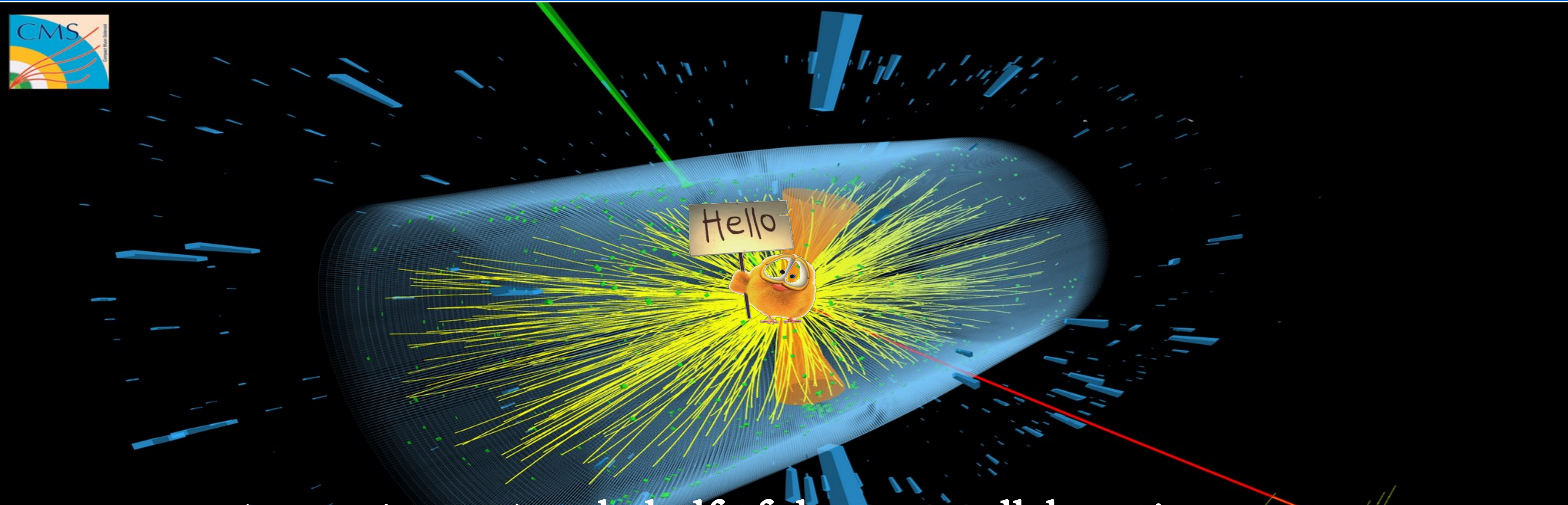
Evidence of top quark production in nucleus-nucleus collisions

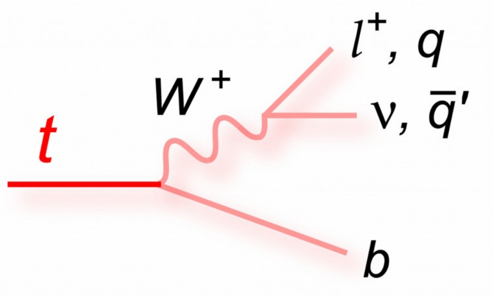
CMS PAS HIN-19-001



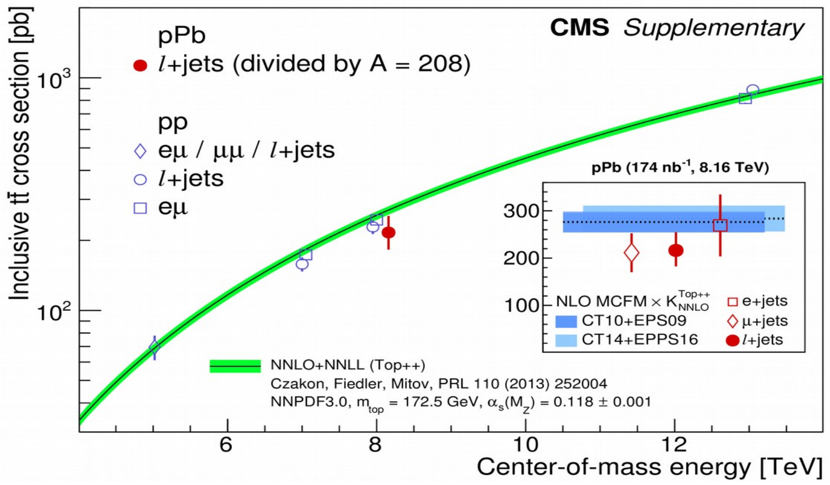
G.K. Krintiras (cern.ch/gkrintir) on behalf of the CMS Collaboration
The University of Kansas

Top quark studies @ LHC: 4 $\sqrt{s_{NN}}$ & 2 systems!

- Top quark is multifaceted
- A wealth of top pair ($t\bar{t}$) production measurements
  - At 5, 7, 8, and 13 TeV
  - In pp and pPb collisions
- A **new era** for nuclear-modification studies on top quark production
  - **Initial** state
    - To probe nuclear PDFs at high (x, Q^2) values
  - **Final** state
    - Novel tool for parton energy loss

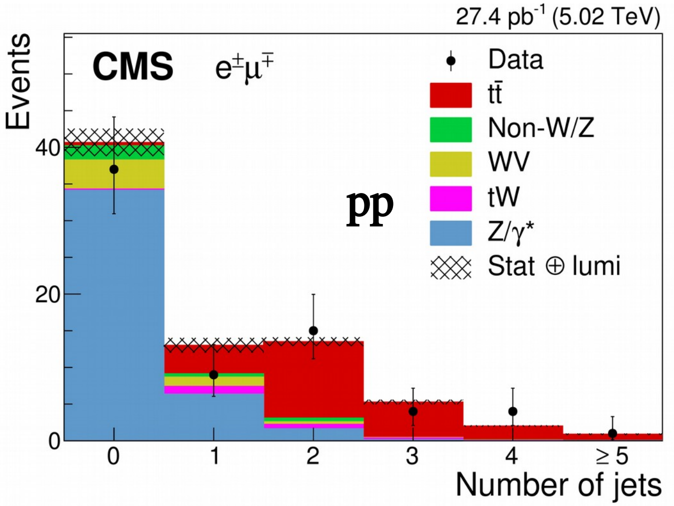


Phys. Rev. Lett. 119 (2017) 242001

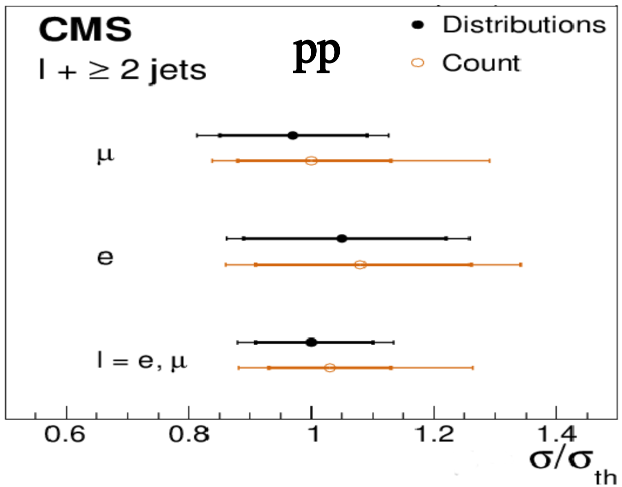


Measurements of $t\bar{t}$ cross section: general approach

- Choose the final state
  - ≥ 1 lepton (+jets)
    - less bkg dominated
- Apply MVA techniques
  - b tagging and signal extraction
- Define the “visible” phase space
  - Kinematic requirements on physics objects
  - In bins of (b) jet multiplicity
- Perform likelihood fits to counts or distributions
  - The cross section (σ) is extracted



JHEP 03 (2018) 115

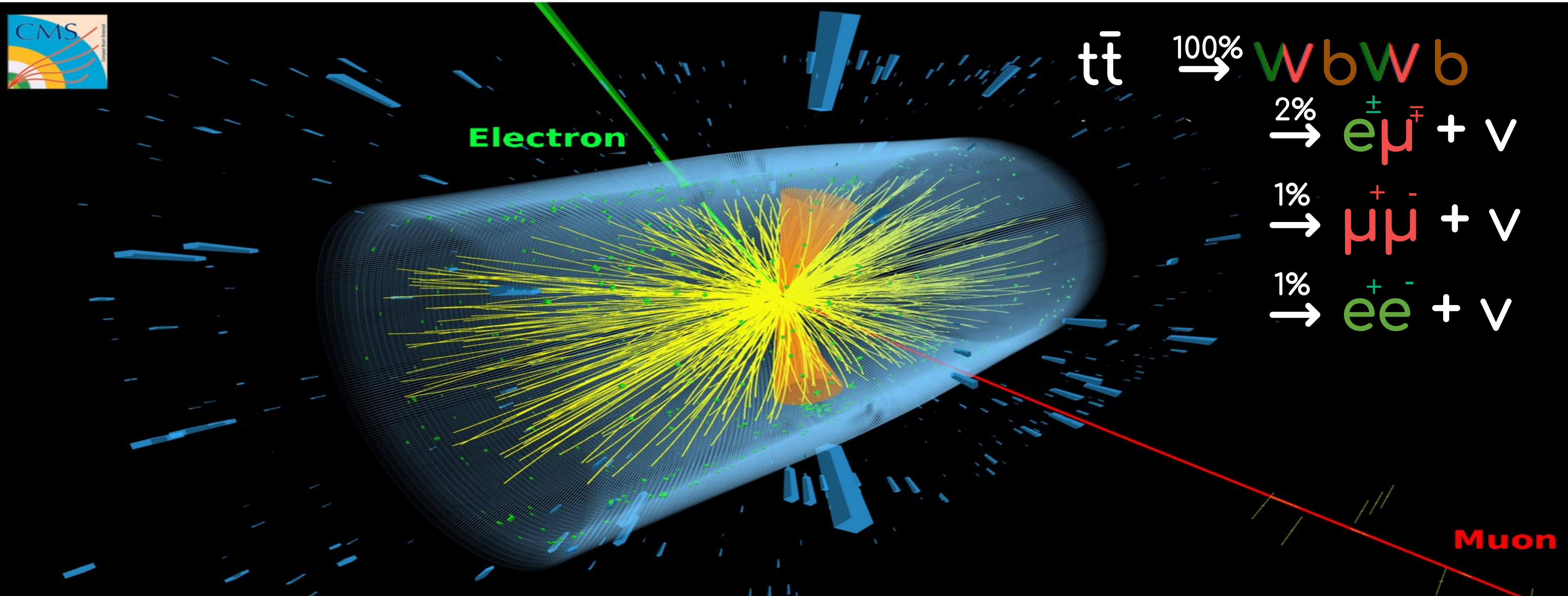


The first search for $t\bar{t}$ using NN (≡PbPb) collisions

- Dileptonic final states: the best S/B for **high event count** and a distinct signature

