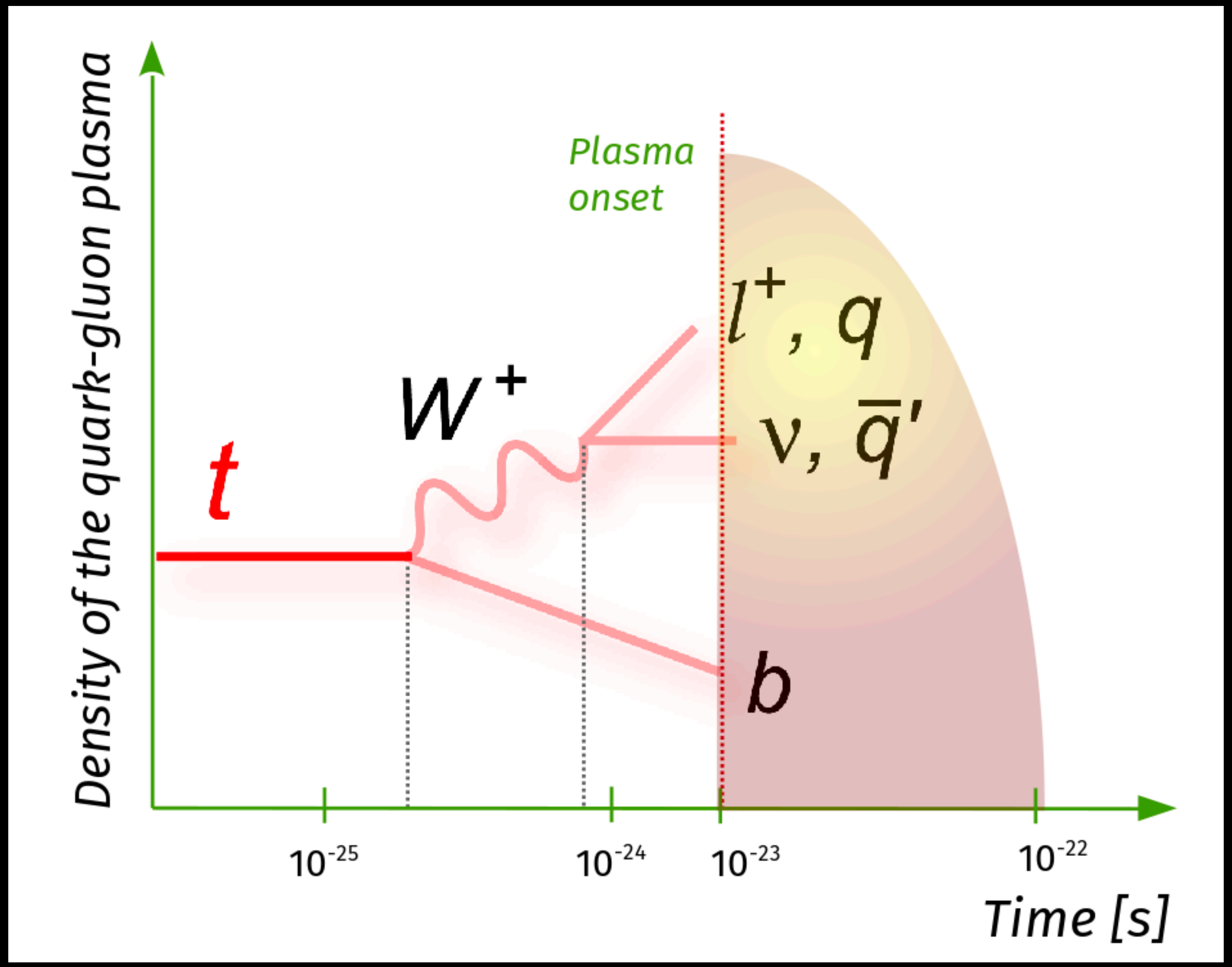
Introduction

Top quark:

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



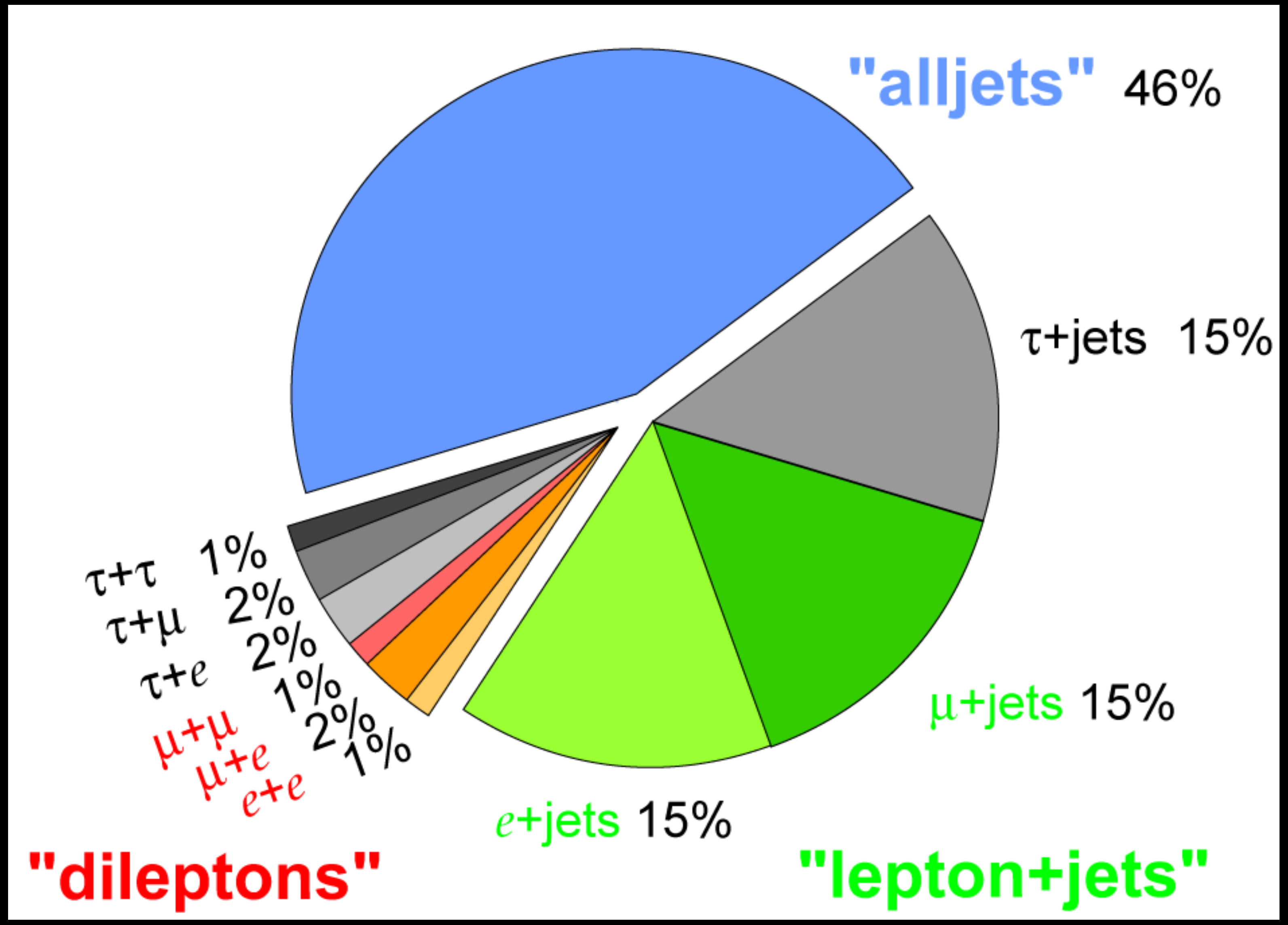
- $t\bar{t}$ in pp
  - Constrain to proton PDF ($x \sim 1/\sqrt{s}$).
  - Determine SM parameters like $|V_{tb}|$
- $t\bar{t}$ in pPb and PbPb:
  - Probe for nuclear PDFs
  - Paves the way for using top to probe QGP.



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

$t\bar{t}$ in pp

- Measurements of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 5$ JHEP 03 (2018) 115, 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
- Relevance:
  - Different $\sqrt{s}$ test different Bjorken -x → gluon distribution functions.
  - pA and AA profit from pp measurements.



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

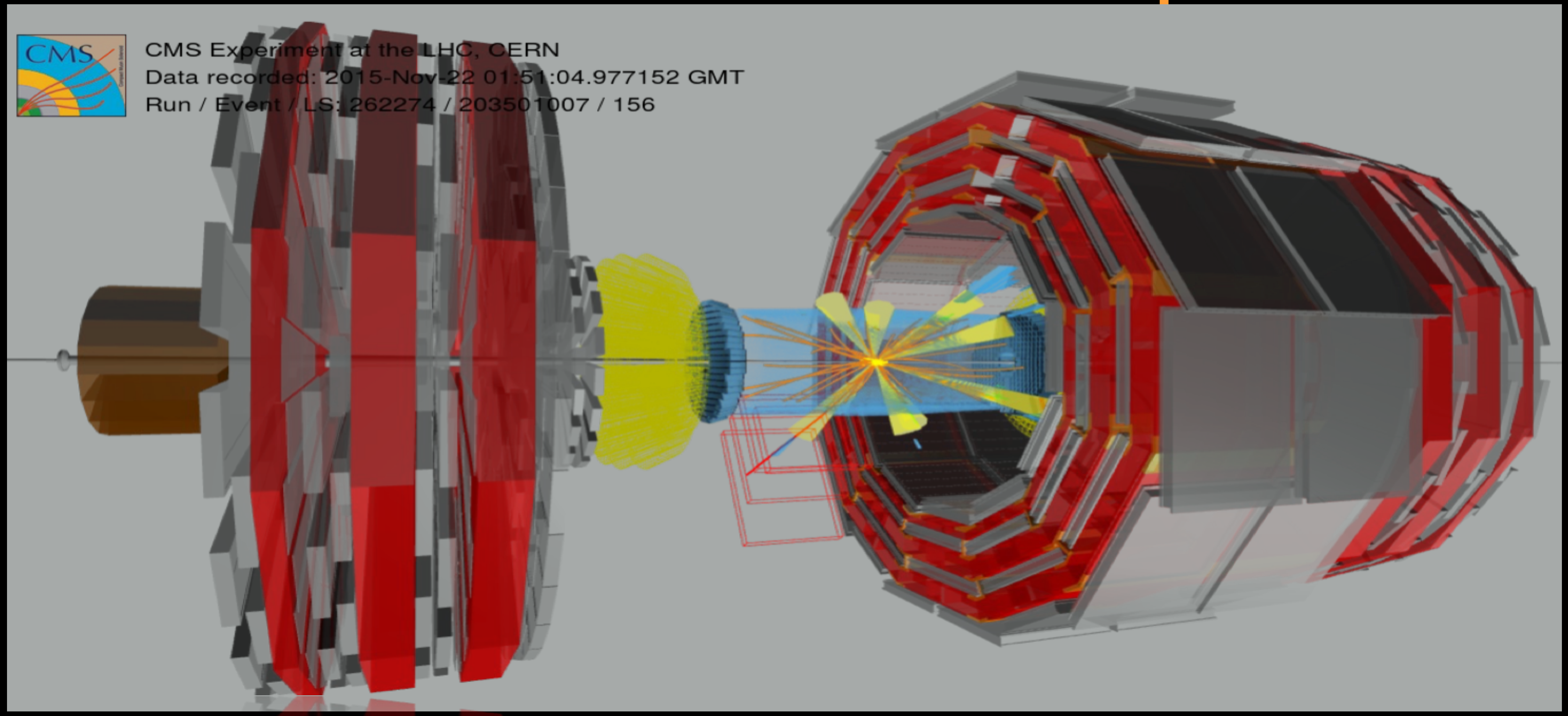
$t\bar{t}$ in pp at 5.02 TeV

- First measurement of $\sigma_{t\bar{t}}$ at 5.02 TeV was performed by CMS using data recorded in November 2015. JHEP 03 (2018) 115
- Data sample corresponds to $\mathscr{L} = 27.4$ pb^{-1}
- Two final states analyzed:
  - $\ell + jets$: $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow q\overline{q}') \rightarrow$ 2b-jets + isolated ℓ + 2 "light" jets + missing energy
  - Dilepton: $t\bar{t} \rightarrow bb'W(\rightarrow \ell\nu)W'(\rightarrow \ell'\nu') \rightarrow$ 2b-jets + 2 leptons (opposite charge) + missing energy with $\ell, \ell' = e, \mu$

- The SM prediction (NNPDF3.0 NNLO) J. Comp. Phys. Comm. Vol. 185.:

$$\sigma_{t\bar{t}}^{NNLO} = 68.9^{+1.9}_{-2.3}\,(\text{scale}) \pm 2.3\,(\text{PDF})\,^{+1.4}_{-1.0}\,(\alpha_s)\ \text{pb}$$

Dilepton final state



CERN-THESIS-2018-320

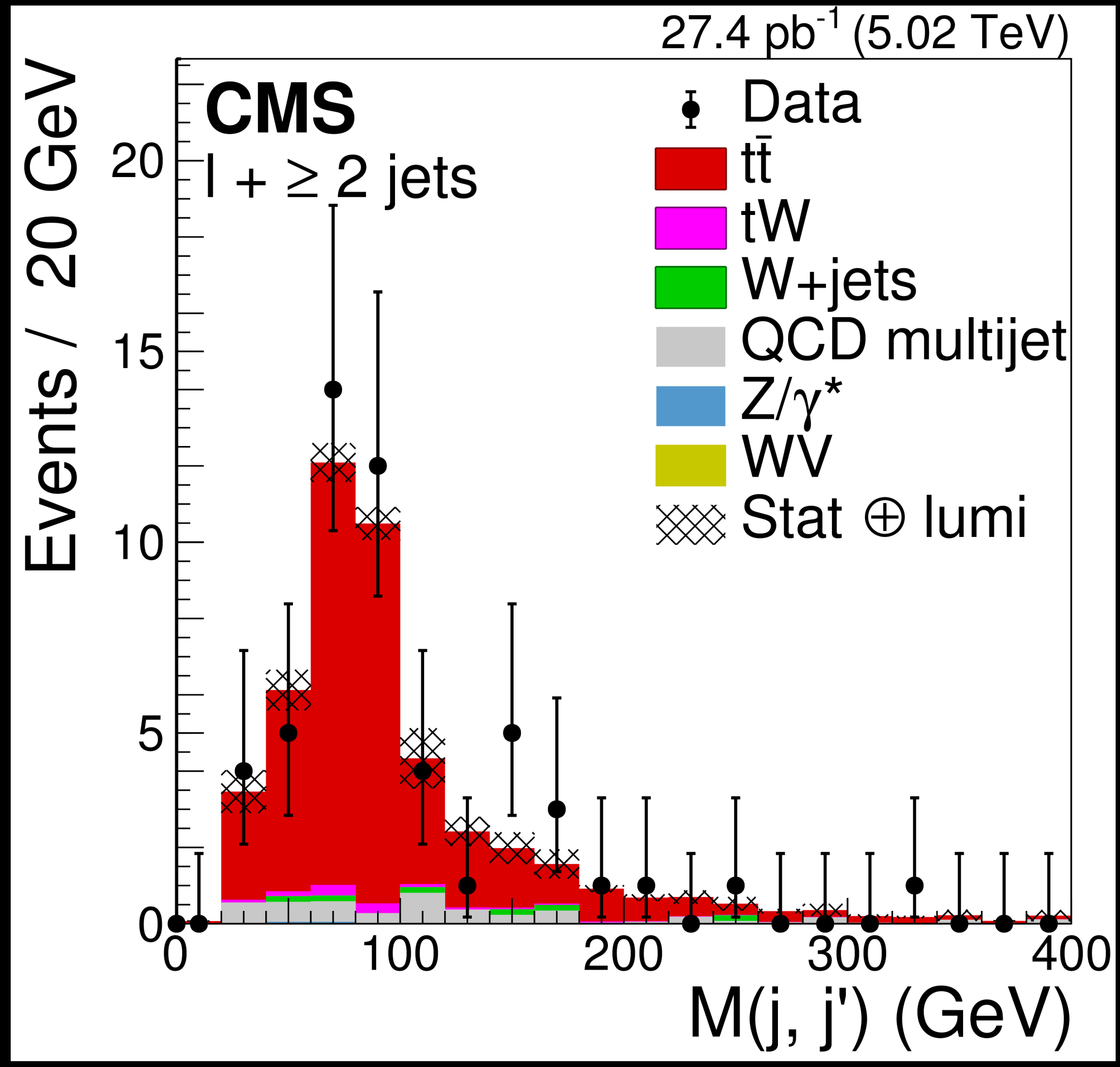
$t\bar{t}$ in pp at 5.02 TeV

Object reconstruction

- PF algorithm to reconstruct individual particles.
- Jets (anti-k_T, $R = 0.4$) reconstructed from PF candidates. b-jets with CSVv2 algorithm.
- p_T^{miss} is the negative vector sum of all PF candidates in the event, projected in the transverse plane.

Background

- $\ell + jets$: multijet background estimated from control samples in data. All other backgrounds is taken from MC.
- Dilepton: $Z/\gamma*$ and fake leptons ($W + jets$, $t\bar{t}$ in $\ell + jets$) extracted from control samples in data. tW and WV from simulation.



Event selection

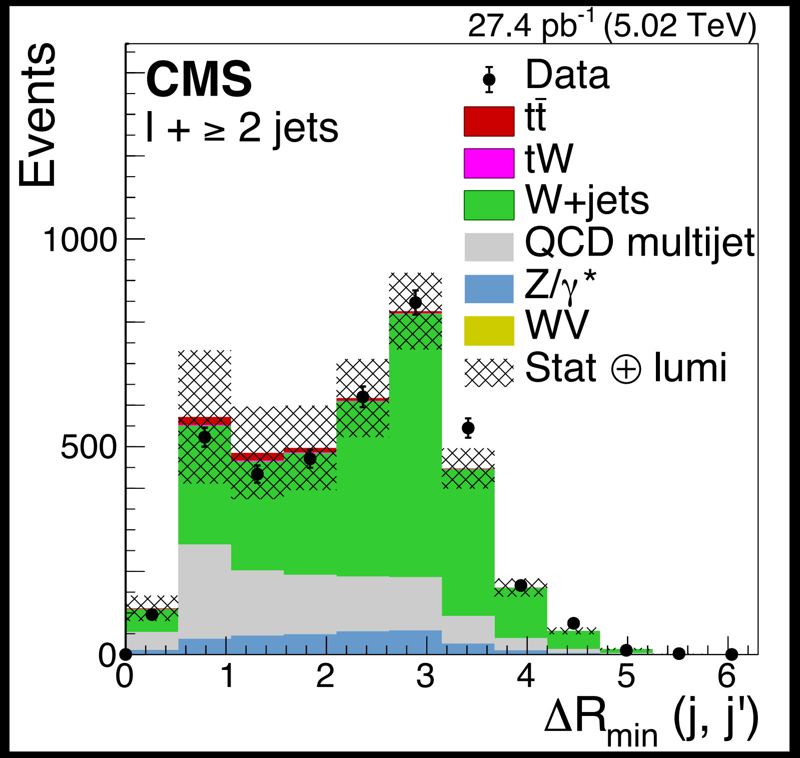
- $\ell + jets$:
  - electrons ($p_T > 40\ GeV$, $|\eta| < 2.1$), muons ($p_T > 25\ GeV$, $|\eta| < 2.1$) .
  - At least 2 light jets ($p_T > 30\ GeV$, $|\eta| < 2.4$).
  - Events are classified into $b-$tag multiplicity: $0b, 1b, \geq 2b$
- Dilepton:
  - At least 1 muon ($p_T > 18\ GeV$, $|\eta| < 2.1$). Electrons ($p_T > 20\ GeV$, $|\eta| < 2.4$).
  - At least 2 jets ($p_T > 25\ GeV$, $|\eta| < 3$)
  - Leptons with opposite charge ($e^{\pm}\mu^{\mp}$ or $\mu^{\pm}\mu^{\mp}$)
  - Z-veto for $\mu^{\pm}\mu^{\mp}$: 76<$M_{\ell\ell}$<106 GeV, $p_T^{miss} > 35\ GeV$
  - $M_{\ell\ell} > 20\ GeV$