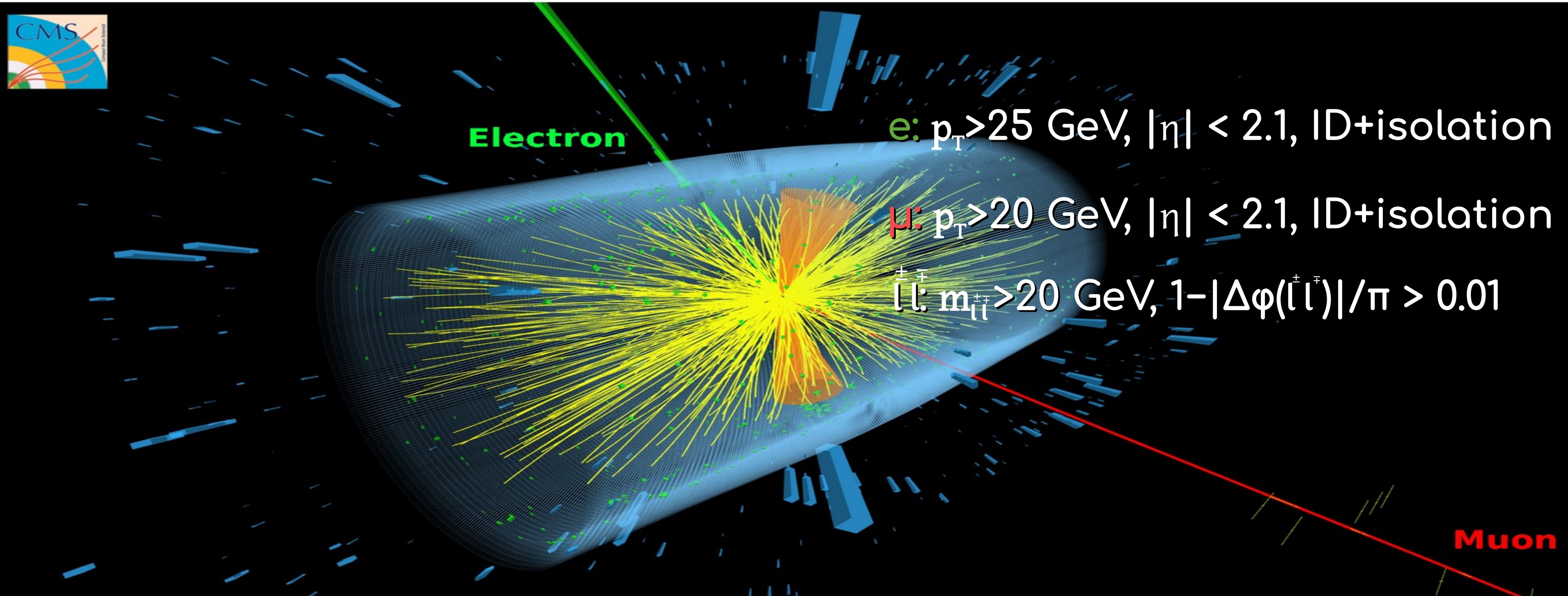
[Phys. Lett. B **746** (2015) 64]

  - Perturbative QCD cross section (3.2 ub) × luminosity (1.7 /nb in 2018): $\mathcal{O}(100)$ candidate events



The first search for $t\bar{t}$ using NN (≡PbPb) collisions

- Dileptonic final states: the best S/B for high event count and a **distinct signature**
  - Leptons (electrons or muons) are of **high p_T**, **isolated**, and **opposite charge**
  - Main background from prompt (e.g., Z/γ^*) or nonprompt (e.g., QCD multijet, W+jets) leptons



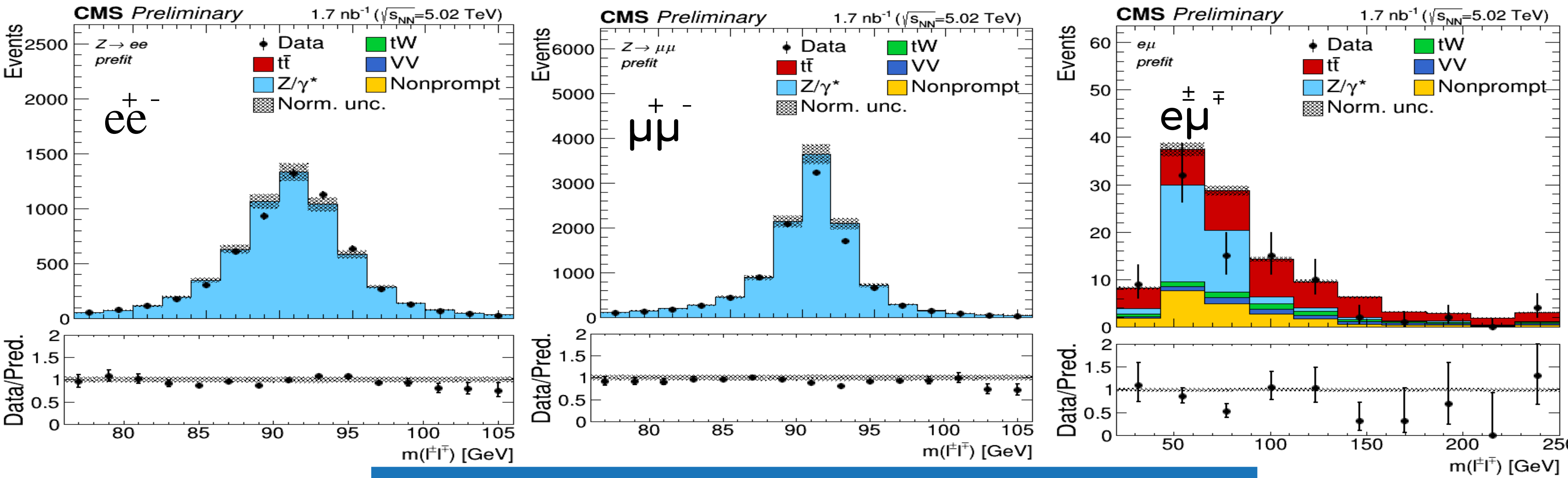
e: $p_T > 25$ GeV, $|\eta| < 2.1$, ID+isolation

μ: $p_T > 20$ GeV, $|\eta| < 2.1$, ID+isolation

$l^{\pm}l^{\mp}$: $m_{l^{\pm}l^{\mp}} > 20$ GeV, $1 - |\Delta\varphi(l^{\pm}l^{\mp})|/\pi > 0.01$

The signal and bkg. modeling

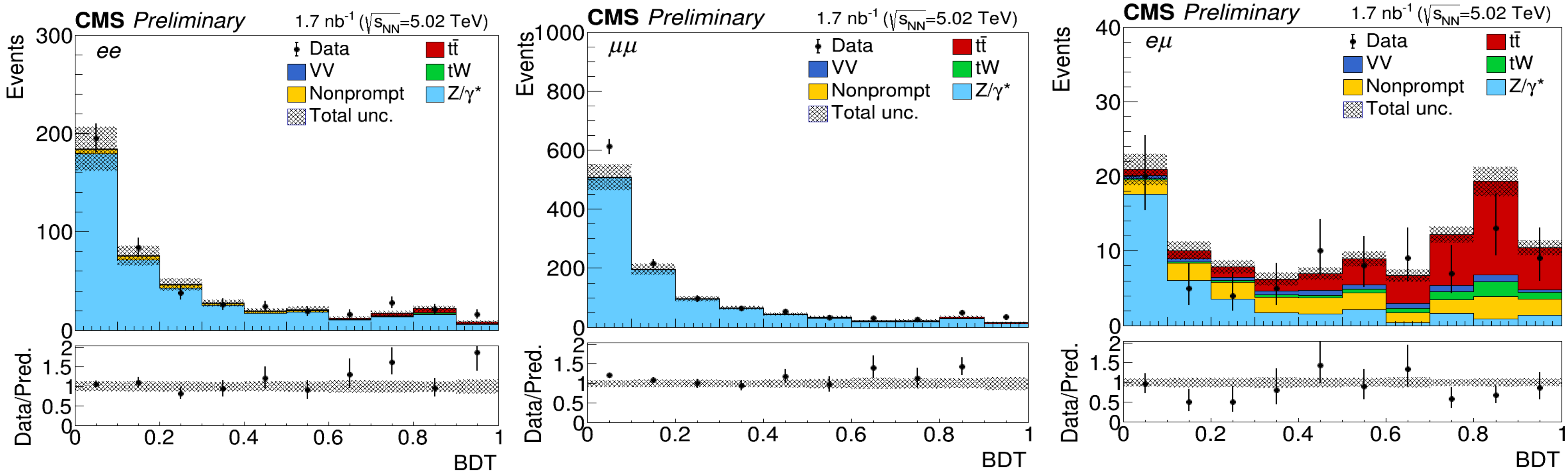
- All NN (N=p,n) → $t\bar{t}$, bkg processes at **next-to-leading order** (NLO) in pQCD
  - EPPS16 nPDFs, embedded to HYDJET
  - Nonprompt bkg from event mixing
    - cross checked with W+jets MC simulation



The predictions are scaled to luminosity!

Optimizing the $t\bar{t}$ extraction with lepton-only MVA

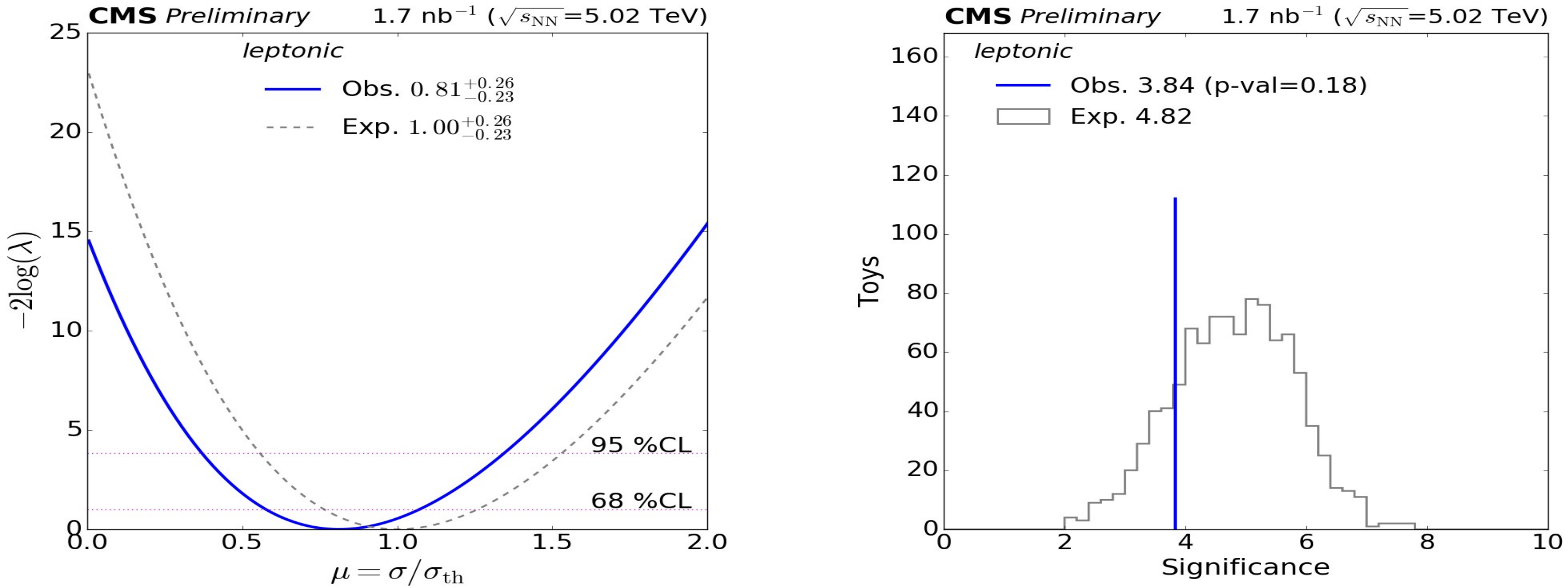
- Boosted Decision Trees (BDTs): kinematics from the two leading-p_T leptons
  - **Easy** to calibrate and **robust** against medium-modification effects
- Very good discrimination between $t\bar{t}$ signal (**high** BDT score) and bkg (**low** BDT score)
  - we fit the BDTs simultaneously in all **three final states**



The cross-flavor final state the most sensitive, as expected!

The significance of the lepton-only measurement

- Basic ingredients: **acceptance** ($\mathcal{A}$), **efficiency** (ε), and **total** (stat $\oplus$ syst) unc
  - $\mathcal{A}$ at NLO; ε from MC with data-driven correction
- The bkg-only hypothesis is excluded at **3.8σ**

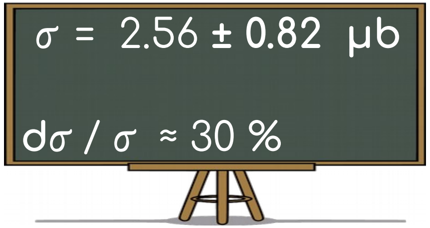


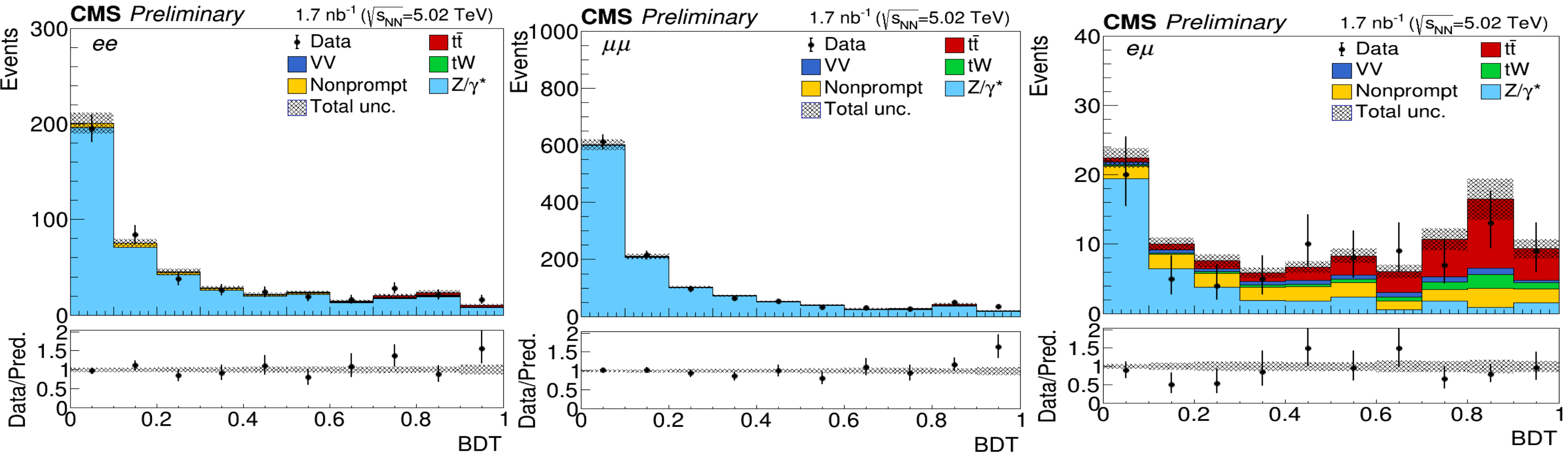
The first evidence of top quarks in PbPb!

Measuring the $t\bar{t}$ cross section with leptons only

- The cross section is measured **2.56** ± **0.69** (stat) ± **0.43** (exp) ± **0.13** (theo) μb
  - The statistical uncertainty is dominant
- Total number of signal events from all three final states: **43**
  - compatible with that we initially **expected**

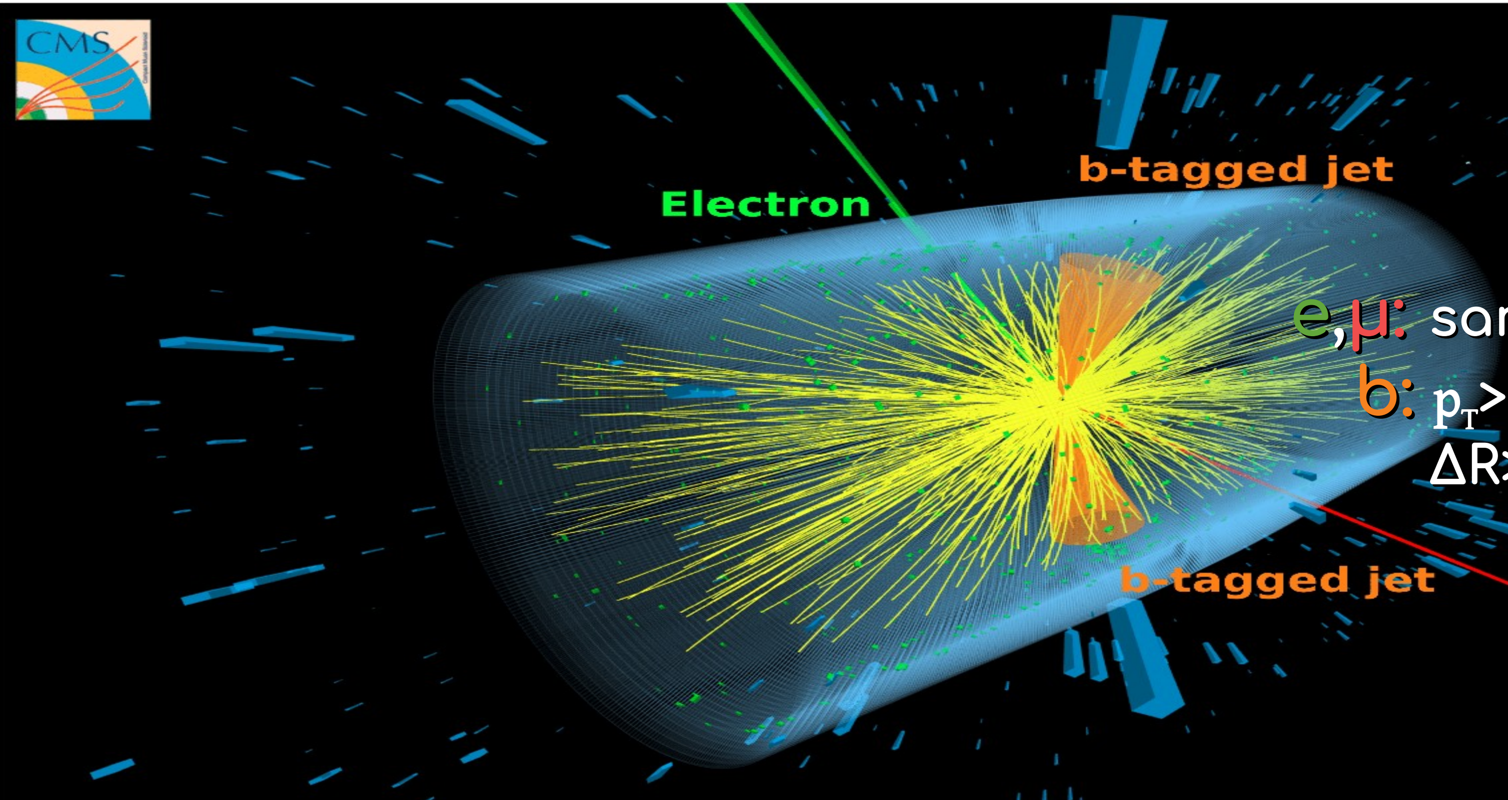
$\mathcal{L}$ =1.7±0.1 /nb





Including the information from jets

- **Enriching** the final state topology with the **b jet** info: phase space regions with different signal purity
  - Jets (anti-k_T, 0.4) are also of **high p_T** with falling η distribution
    - An optimized algorithm successfully tags 60–70% of the b jets