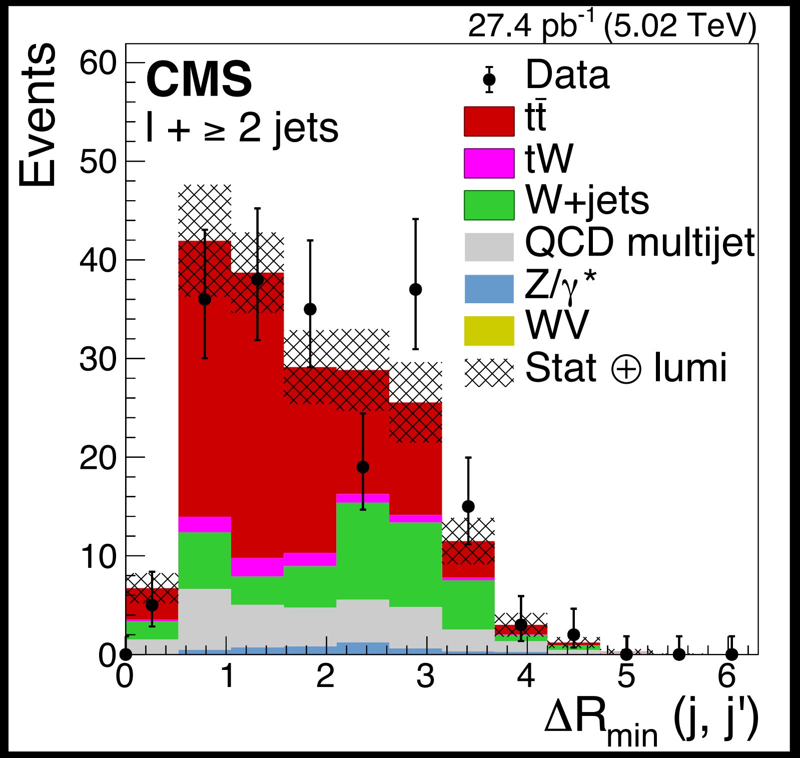
$t\bar{t}$ in pp at 5.02 TeV

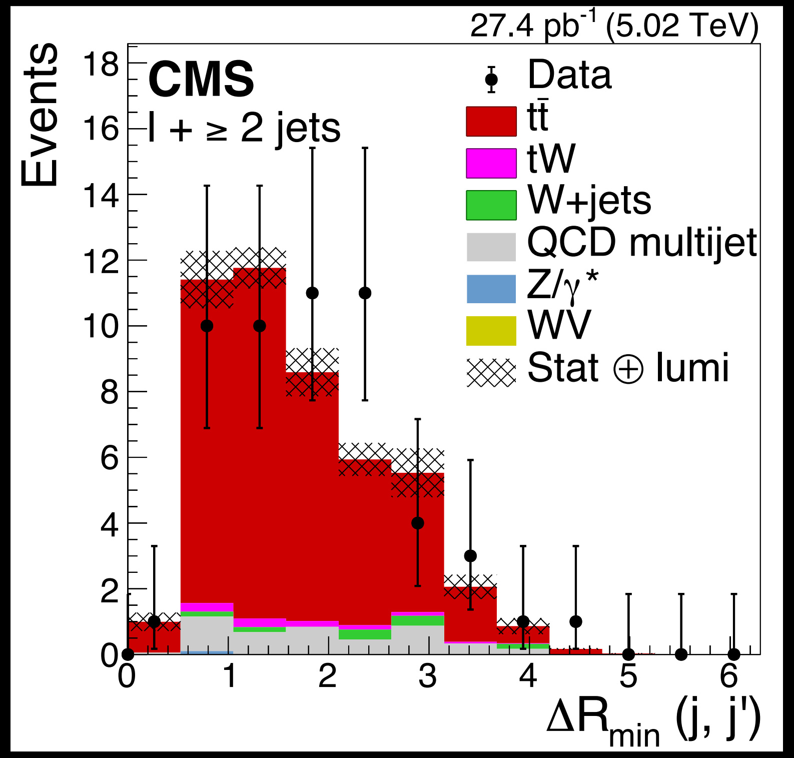
Results

- $\ell + jets$: $\sigma_{t\bar{t}}$ extracted by likelihood fits

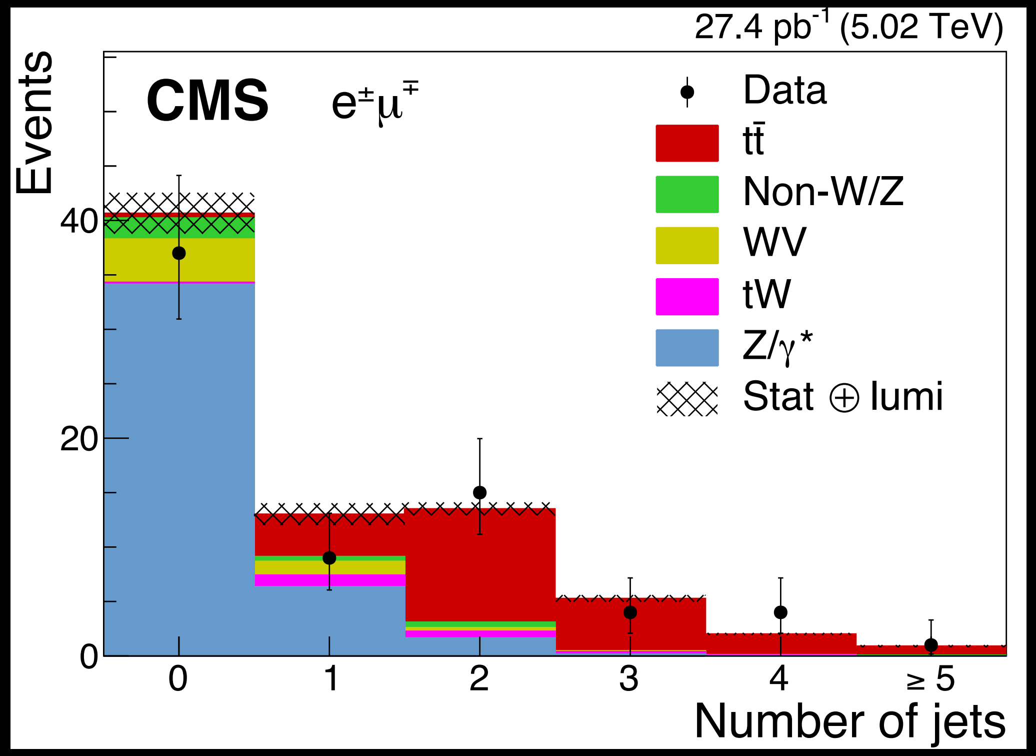
0b **1b** **$\geq$ 2b**

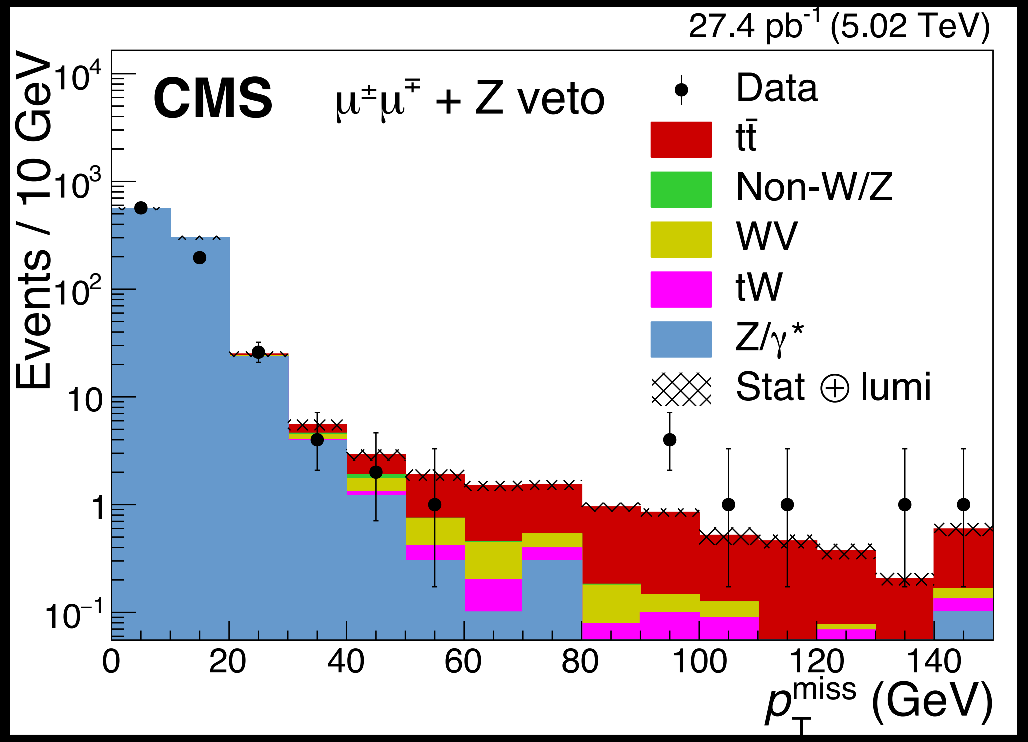




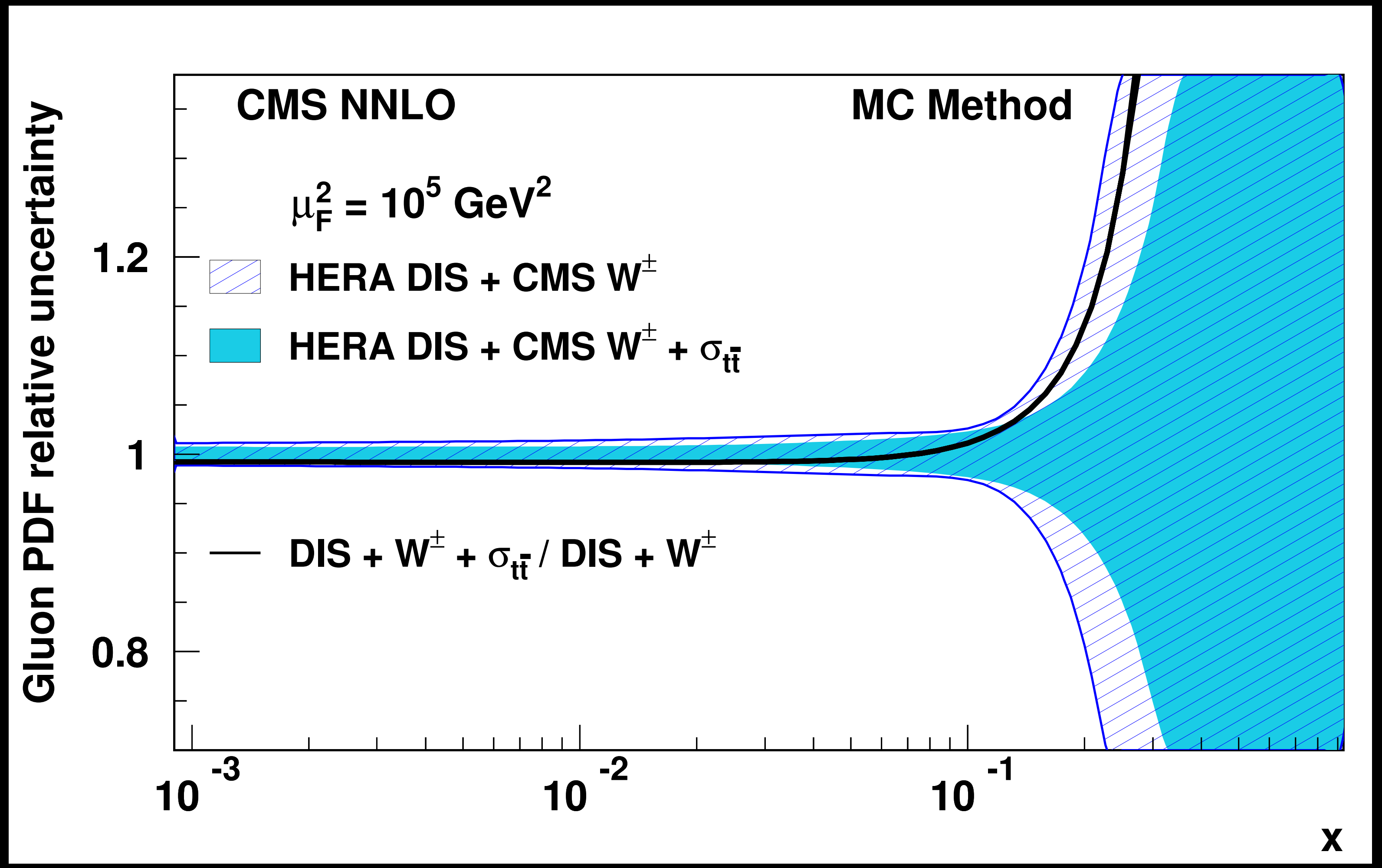


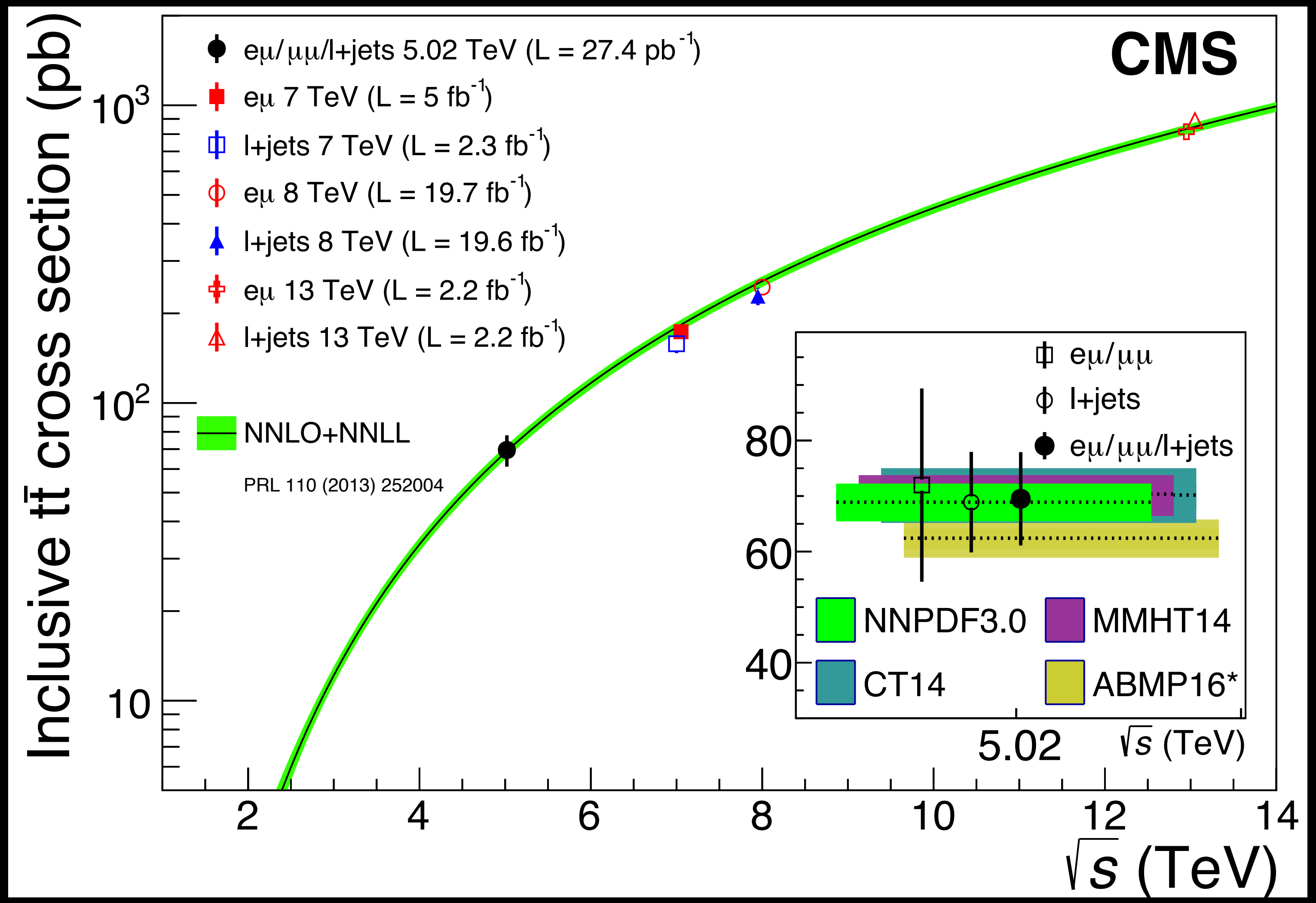
- Dilepton: $\sigma_{t\bar{t}}$ with counting technique





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

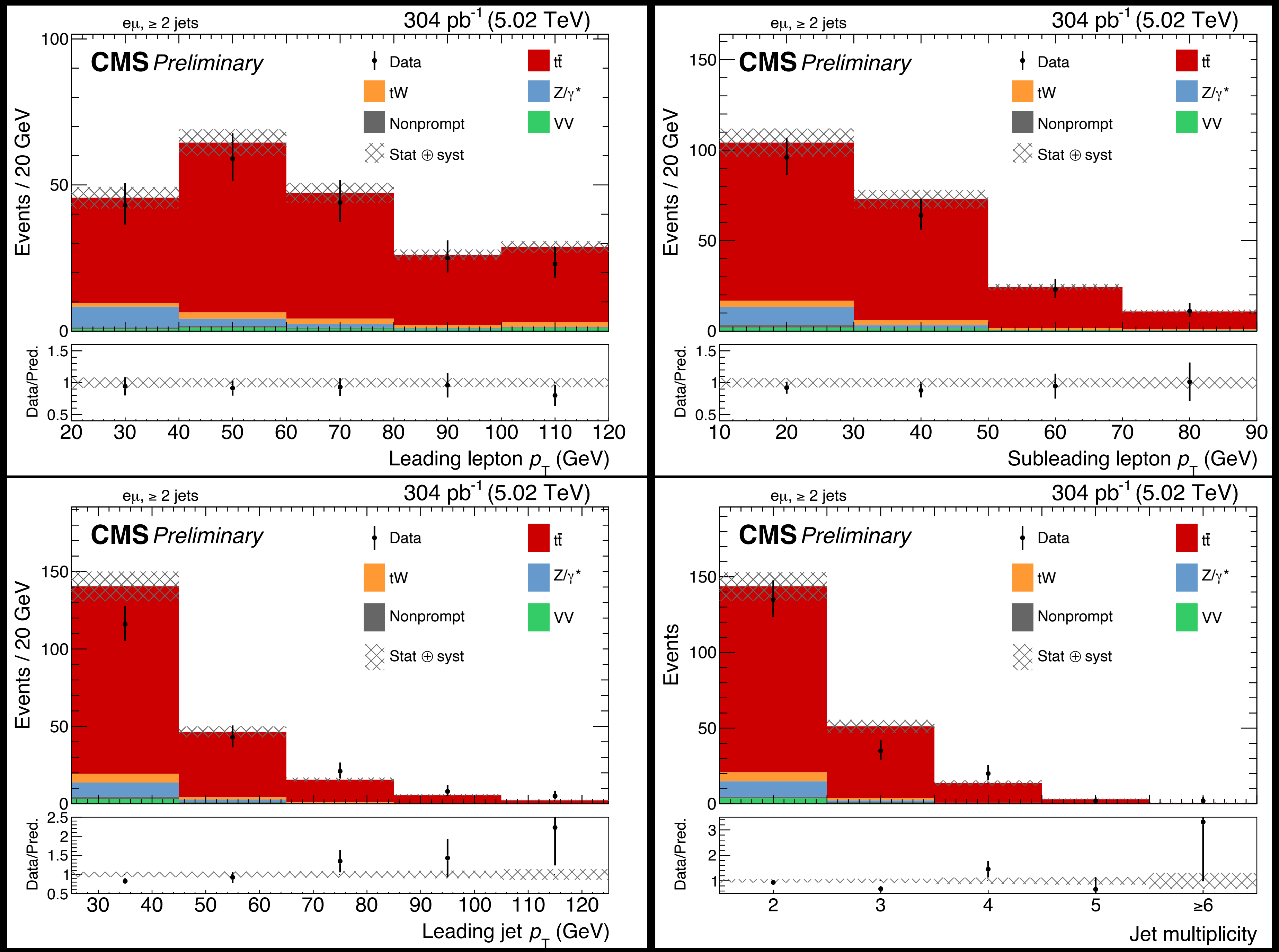




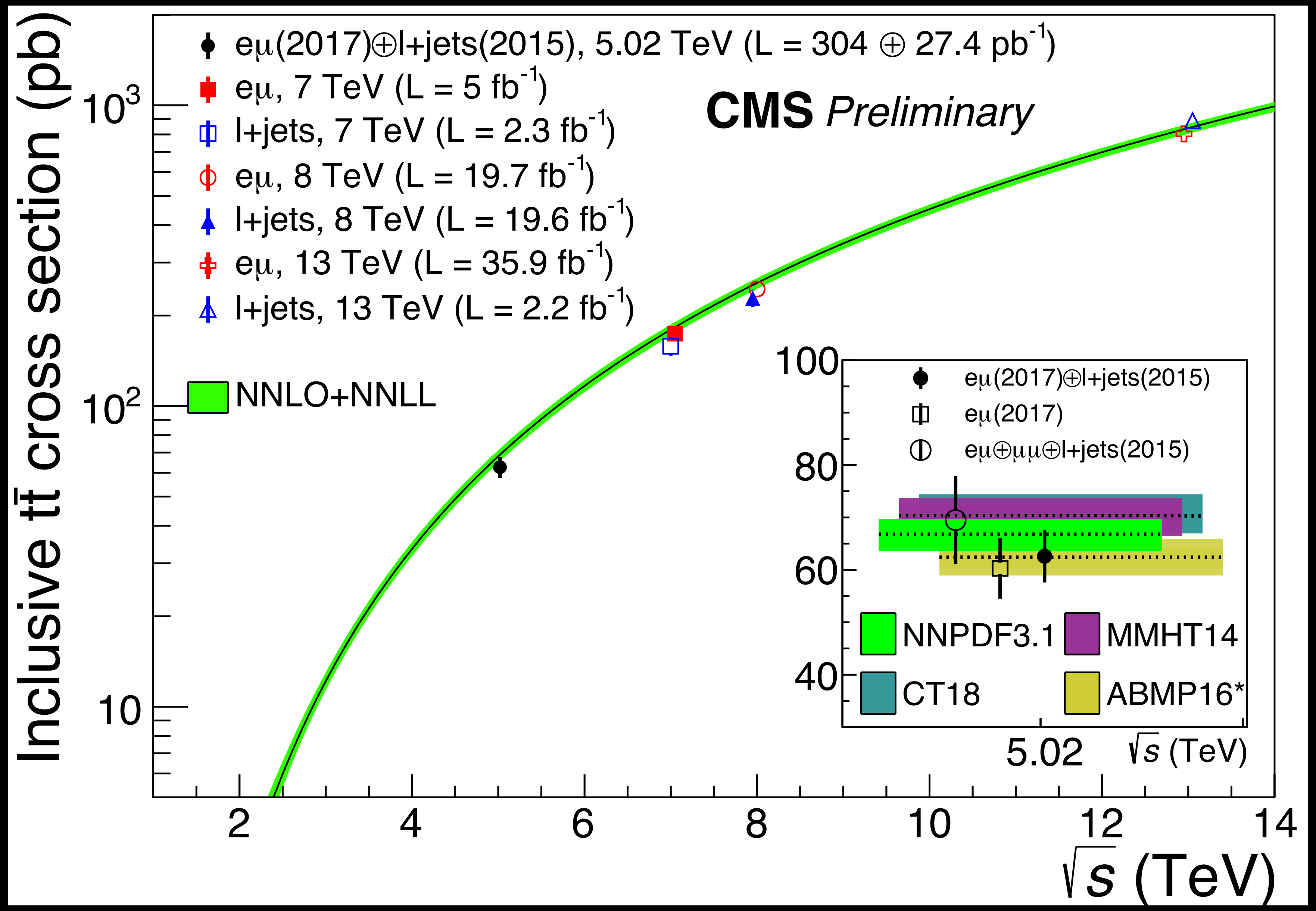
$t\bar{t}$ in *pp* at 5.02 TeV

Improvement with the 2017 data set

- Improvement expected with x10 higher luminosity and lower pileup! [CMS-PAS-TOP-20-004]

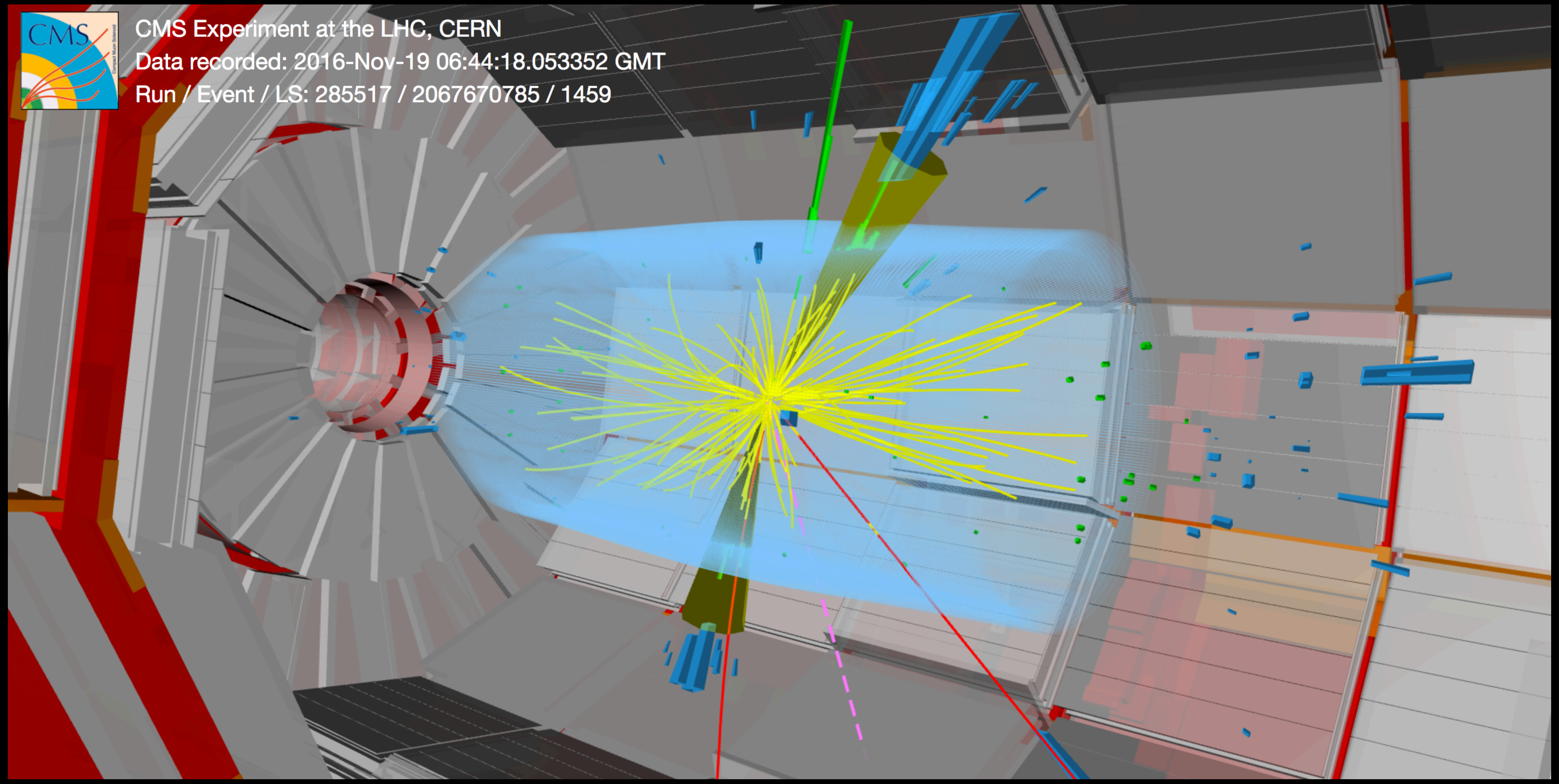


$$\sigma_{t\bar{t}} = 62.6 \pm 4.1\,(stat) \pm 3.0\,(syst + lumi)\,pb$$



$t\bar{t}$ in pPb at 8.16 TeV

- First observation of $t\bar{t}$ in pPb collisions by CMS Phys. Rev. Lett. 119, 242001
- Data sample corresponds to $\mathscr{L} = 174\ nb^{-1}$
- Semileptonic $t\bar{t}$ decays considered:
  - High BR: ~ 34% $(e, \mu, \tau \to e, \mu)$
  - Moderate background contamination
- The cross section $\sigma_{t\bar{t}}$ is extracted from likelihood fits of the invariant mass of the light jets $(W \to q\bar{q})$ in different categories of b-jet multiplicity (0,1 and ≥ 2).