$t\ (\bar{t}) \rightarrow Wb$

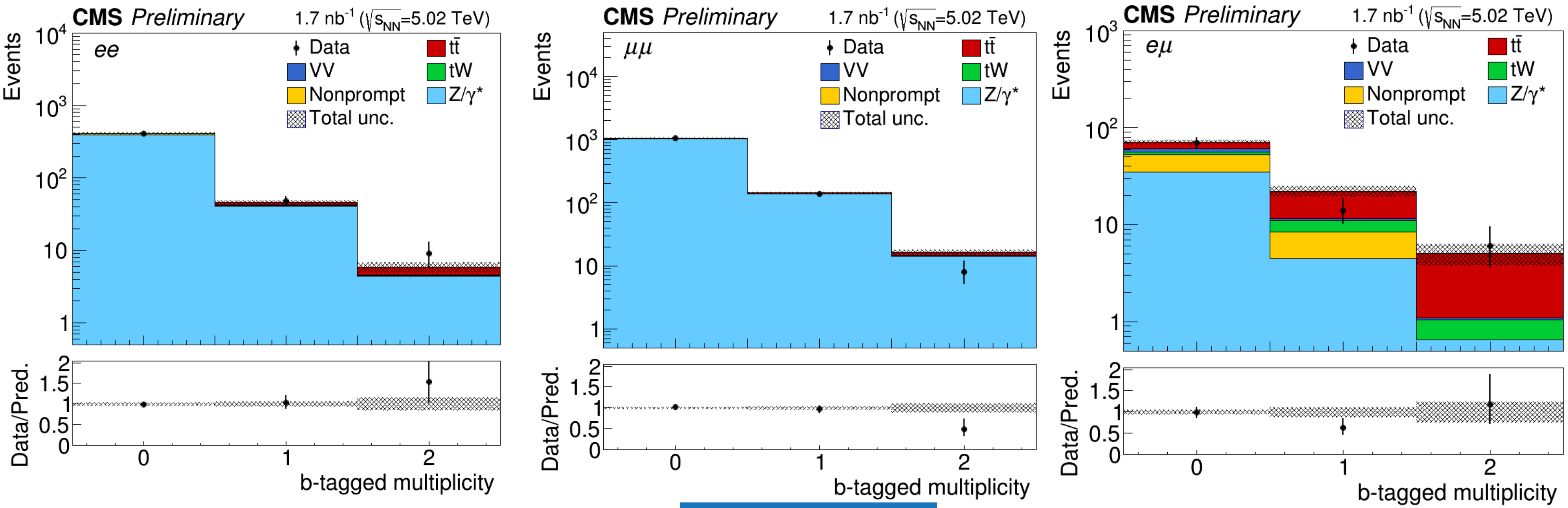
e,μ: same requirements

b: p_T>30 GeV, |η| < 2.0, ΔR>0.4 away from e, μ

The signal and bkg b jet multiplicity

- We count the number of events in the three final states with 0, 1, and 2 b-tagged jets
  - selecting the jets with the **highest** b tagging score
- Additional systematic uncertainties well under control
  - Experimental (b-tagging efficiency, JES/JER) ⊕ jet quenching parametrization uncertainty in signal

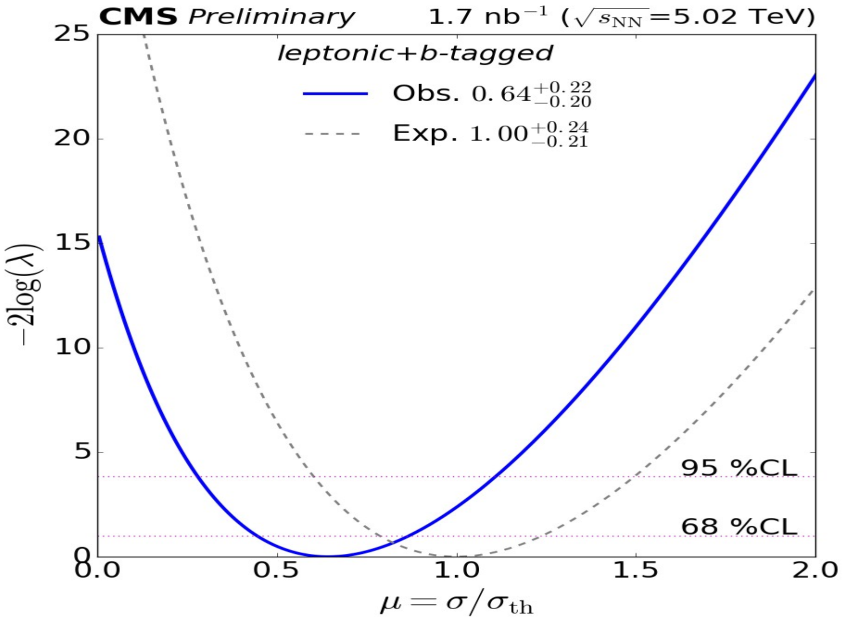
[Phys. Rev. Lett. **119** (2017) 062302]

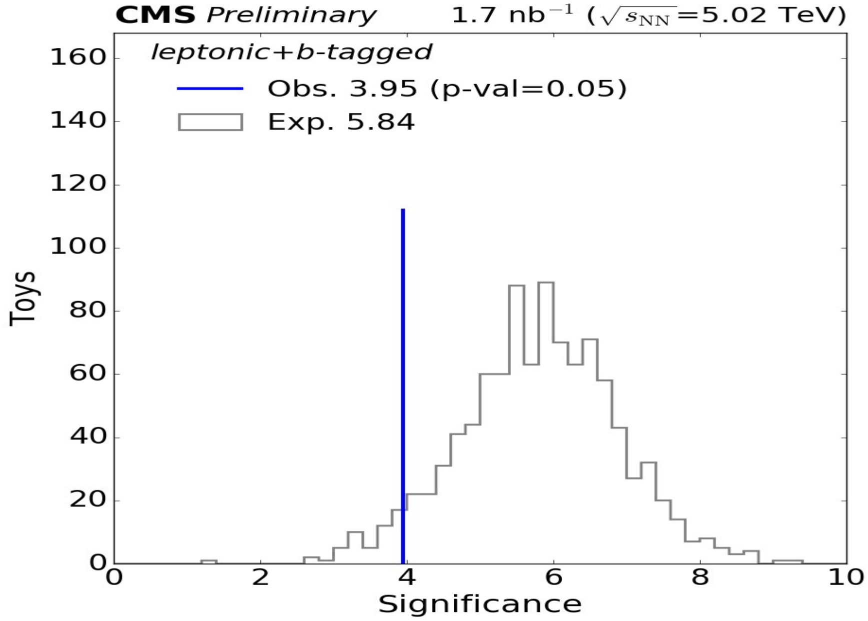


Z/γ* from data

The significance of the leptons+b-tags measurement

- We fit the lepton-only BDT classifier **simultaneously** at all three final states
  - correlating the number of events with 0, 1, and 2 b-tagged jets
  - This boosted our **expected** significance > 5σ
- The bkg-only hypothesis excluded at a similar level, i.e., 4σ



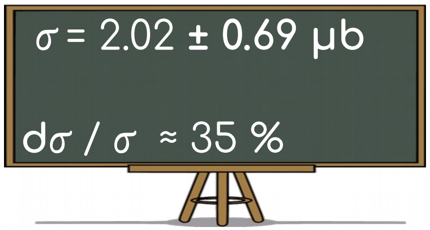


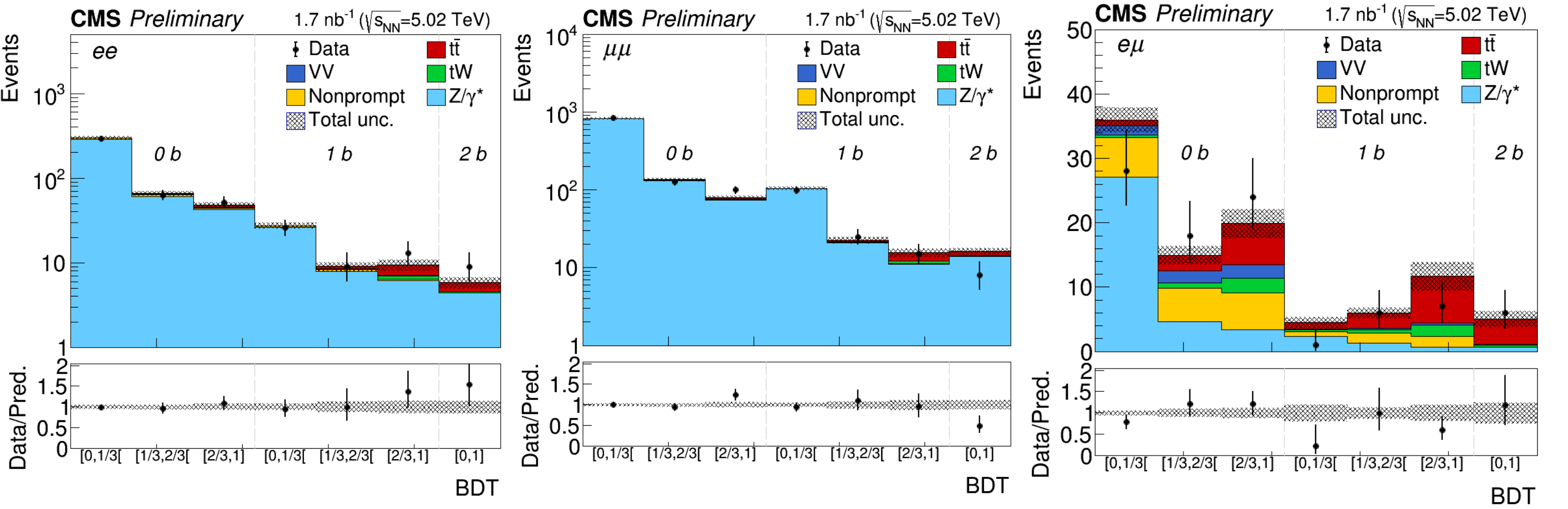
Increased sensitivity by adding jets

Measuring the $t\bar{t}$ cross section with leptons+b-tags

- We extracted σ with a **similar precision** relative to the lepton-only measurement
  - compatible with each other
- b-tagging is *a* powerful tool to flag $t\bar{t}$ production
  - $t\bar{t}$ provides a **pure** sample of b jets throughout the QGP evolution

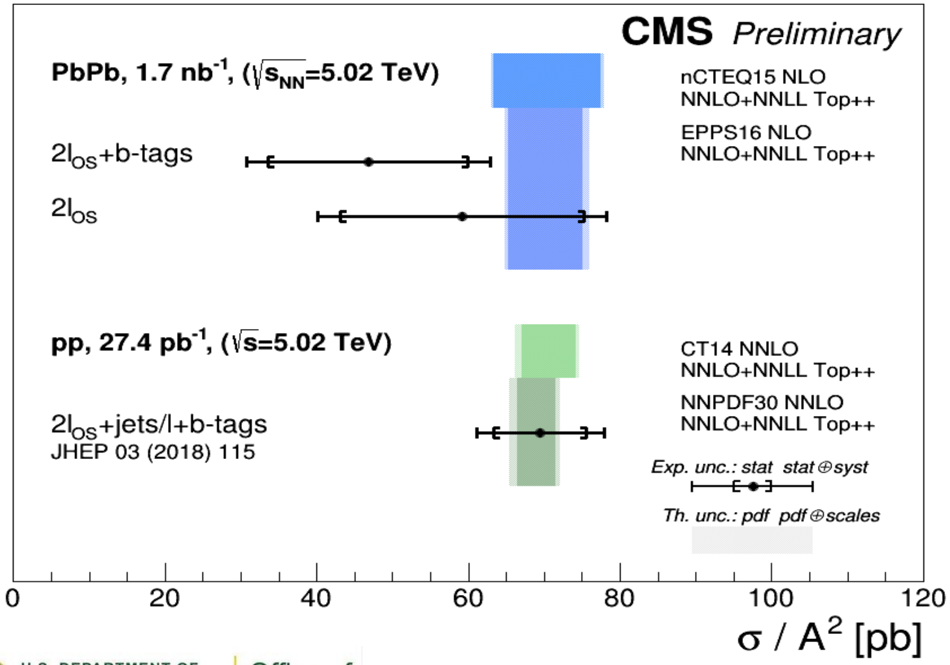
$\mathcal{L}$ =1.7±0.1 /nb

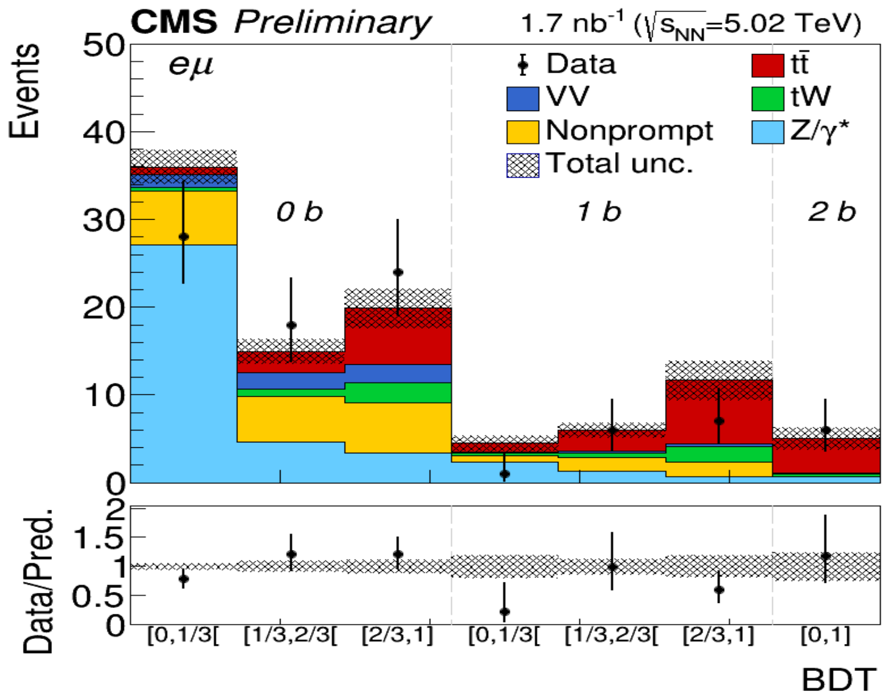




Up-to-date compilation: 4 √sNN & 3 systems @ LHC!

- **First** experimental evidence of the top quark in **nucleus-nucleus** collisions
  - using leptons only and leptons+b jets
- It establishes a **new tool** for probing nPDFs as well as the QGP properties





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CMS PAS HIN-19-001

s slides

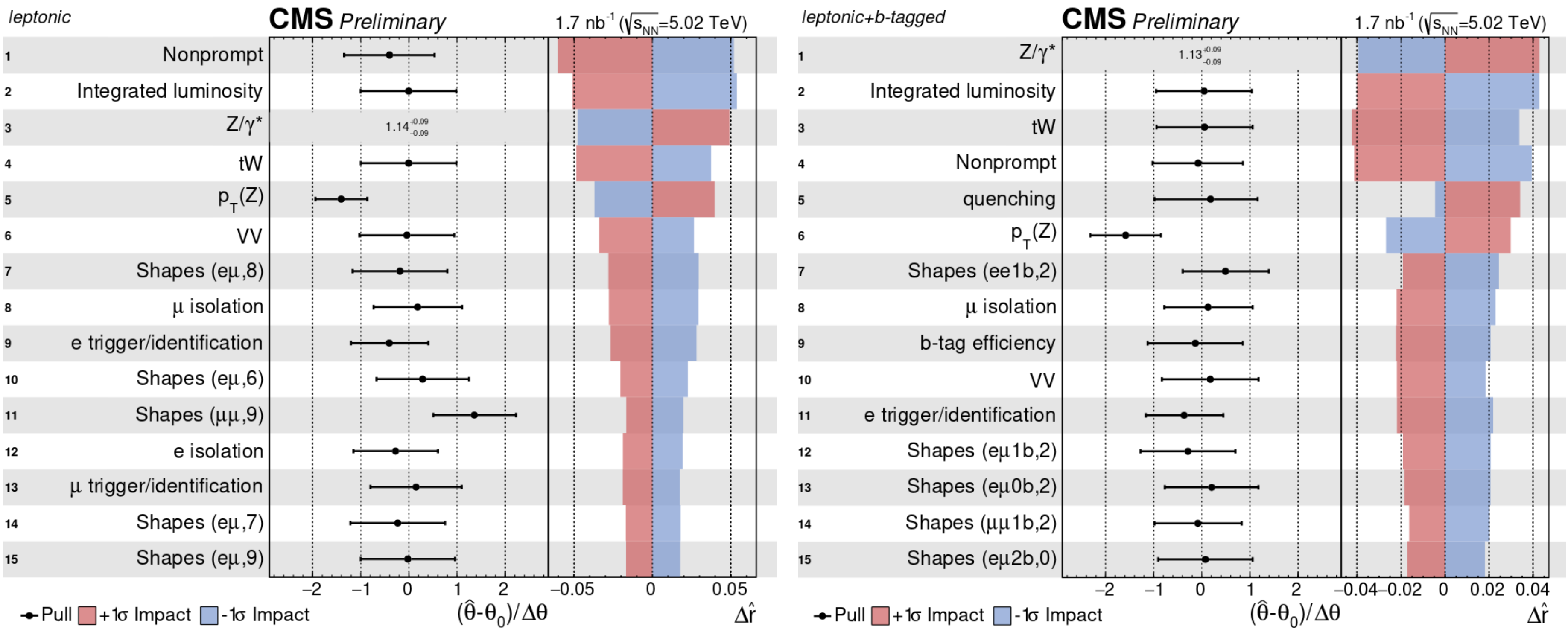
Splitting uncertainty in a stat & syst component

- There is no unique method
  - **stat**: fix nuisances to post-fit values and refit with floating σ_{tt}
  - **syst**: fix nuisances once at a time to post-fit unc and refit with

Table 2: Observed impact of each source of uncertainty in the signal strength μ, for the leptonic-only and leptonic+b-tagged analyses. The total uncertainty is obtained from the covariance matrix of the fits. The values quoted are symmetrized.

Source	$\Delta\mu/\mu$	
	leptonic-only	leptonic+b-tagged
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 tagging efficiency	—	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 Z boson p_T modeling	0.05	0.05
Top quark mass	<0.01	<0.01
Total uncertainty	0.32	0.34

Impacts (observed)



Impacts and post-fit nuisance values obtained after the leptonic-only (left) and the leptonic+b-tagged (right) fits. Only the 15 leading nuisance parameters are shown.

Per-channel sentitivity

Table 3: Signal strength μ and significance in standard deviations including only the $e^{\pm}\mu^{\mp}$channel in the fit and compared to the $e^{+}e^{-}$,$\mu^{+}\mu^{-}$, and $e^{\pm}\mu^{\mp}$ measurements. The observed (expected) results of the fits are reported.