- Theoretical prediction (CT14 proton PDF +EPPS16 nPDF for Pb) arXiv:1706.09521:

$$\sigma_{t\bar{t}}^{th} = 59.0 \pm 5.3(\text{PDF})^{+1.6}_{-2.1}(\text{scale})\ \text{nb}$$

$t\bar{t}$ in pPb at 8.16 TeV

Object reconstruction

- PF algorithm reconstruct individual particles.
- Jets with anti-k_T (R=0.4) clustering algorithm.
- b-jets tagged with CSVv2 discriminator.

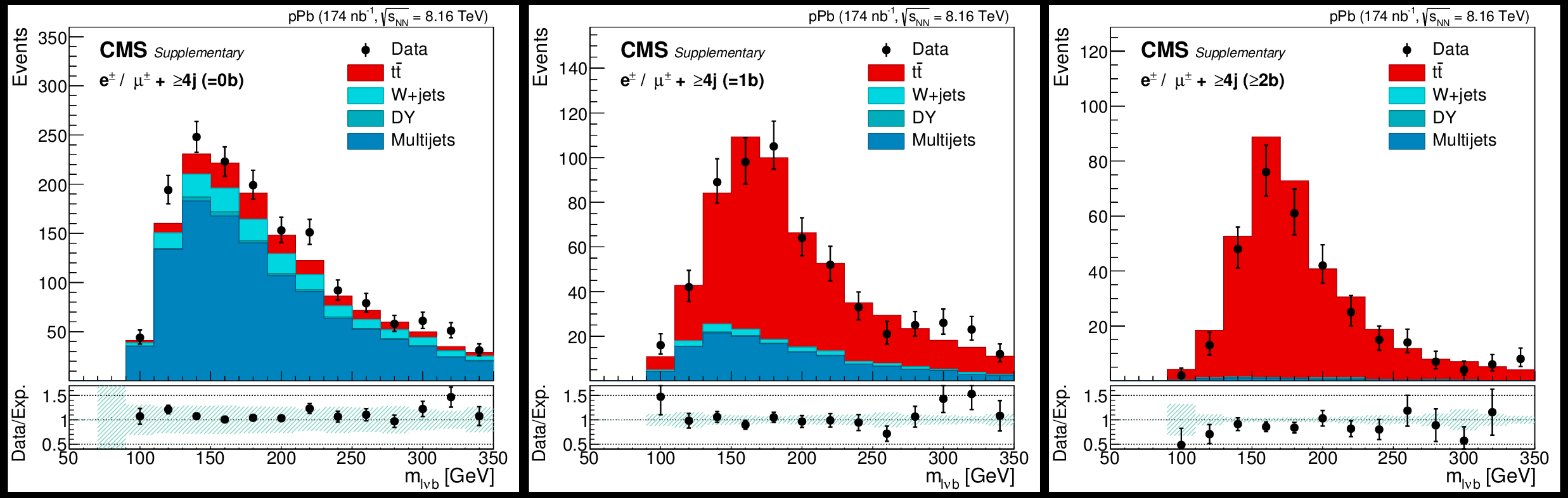
Background

- Main background: $W + jets$ and QCD multi jet production.
- $W + jets$ assumed as a Landau distribution and QCD multijet from control samples in data

Event selection

- Exactly one isolated μ or e with $p_T > 30\ GeV$, $|\eta| < 2.1$
- At least 4 jets with $p_T > 25\ GeV$, $|\eta| < 2.5$ and $\Delta R = 0.3$ (from ℓ).

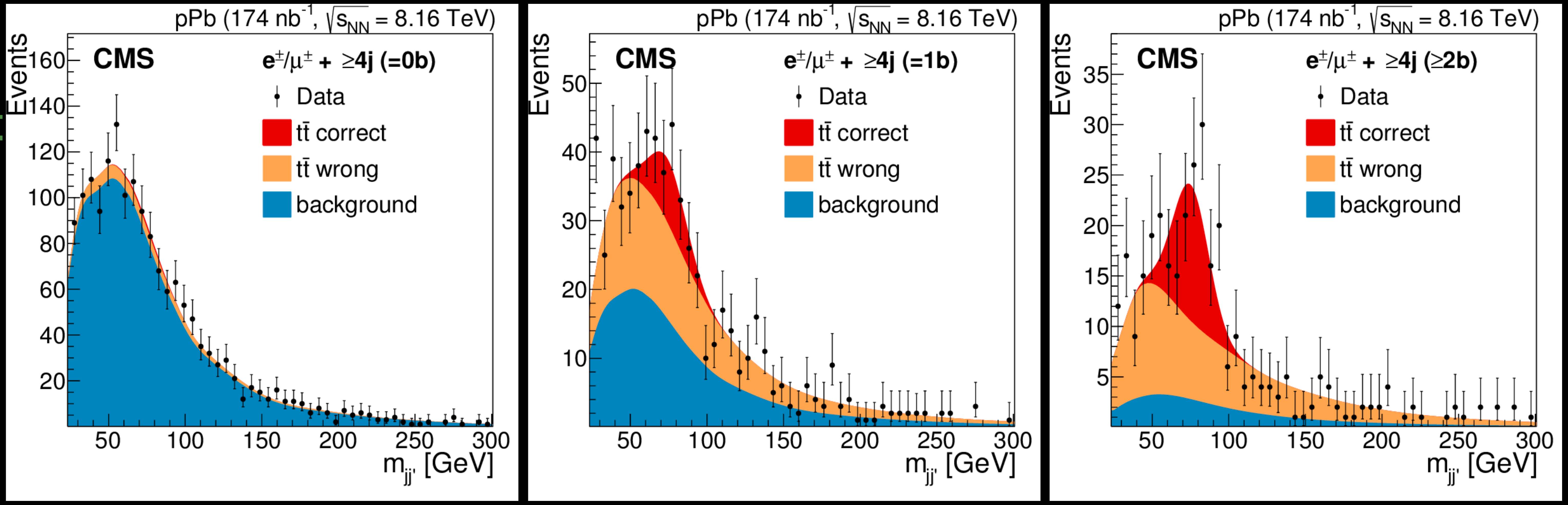
Pre-fit



HIN-17-002

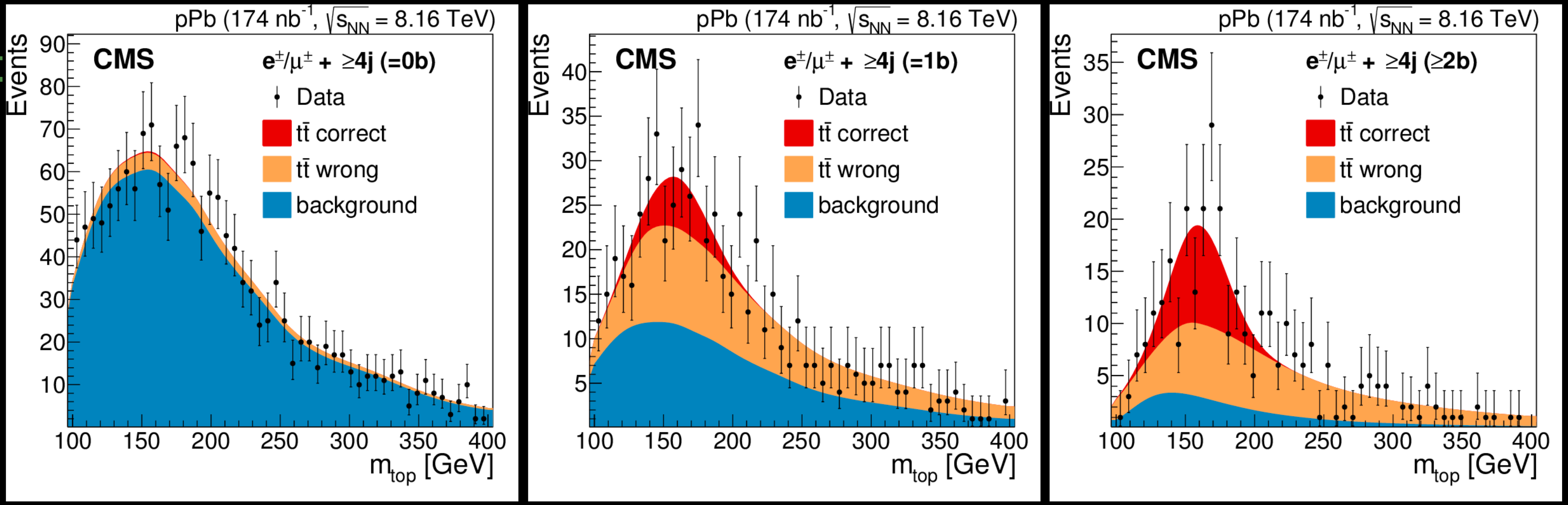
$t\bar{t}$ in *pPb* at 8.16 TeV

- $t\bar{t}$ signal includes “correct” and “wrong” assignments. → Post-fit



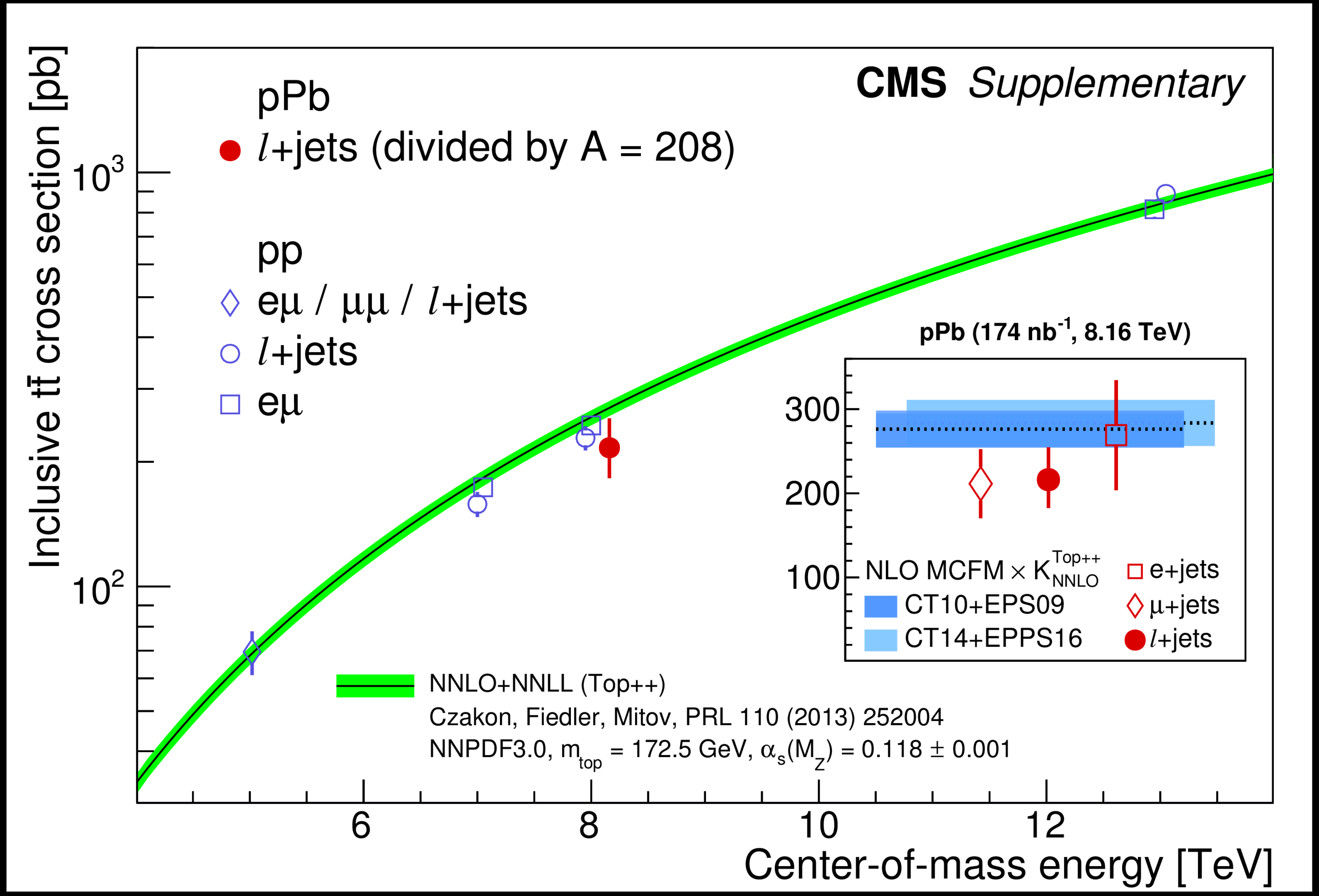
- If $W \to q\bar{q}$ → “Correct”