Fit alternative	Signal strength μ	Significance
$e^{\pm}\mu^{\mp}$ (leptonic only)	$0.66^{+0.24}_{-0.22}$ $(1.00^{+0.27}_{-0.25})$	3.3 (4.7)
$e^{+}e^{-}$,$\mu^{+}\mu^{-}$, and $e^{\pm}\mu^{\mp}$ (leptonic only)	$0.81^{+0.26}_{-0.23}$ $(1.00^{+0.26}_{-0.23})$	3.8 (4.8)
$e^{\pm}\mu^{\mp}$ (leptonic+b-tagged)	$0.61^{+0.23}_{-0.20}$ $(1.00^{+0.26}_{-0.23})$	3.8 (5.3)
$e^{+}e^{-}$,$\mu^{+}\mu^{-}$, and $e^{\pm}\mu^{\mp}$ (leptonic+b-tagged)	$0.64^{+0.22}_{-0.20}$ $(1.00^{+0.24}_{-0.21})$	4.0 (6.0)

Event yields

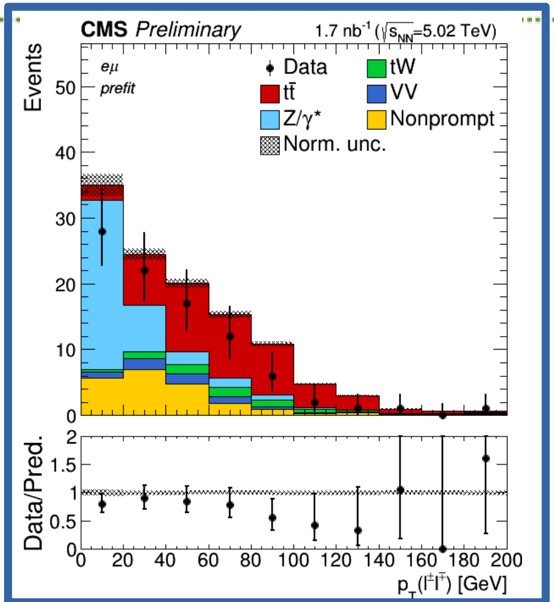
Table 1: Number of expected background and signal events, and observed event yields in the e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ event categories for the three b jet multiplicities (0b, 1b, 2b) after all selection criteria and the signal extraction fit.

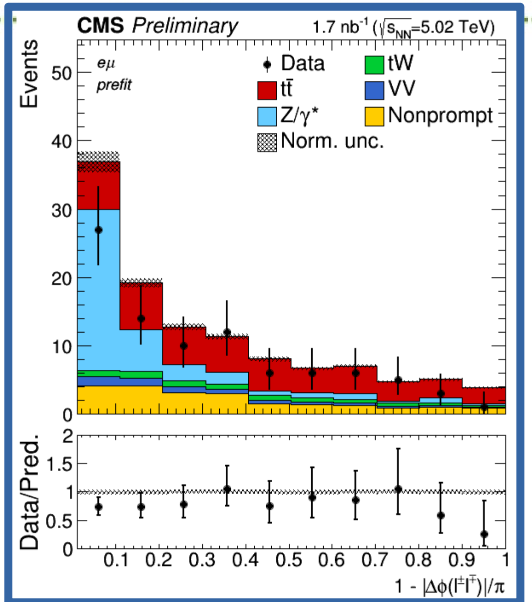
Process	Final state e^+e^-			Final state $\mu^+\mu^-$			Final state $e^\pm\mu^\mp$		
	0b	1b	2b	0b	1b	2b	0b	1b	2b
Z/γ^*	389.8±15.4	40.4±2.7	4.4±0.8	1027.5±27.3	136.1±5.7	14.1±1.7	35.1±1.7	4.4±0.9	0.7±0.2
Nonprompt	17.3±2.2	1.4±0.2	$\leq$ 0.1	7.6±1.0	0.8±0.1	$\leq$ 0.1	17.1±1.9	4.0±0.4	$\leq$ 0.1
tW	1.1±0.2	0.9±0.2	$\leq$ 0.1	1.8±0.4	1.3±0.3	0.2±0.1	3.4±0.7	2.5±0.5	0.4±0.1
VV	1.9±0.3	0.2±0.1	$\leq$ 0.1	3.3±0.6	0.4±0.1	$\leq$ 0.1	5.4±0.9	0.6±0.1	$\leq$ 0.1
Total background	410.2±15.1	42.8±2.7	4.5±0.8	1040.2±27.1	138.6±5.7	14.4±1.8	61.1±2.9	11.5±1.3	1.1±0.2
$t\bar{t}$ signal	2.8±0.8	3.2±0.8	1.3±0.4	4.5±1.2	5.1±1.2	1.9±0.6	9.7±2.5	10.7±2.4	4.0±1.2
Observed (data)	410	48	9	1064	139	8	70	14	6

Signal separation: measuring $t\bar{t}$ with leptons only

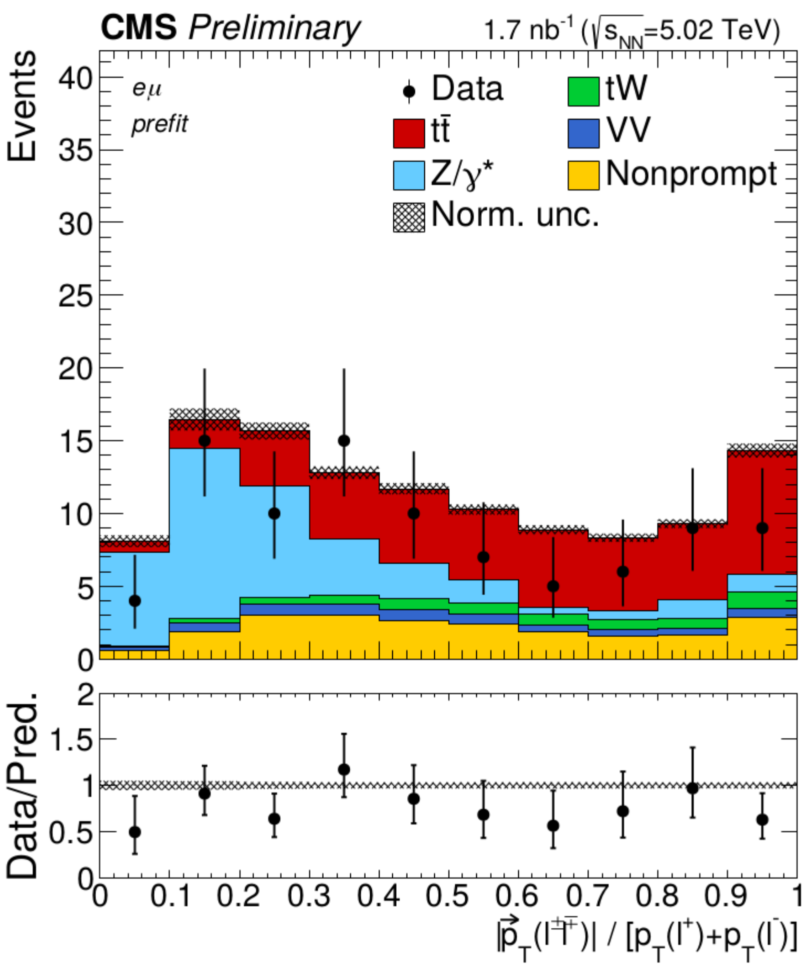
- Use the kinematics of the two leading-p_T leptons to train a BDT

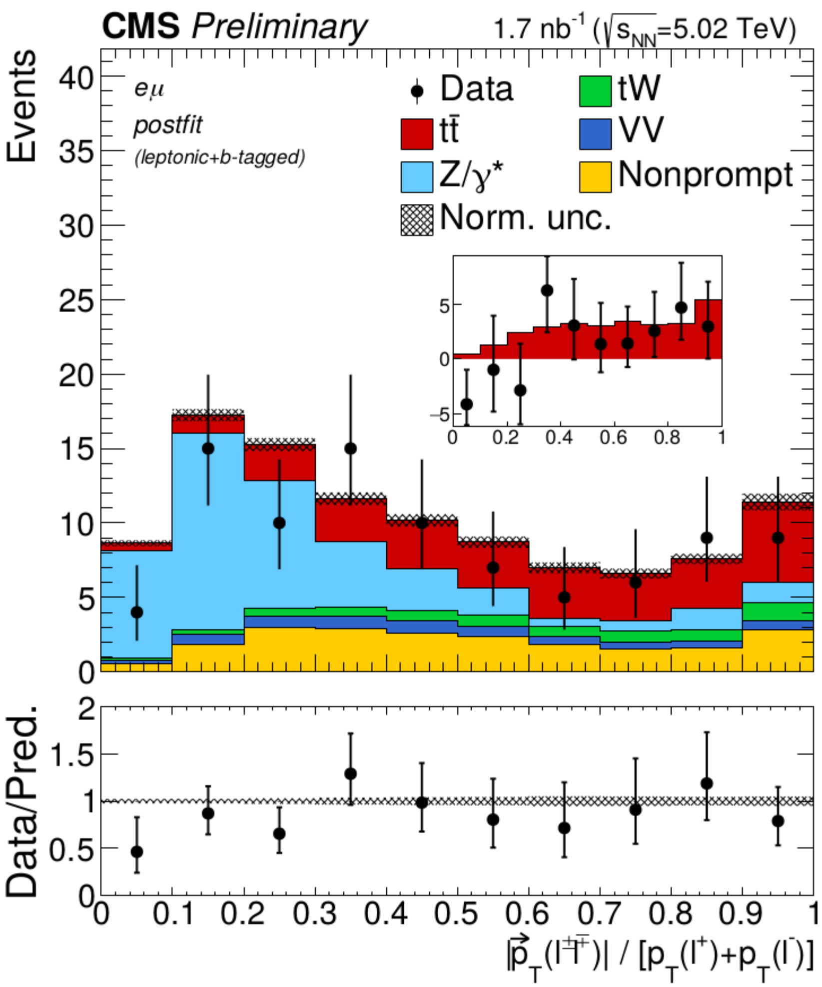
- $p_T(\ell_1)$, the p_T of the highest-p_T lepton,
- A_{p_T}, the asymmetry in the lepton-p_T's, namely $\frac{p_T(\ell_1)-p_T(\ell_2)}{p_T(\ell_1)+p_T(\ell_2)}$,
- $p_T(\ell\ell)$, the p_T of the dilepton system,
- $|\eta(\ell\ell)|$, the absolute η of the dilepton system,
- $|\Delta\phi(\ell\ell)|$, the absolute value of the separation in ϕ of the two leptons, and
- $\Sigma|\eta_i|$, the sum of the absolute η's of the leptons.



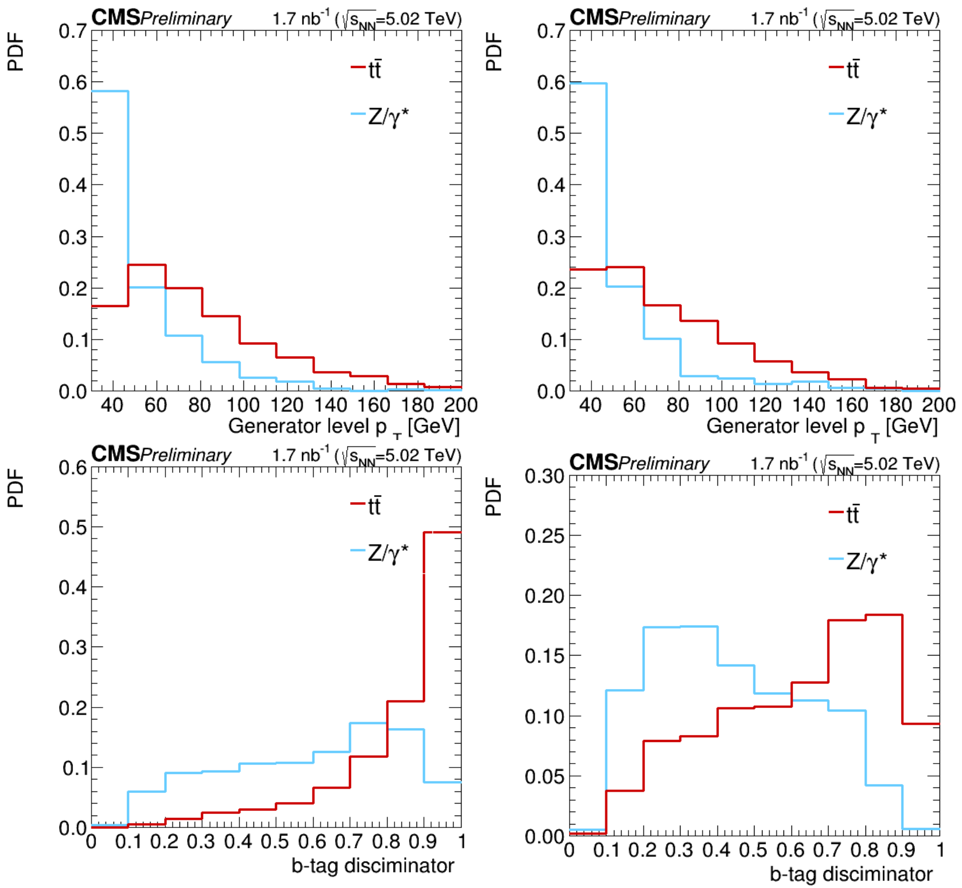


Dilepton sphericity: prefit (left) and postfit (right)





GEN and RECO level b jet distributions



Distributions for the two reconstructed jets with highest b-tag discriminator value in tt and DY simulations. The generator level transverse momentum is shown on the top, while the b-tag discriminator is shown on the bottom. The left (right) distributions correspond to the best (second-best) ranked jet in the b-tag discriminator.

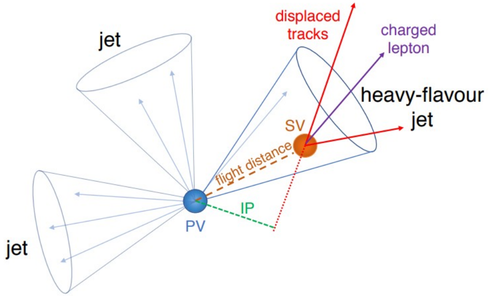
Fit procedure

- A profile likelihood method is used to extract the signal strength
- Systematic uncertainties are encoded as nuisance parameters
  - Log-normal for rate-related or Gaussian nuisances for shapes
- Experimental
  - Luminosity
  - centrality/p_{T}/η-dependent trigger/ID/isolation scale factors
  - Nonprompt normalization based on same-sign data counts
  - Shape statistical uncertainties (Barlow-Beeston)
- Theory
  - Nuclear PDFs/QCD scales
  - Top p_T based on pp prescription
  - Δmt=±1 GeV
  - Z p_T modeling based on data/MC uncertainty

Identification of heavy-flavour jets

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

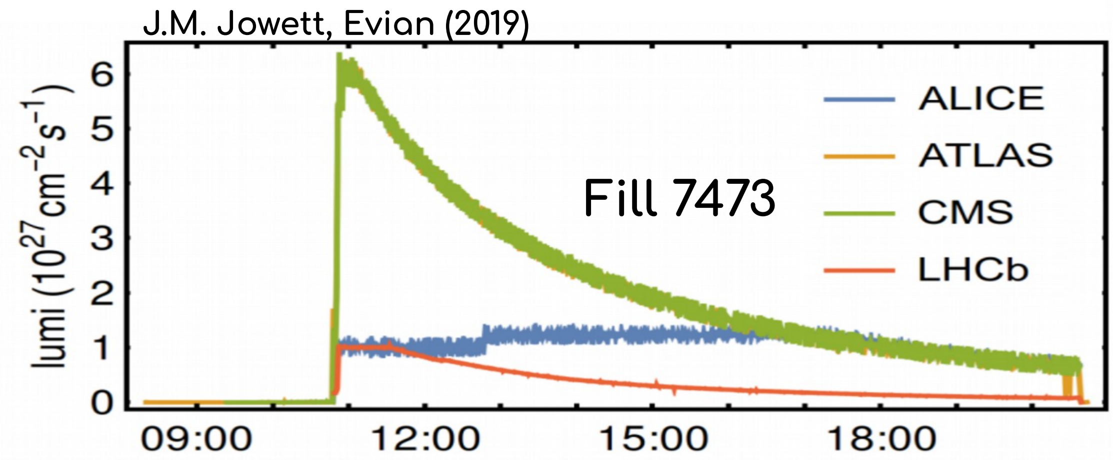
Input variable	Run 1 CSV	CSVv2
SV 2D flight distance significance	x	x
Number of SV	—	x
Track η_{rel}	x	x
Corrected SV mass	x	x
Number of tracks from SV	x	x
SV energy ratio	x	x
ΔR(SV, jet)	—	x
3D IP significance of the first four tracks	x	x
Track $p_{\mathrm{T,rel}}$	—	x
ΔR(track, jet)	—	x
Track $p_{\mathrm{T,rel}}$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

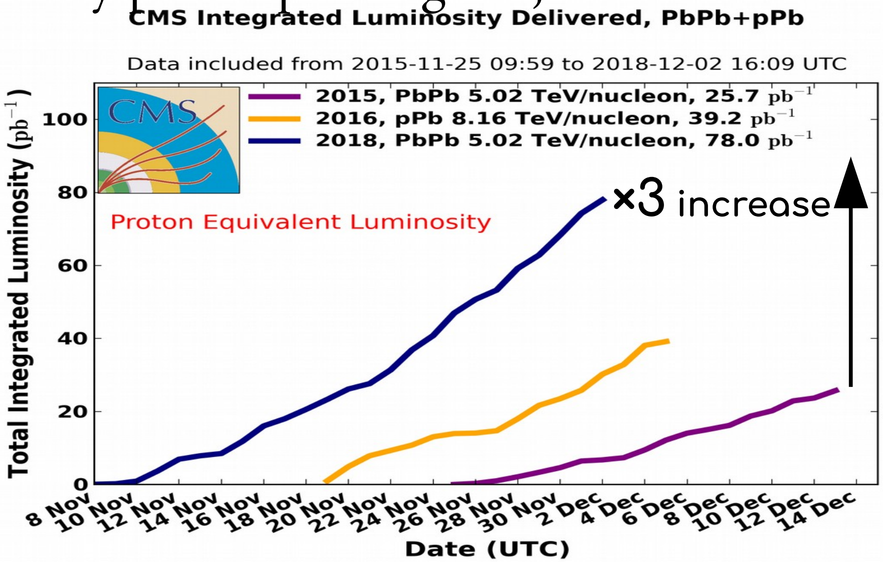


JINST 13 (2018) P05011

Surpassing the baseline luminosity goals

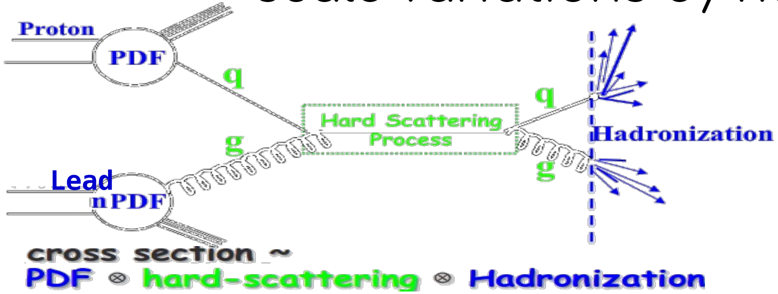
- LHC collided more types of beam, than originally foreseen, with better performance
  - In practice, we've come close to the "HL-LHC" performance with PbPb and pPb collisions
    - In 2018 the peak luminosity at IP1/5 reached ×6 the design **without** magnet quenches
- Opens up further opportunities for high-density QCD studies
  - For probes **not accessible** so far due to lower luminosity or energy
    - **All** 4 experiments participate → complementary phase space regions, cross checks