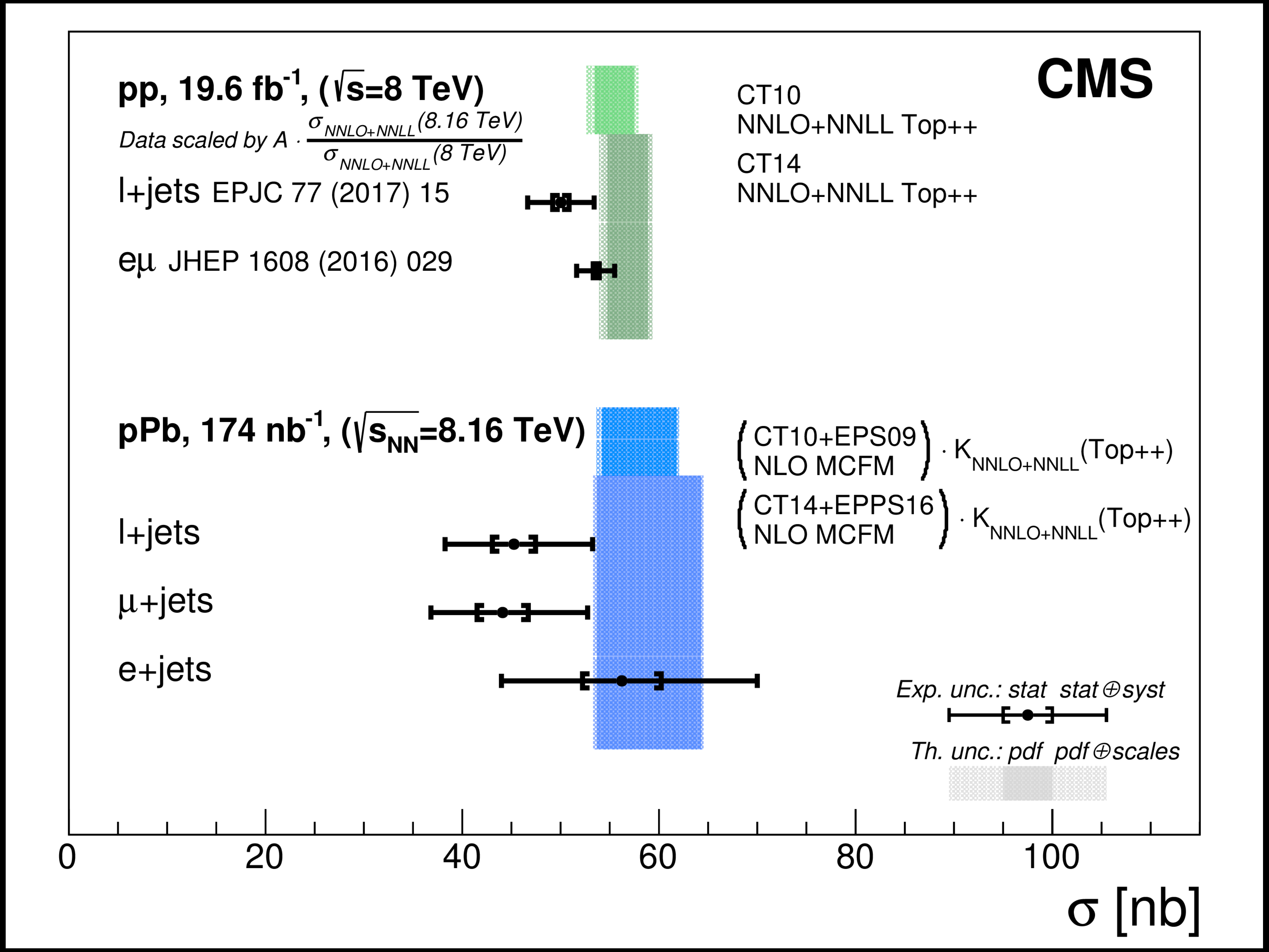
- Fitted signal events = 710 → Post-fit
- Combination dominated by $\mu + jets$ channel



$t\bar{t}$ in pPb at 8.16 TeV

- $\sigma_{t\bar{t}} = \dfrac{S}{A\epsilon\mathscr{L}}$
- $\sigma_{t\bar{t}} = 45 \pm 8(total)$ nb
- $\sigma_{t\bar{t}}^{\mu+jets} = 44 \pm 3(stat) \pm 8(syst)$ nb
- $\sigma_{t\bar{t}}^{e+jets} = 56 \pm 4(stat) \pm 13(syst)$ nb





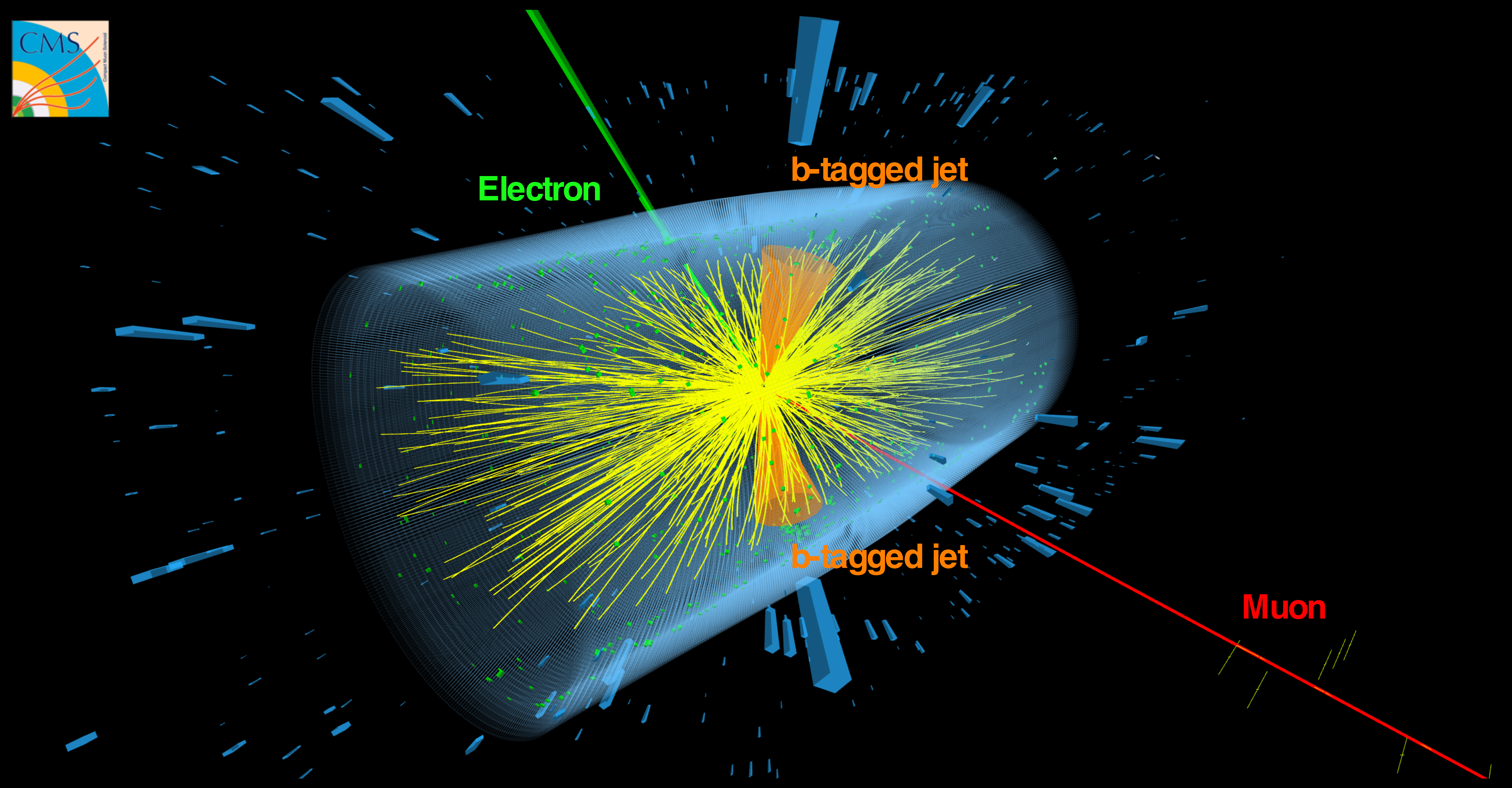
Significance of > 5σ

$t\bar{t}$ in $PbPb$ at 5.02 TeV

- First evidence of $t\bar{t}$ in nucleus-nucleus using PbPb collision data recorded by CMS. Phys. Rev. Lett. 125, 222001
- Data sample corresponds to $\mathscr{L} = 1.7\ nb^{-1}$
- Dilepton ($t\bar{t} \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$) final states were analyzed.
  - Cleanest channel
  - 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: Inclusion of b-jets from b-quarks passing through the QGP ("jet quenching")

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

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



$t\bar{t}$ in $PbPb$ at 5.02 TeV

Object reconstruction

- PF algorithm reconstruct individual particles.
- Jets with anti-k_T (R=0.4) clustering algorithm.
- b-jets tagged with CSVv2 discriminator.

Background

- Main background is DY ($Z/\gamma*$). Estimated from MC and data.
- Nonprompt (QCD multijet, W+jets,…) from event mixing.

Event selection

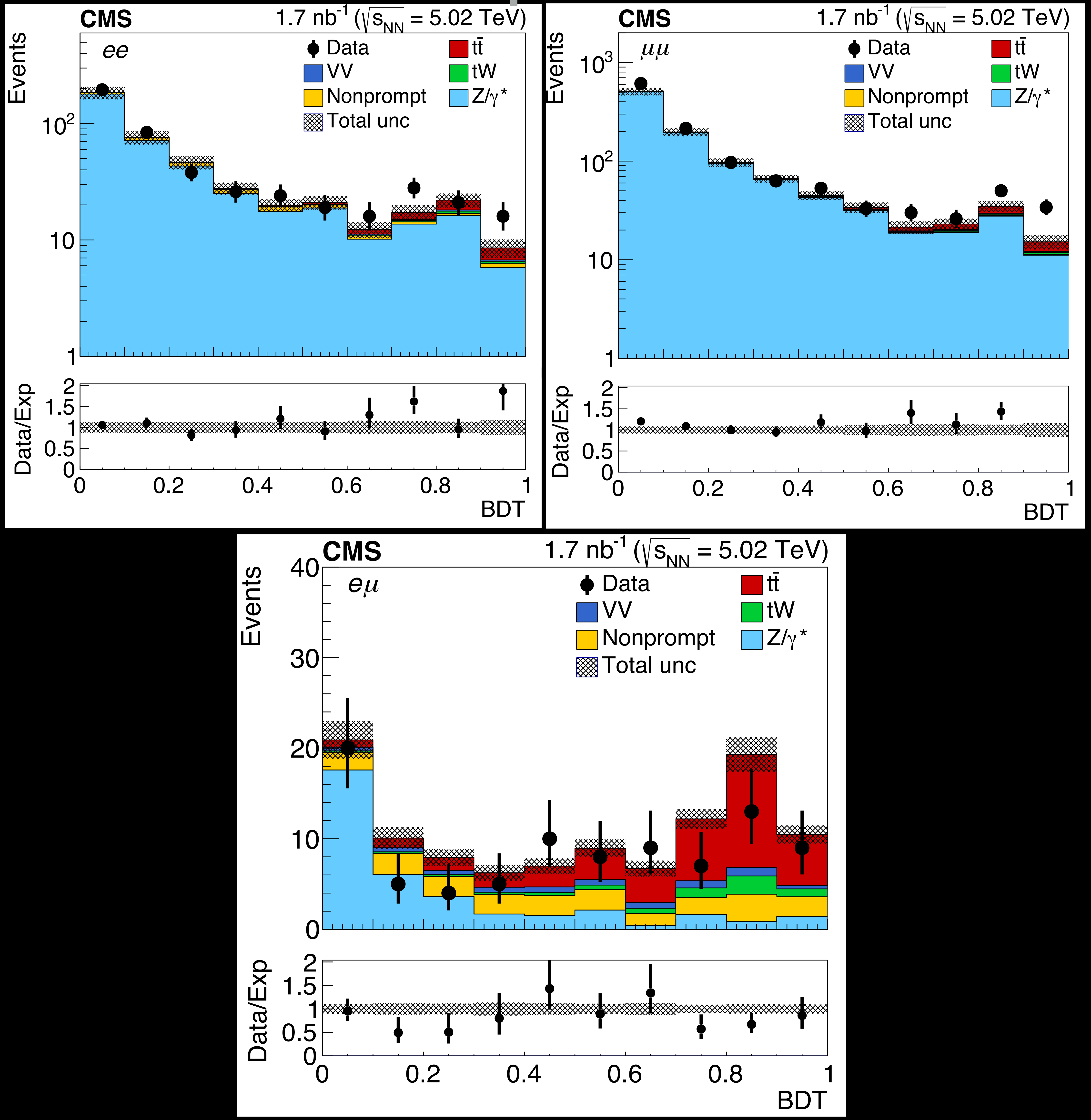
- Opposite sign high-p_T leptons with $p_T > 25, |\eta| < 2.1$ for electrons and $p_T > 20, |\eta| < 2.4$ for muons.
- Jets: $p_T > 30, |\eta| < 2.0$

Signal extraction

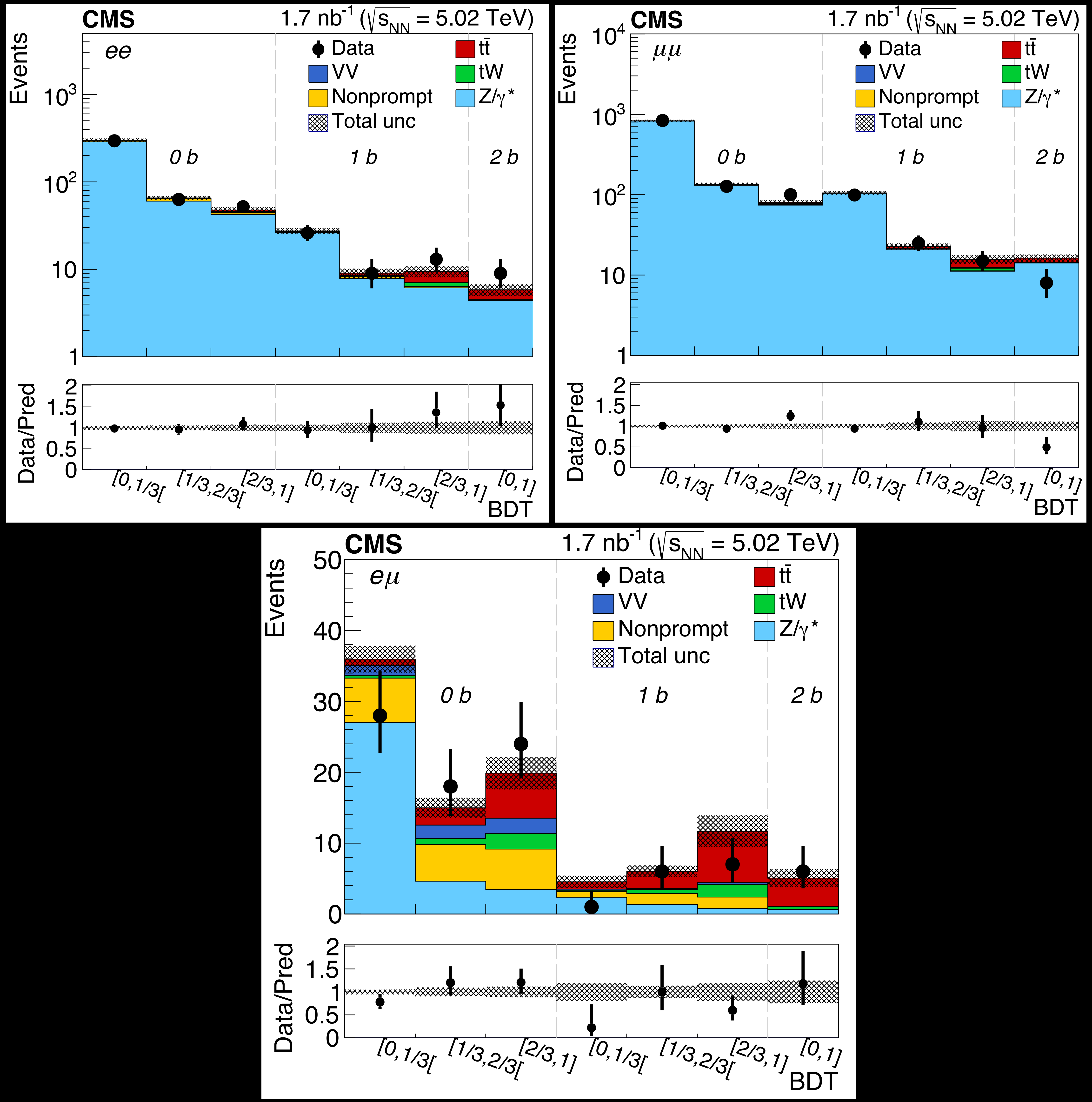
- $e^{\pm}\mu^{\mp}$ is the highest sensitivity final state
- Boosted decision trees (BDT): based on kinematics of the leading and sub-leading p_T leptons.
- Leptons are not affected by QGP.
- Likelihood fits to binned BDT distributions are performed separately for the two methods.

$t\bar{t}$ in *PbPb* at 5.02 TeV

Dilepton



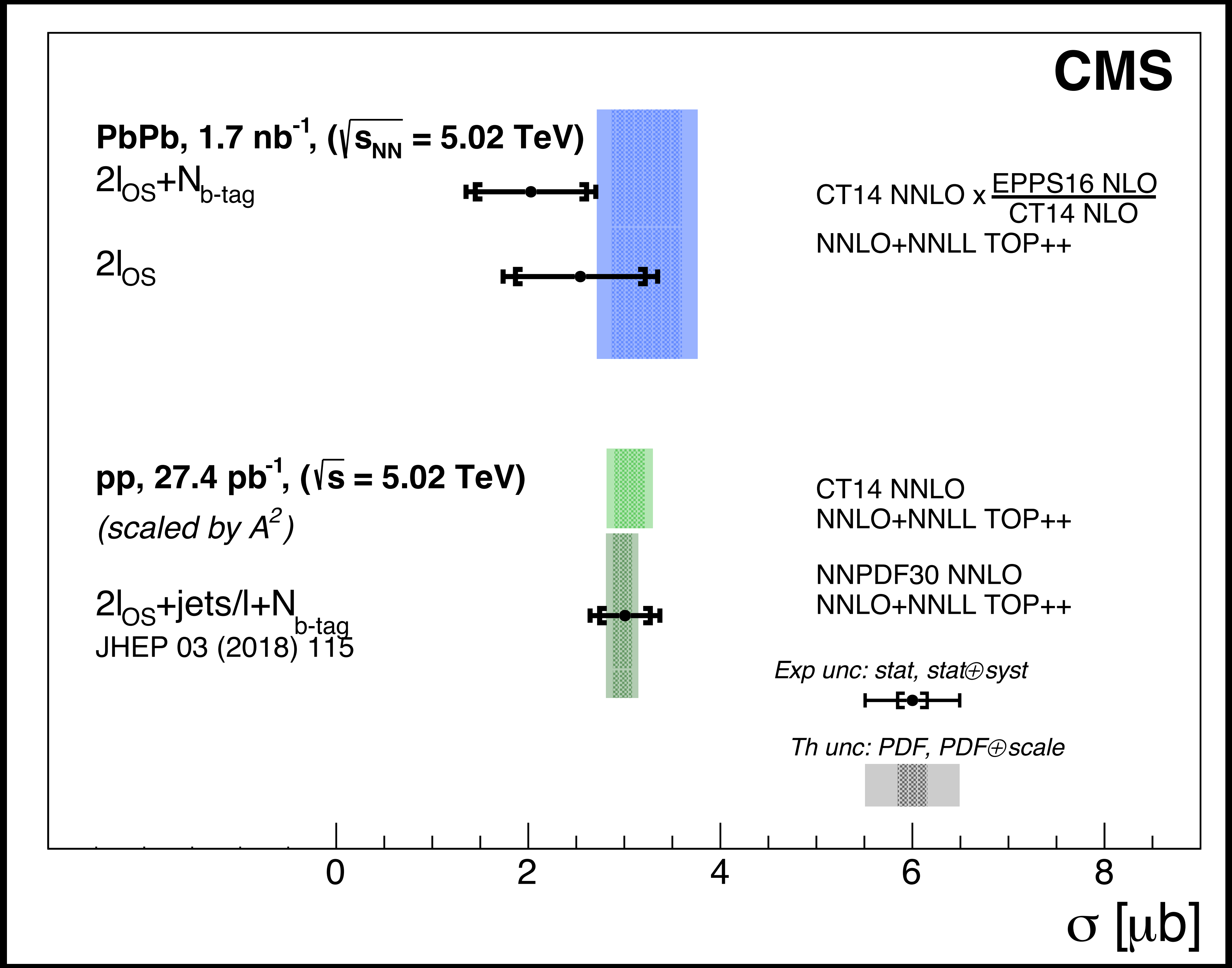
Dilepton + b-jets



$t\bar{t}$ in *PbPb* at 5.02 TeV

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

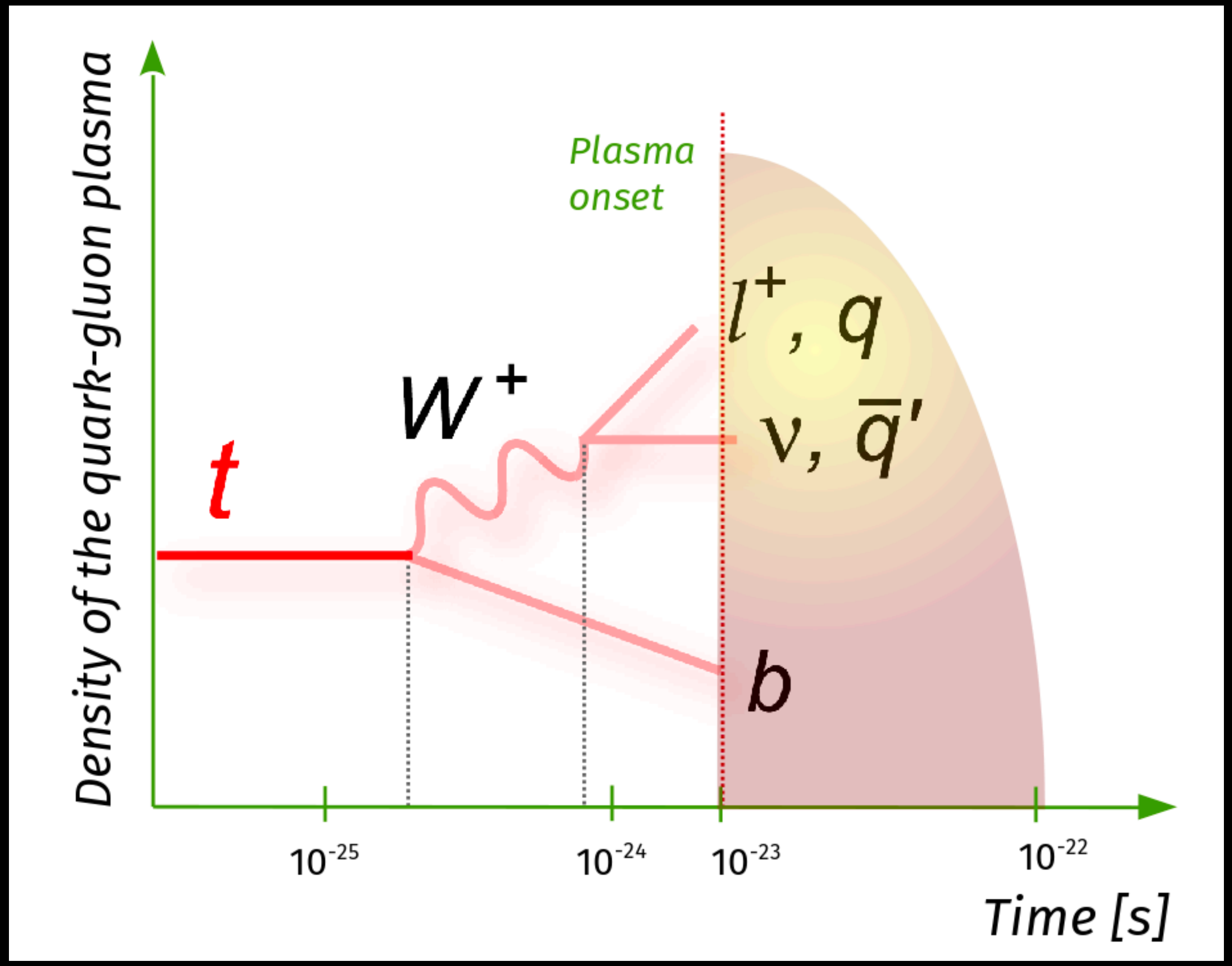
Dilepton → $\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}\ \mu b$



- Compatible with *pp* scaled data and QCD calculations.
- Evidence of top production in PbPb

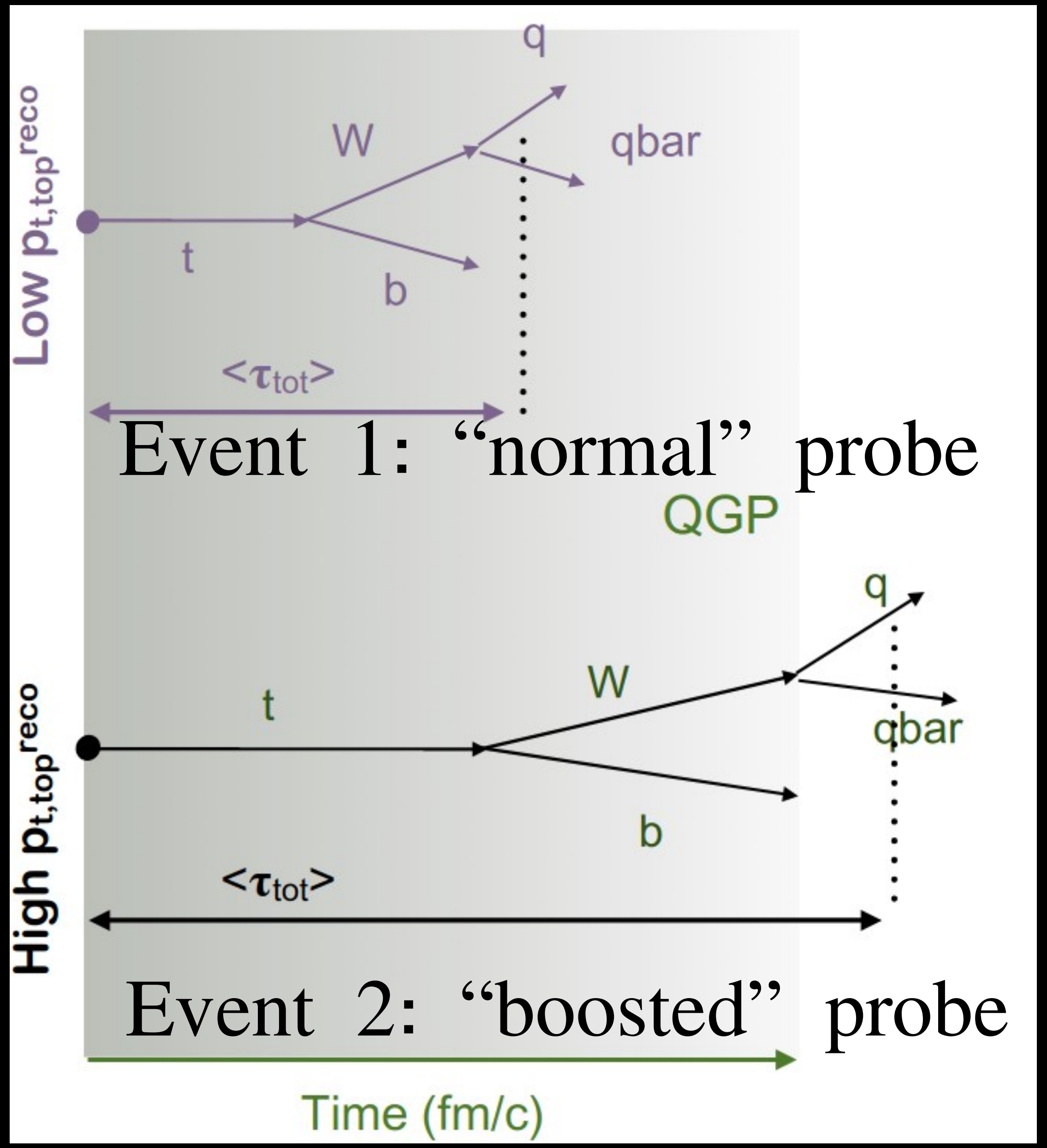
Top quark as a probe for QGP

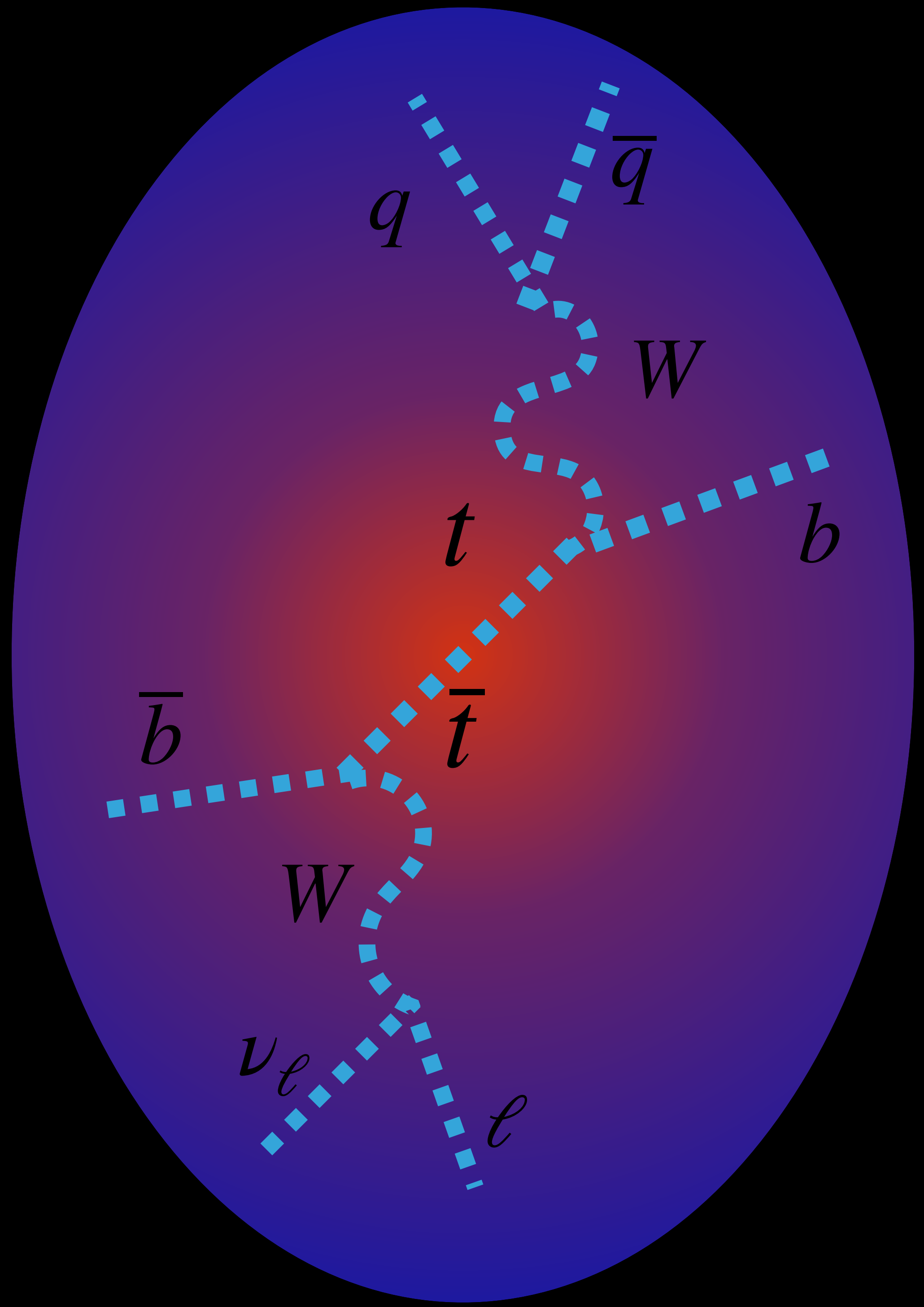
- $\tau_t \sim 10^{-24}$ sec. Does not hadronize and decays before QCD mechanisms start acting.
- Unlike other jet quenching probes (dijets, $Z/\gamma + jets$) which are produced simultaneously with the collision, tops can resolve the time evolution of QGP:



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

- 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
  - "Tag" and "probe"





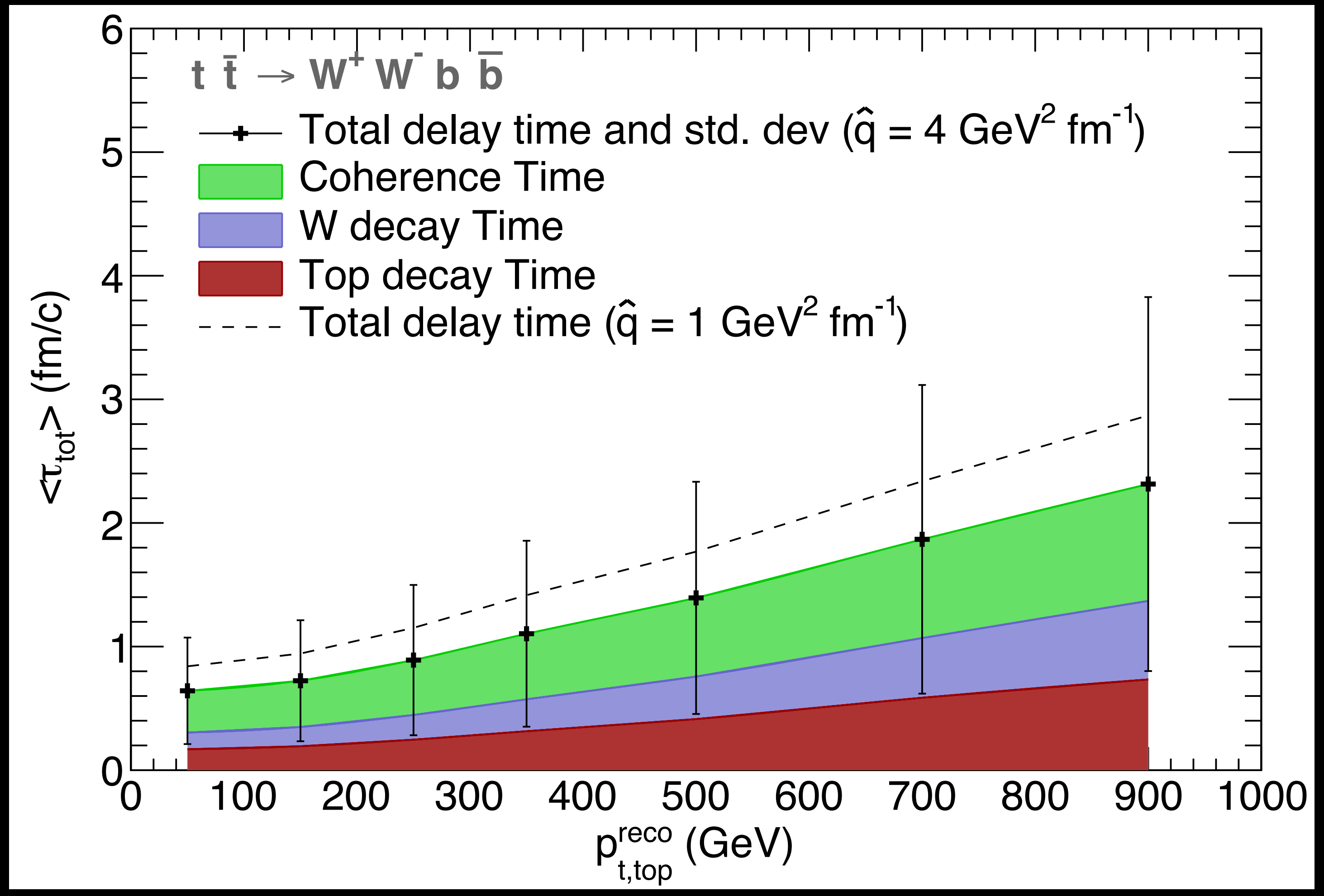
Top quark as a probe for QGP

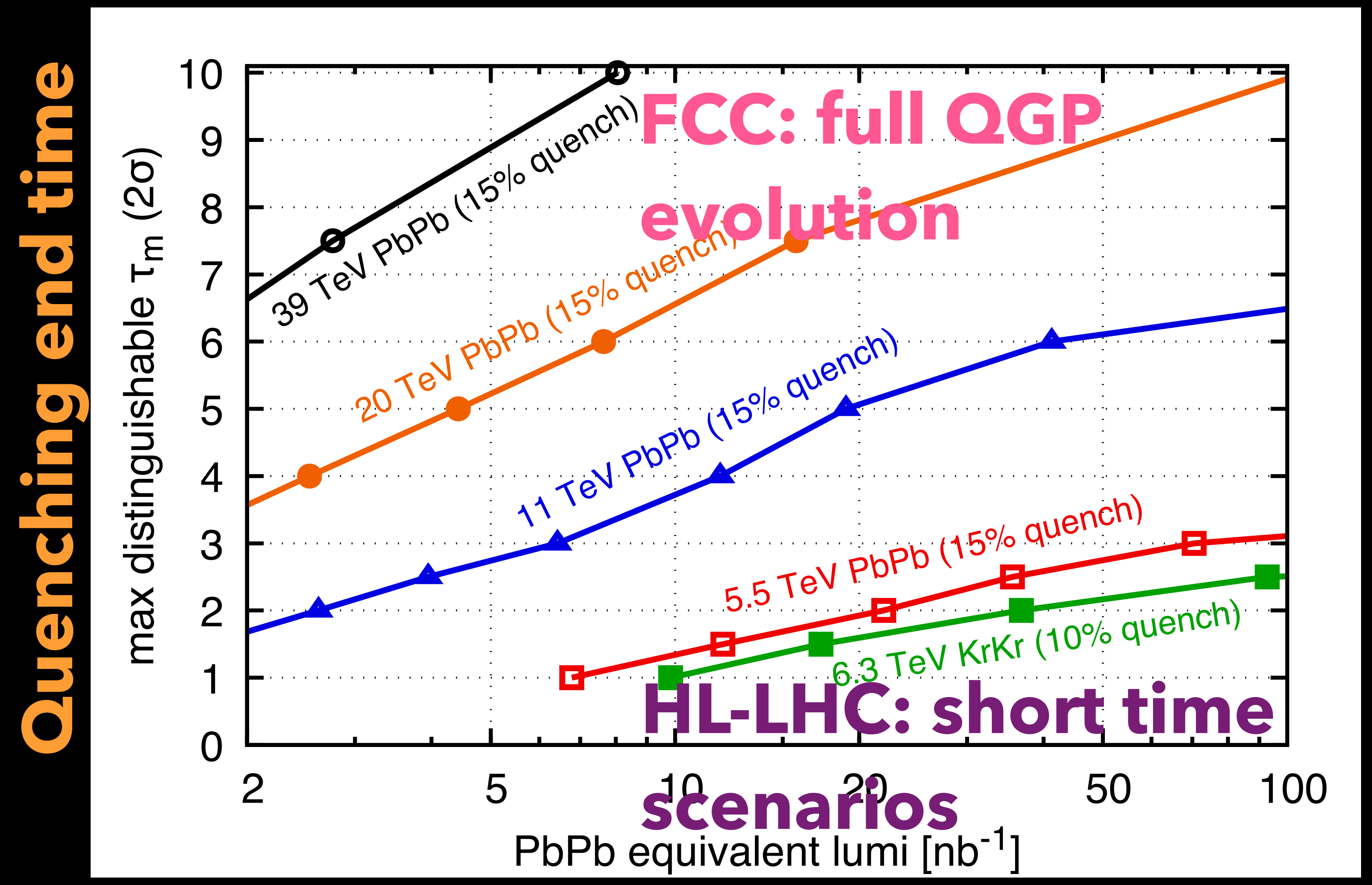
Pheno study PRL 120 (2018) 232301

- Channel: Semimuonic $t\bar{t} \rightarrow W(\rightarrow \mu\nu_{\mu})W(\rightarrow q\bar{q})$
- The products of $W(\rightarrow q\bar{q})$ do not immediately interact with the QGP.
- $q\bar{q}$ propagates a in a certain decoherence time (τ_d) before starts interacting with the medium.
- So $t \rightarrow b + W \rightarrow q\bar{q}$ does not see the full QGP, only the portion after:

$$\tau_{tot} = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d$$

- MC for feasibility about using tops to resolve QGP.





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 pp, pPb and $PbPb$ consistent with SM and pp scaling data.
- $t\bar{t}$ in AA collisions has the potential to resolve the time structure of the QGP.

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

Backup slides

Backup

A glimpse to heavy ion physics

- Two Lorentz contracted discs of highly complex systems of partons collide.
- When the discs overlap:
  - soft interactions dominate (small p_T transfer) + tiny amount of hard perturbative processes.
  - High p_T particles production at very early times.
- ~ 1 fm after the collision:
  - $\epsilon_{medium} \gg \epsilon_{hadron}$ and enormous entropy.
  - Pressure-driven hydrodynamic expansion builds up p_T
- As the two discs move apart:
  - QGP is continually producing.
  - Each droplet of QGP hydrodynamically expands, flow and cools down until $\epsilon_{droplet} \sim \epsilon_{hadron}$.
  - Mist of hadrons that scatter off each other and then stream away freely.
- The process ends once each participant loses ~ 85% of their energy in particle creation.

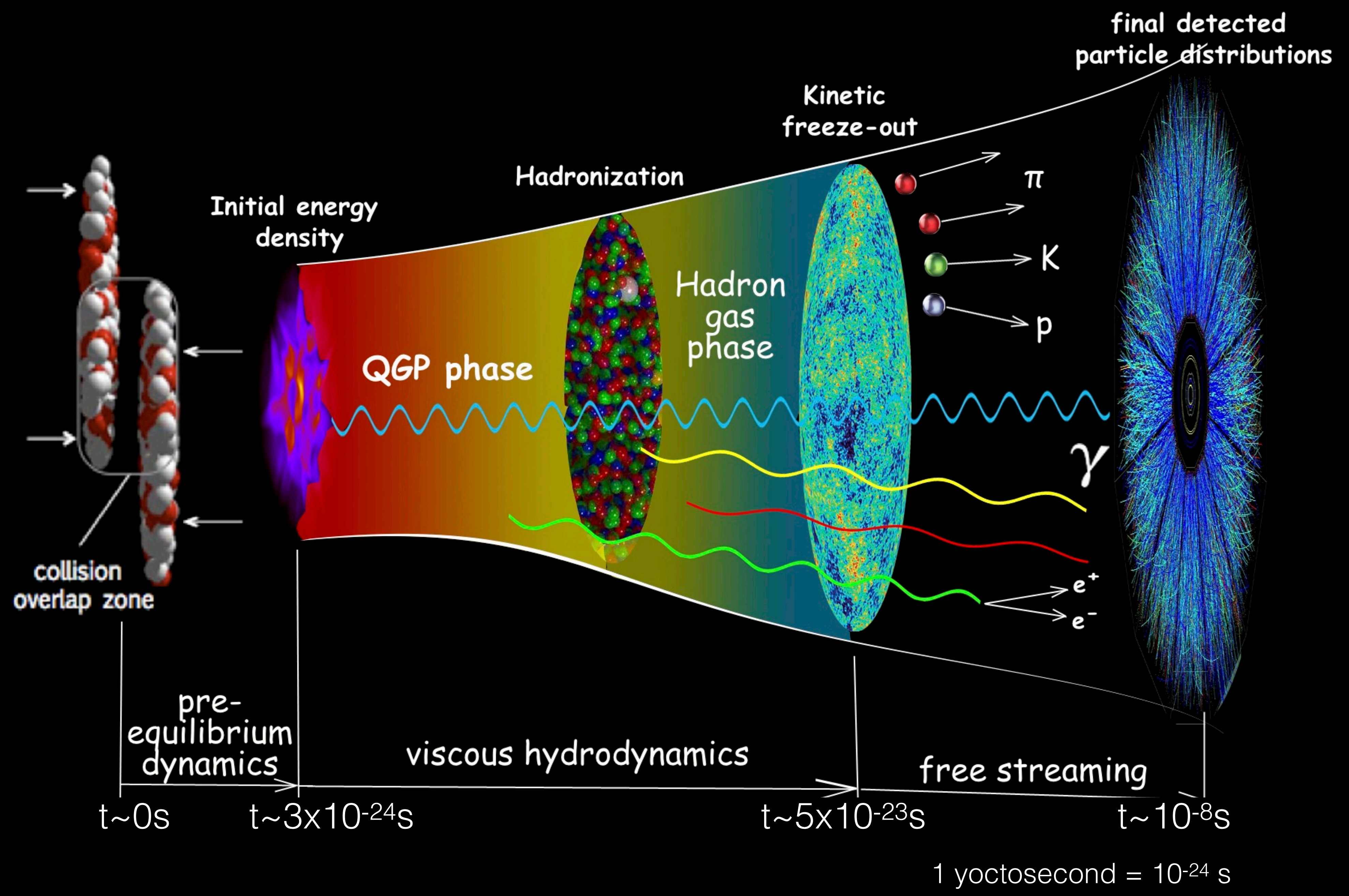


Image by Chun Shen

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.

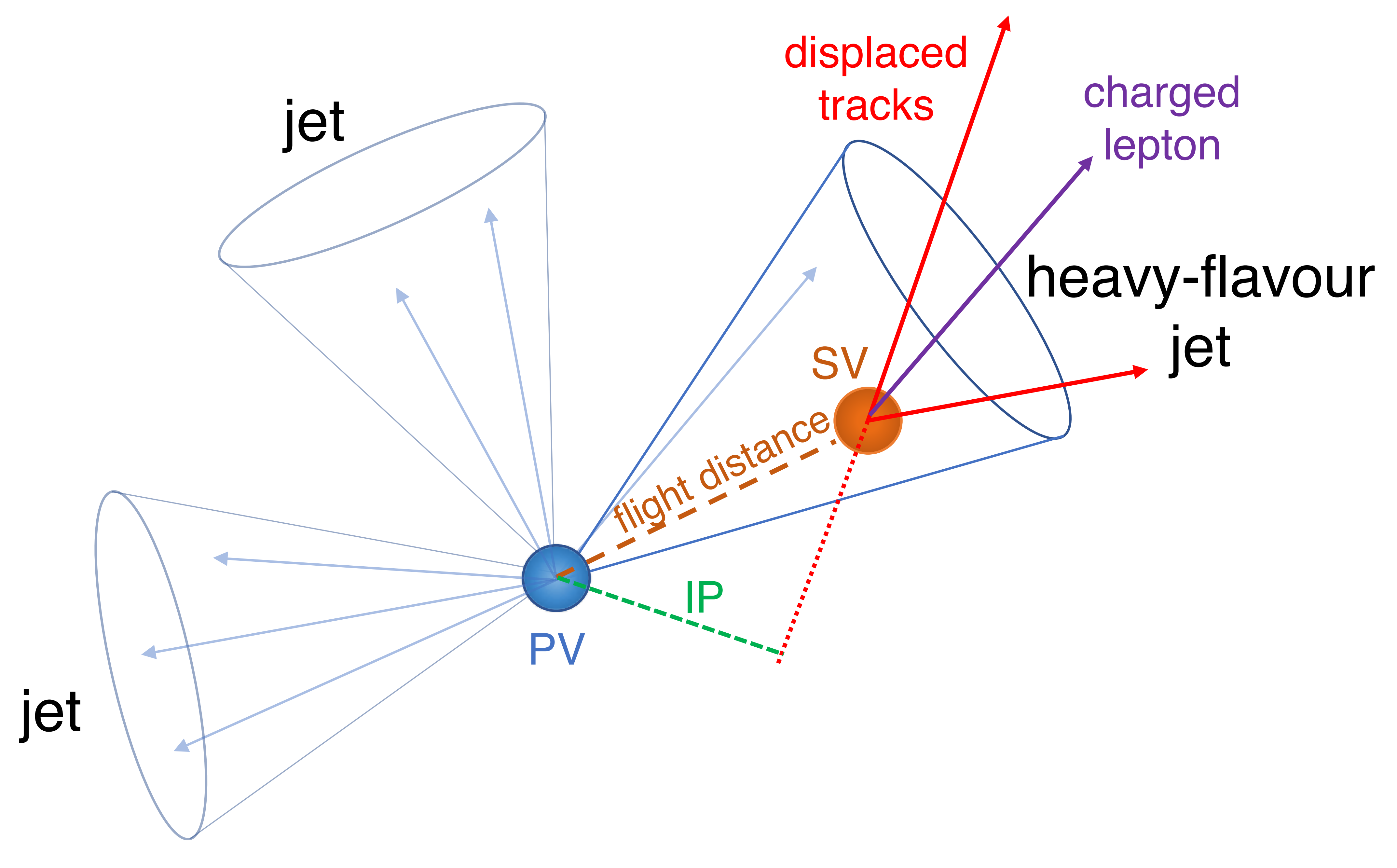


Table 1: Input variables used for the Run 1 version of the CSV algorithm and for the CSVv2 algorithm. The symbol "x" ("—") means that the variable is (not) used in the algorithm

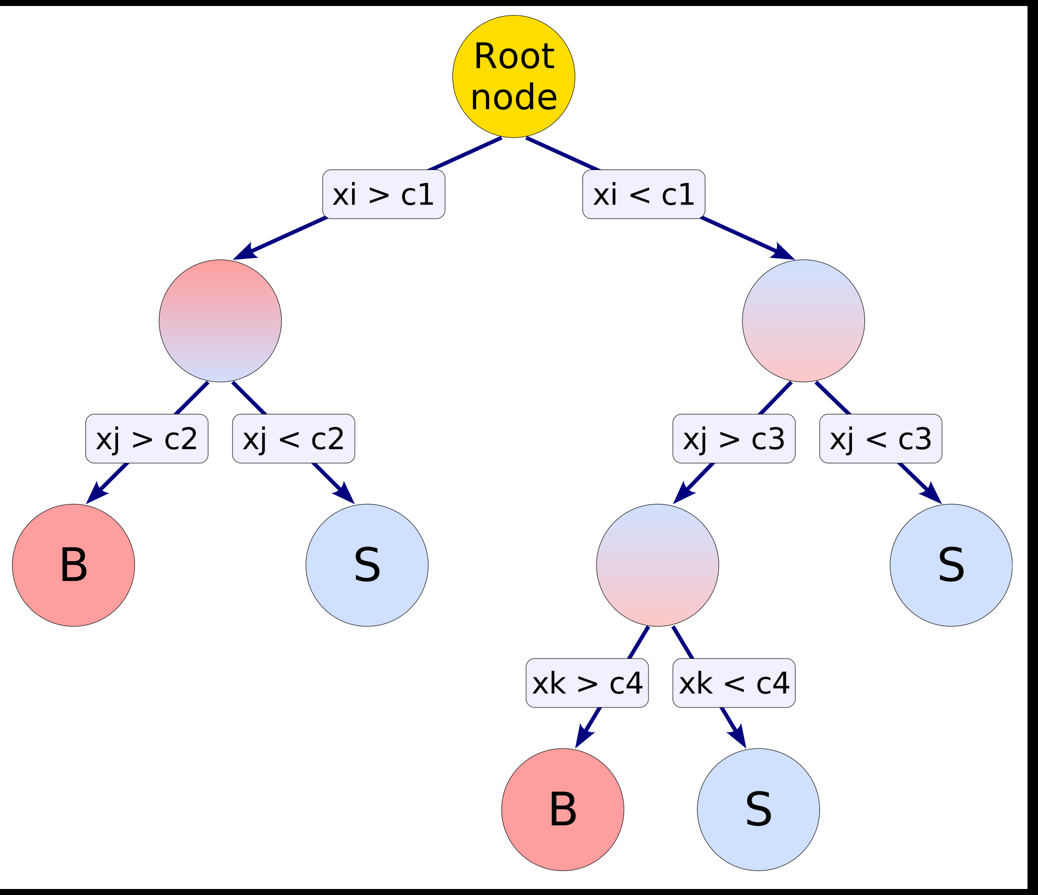
Input variable	Run 1 CSV	CSVv2
SV 2D flight distance significance	x	x
Number of SV	—	x
Track η_{rel}	x	x
Corrected SV mass	x	x
Number of tracks from SV	x	x
SV energy ratio	x	x
ΔR(SV, jet)	—	x
3D IP significance of the first four tracks	x	x
Track $p_{T,rel}$	—	x
ΔR(track, jet)	—	x
Track $p_{T,rel}$ ratio	—	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

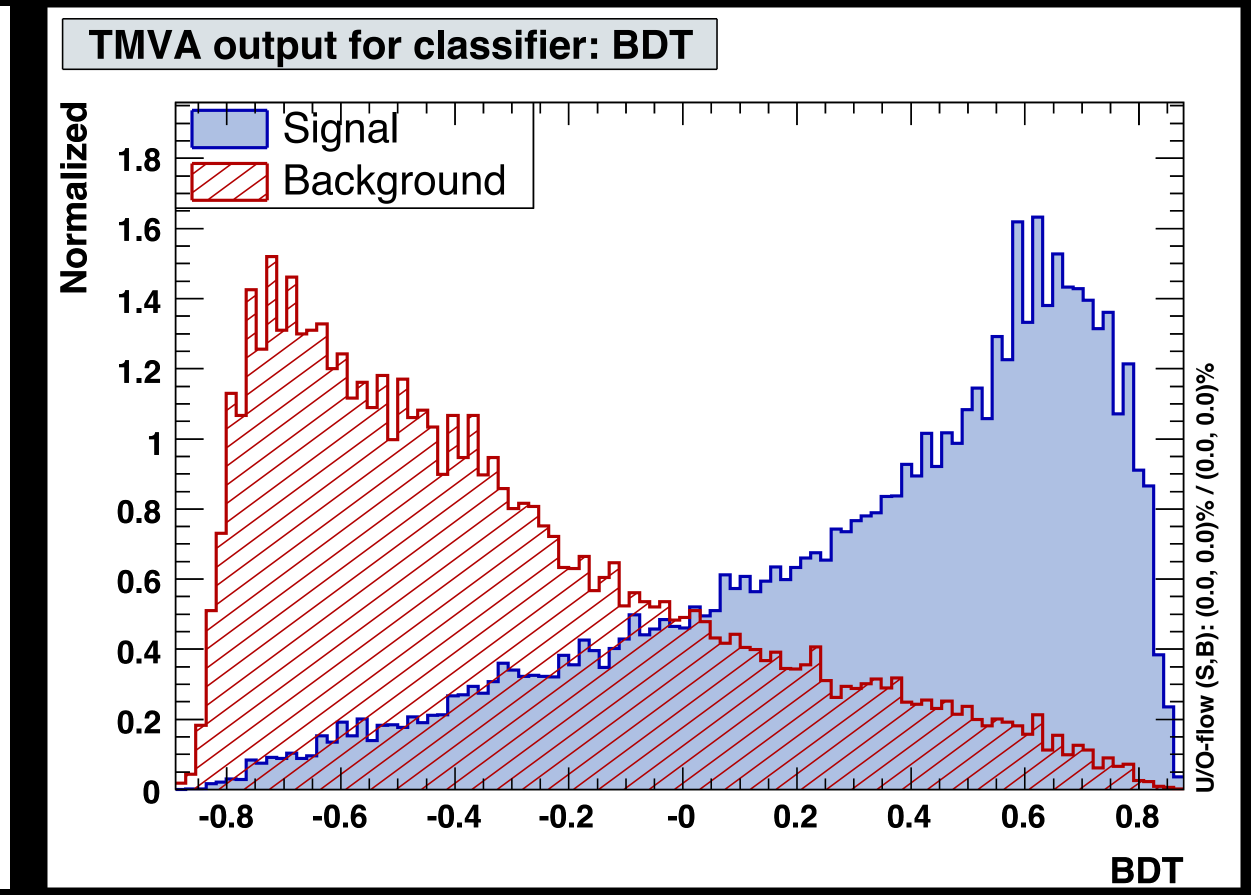
JINST 13 (2018) P05011

Backup

Boosted Decision Trees (BDT)

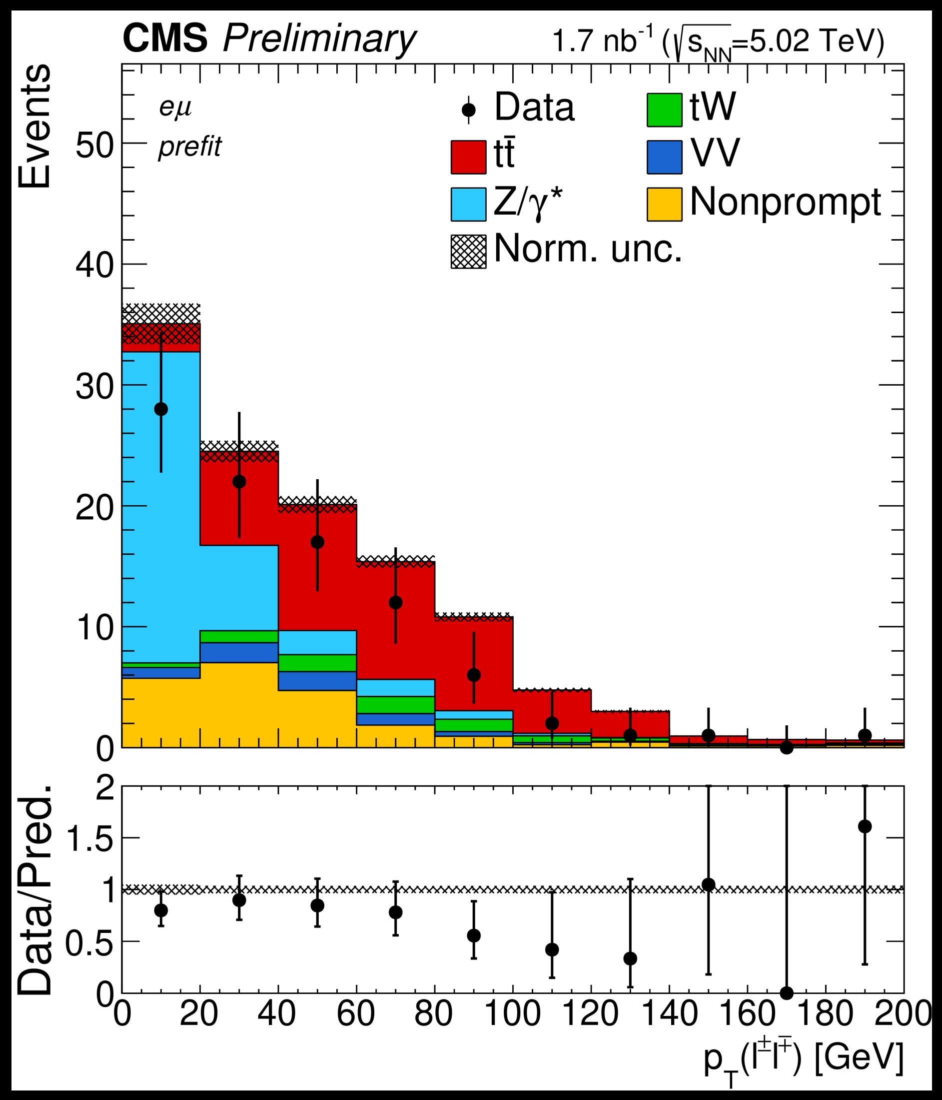
- Decision Tree (DT): binary classifier in which repeated decisions are taken until a stop criterion is reached.
- Boosted DT (BDT): extends the idea from one tree (weak classifier) to several trees (forest)
  - ➔ Better performance classifier
- By convention, signal (background) events accumulate at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

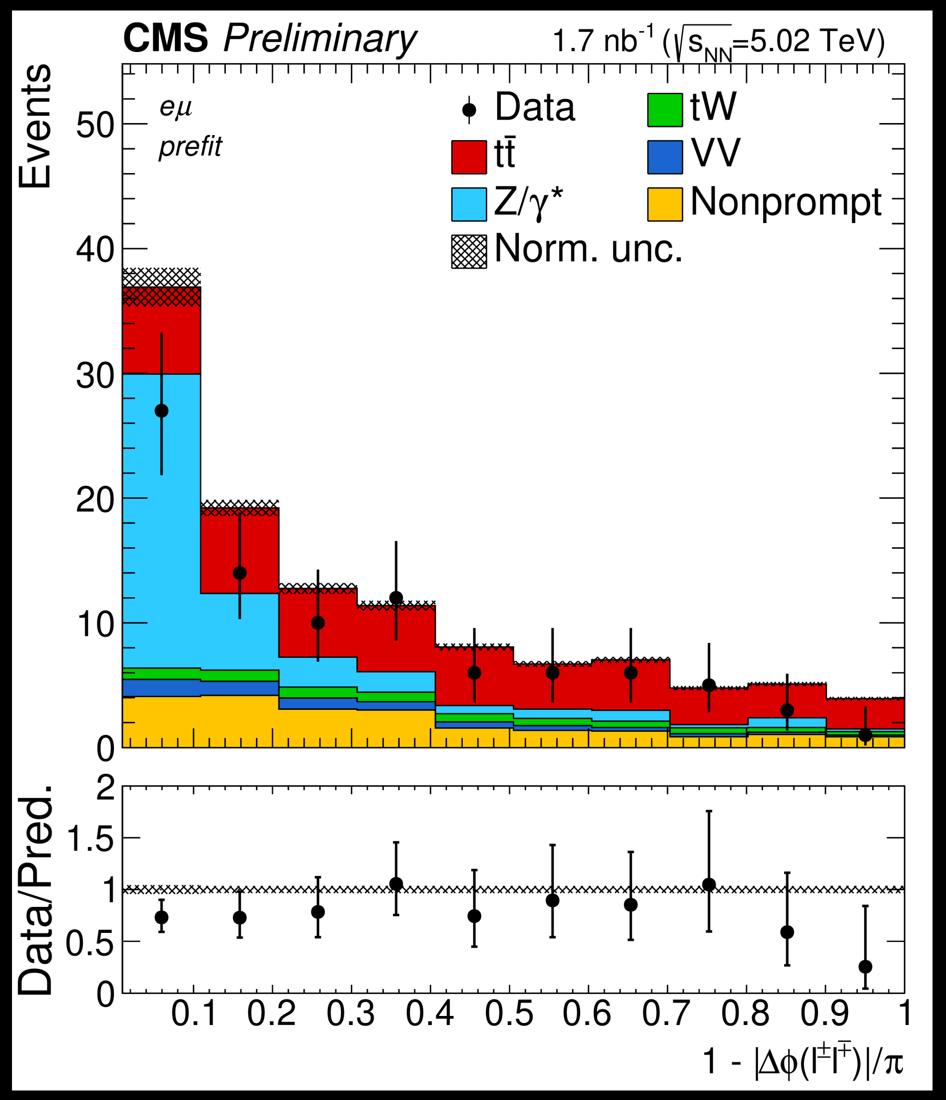




CERN-OPEN-2007-007

- $t\bar{t}$ 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, $\sum_i |\eta_i|$





CMS-PAS-HIN-19-001