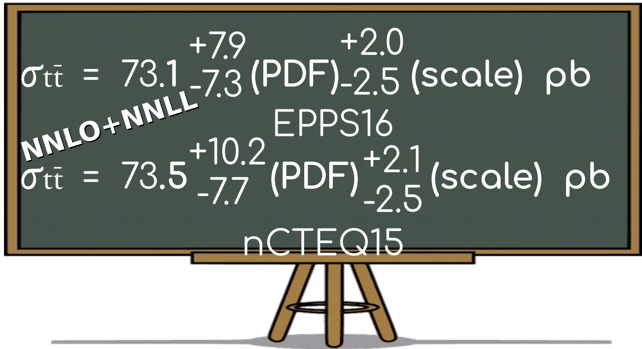


Theoretical setup for cross section calculation

- Rely on the two fundamental concepts of QCD
  - **factorization** (calculable) and **universality** (input from PDFs)
    - $\sigma_{AA} = A \times A \times \sigma_{pp}$
- **top++**(v2.0) NNLO+NNLL calculator with state-of-the-art (n)PDFs
  - bound nucleons' PDF: **EPPS16 NLO** ; baseline free proton PDF: **CT14 NLO**
    - nPDF net effects result in a small +6% modification (**R_{PbPb}**) of σ_{tt}
  - nPDF⊗ PDF uncertainty from the provided 56+40 eigenvalues → **10%**
  - full calculation repeated with **nCTEQ15**
    - considering the 33 error sets
  - QCD scales choice: $\mu_R = \mu_F =$ **172.5** GeV
    - scale variations by halving/doubling the μ_R, μ_F



@ $\sqrt{s_{NN}}$=5.02 TeV



Key characteristics of the latest fits of nPDFs (in chronological order from left to right)

arXiv:1704.04036

	EPS09	DSSZ12	KA15	nCTEQ15	EPPS16
Order in α_s	LO & NLO	NLO	NNLO	NLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan dilepton π+A					✓
LHC p+Pb jet data					✓
LHC p+Pb W, Z data					✓
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	17	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	not given	35	52
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavor separation				some	✓
Reference	[JHEP 0904 065]	[PR D85 074028]	[PR D93, 014026]	[PR D93 085037]	[EPJ C77 163]

$$\chi^2_{\rm global} \approx \chi^2_0 + \sum_{i,j} (a_i - a_i^0) H_{ij} (a_j - a_j^0) = \chi^2_0 + \sum_i z_i^2$$

Hessian matrix

Parameter variations

arXiv:1704.04036

90% CL defined by the global

As compared to the PDF fitting landscape

Ubiali, DIS2017

April 2017	NNPDF3.0	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1.645$	Hessian $\Delta\chi^2=1$
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR'	ACOT-χ	TR'	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

What HION questions could top production elucidate?

- What happens to the **gluon density** in nuclei?
- How the **confined** hadronic states emerge from partons?
  - **impact** of ~0.5 GeV* on the top mass (M_{top}) reconstruction
  - CR is **modified** in higher color charge density regimes wrt. to the vacuum
    - e.g., in pA/AA collisions with increased UE activity
- How color-charged partons, and colorless jets, interact with a **nuclear medium**?
  - measure the space-time evolution of the medium

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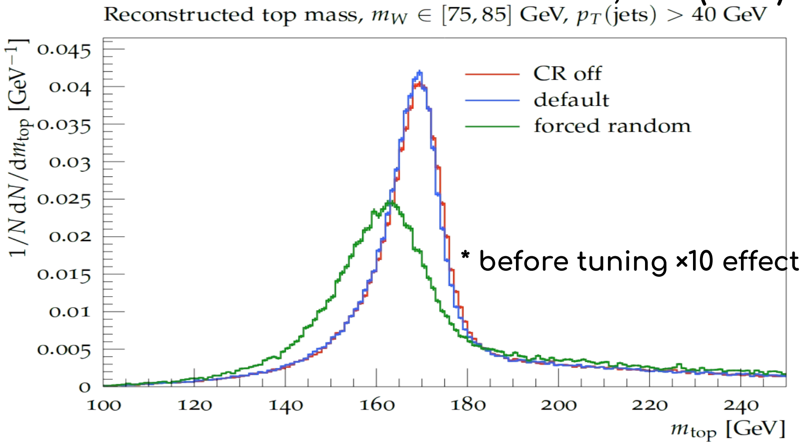

* before tuning ×10 effect

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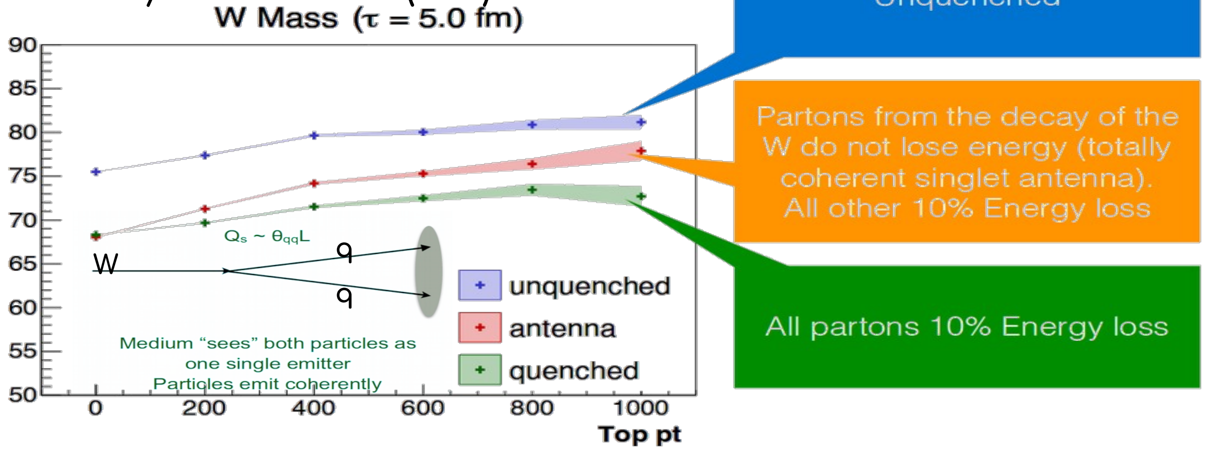
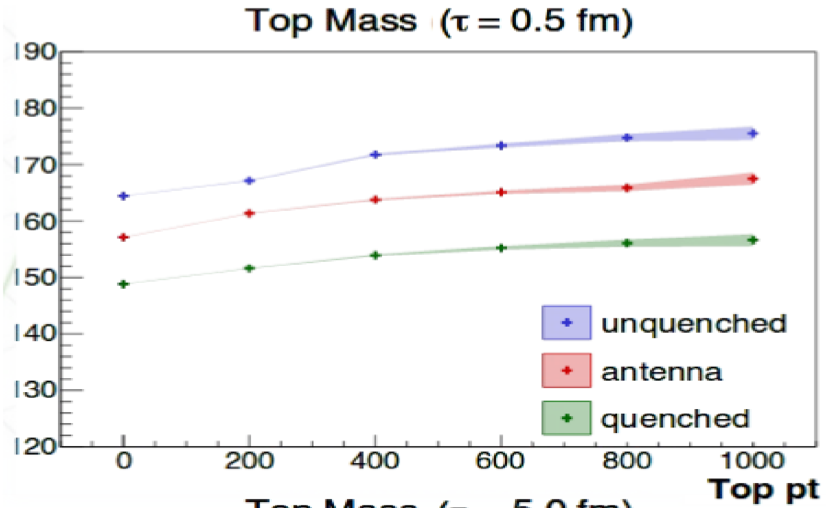
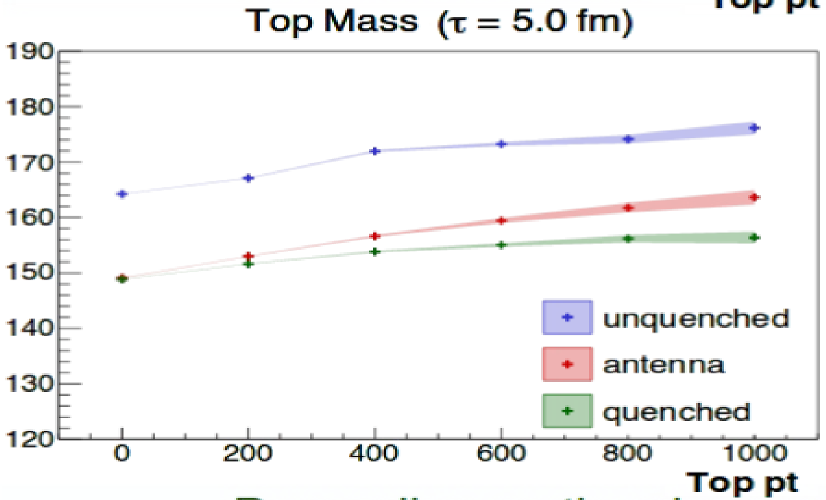


A tomography of **in-medium losses**

Idea for a perfect yocto-chronometer!





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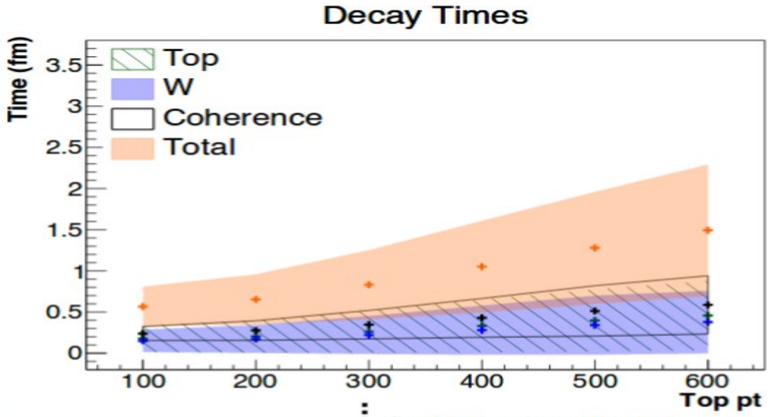
L. Apolinário et al. 4th HIN Jet WKSH



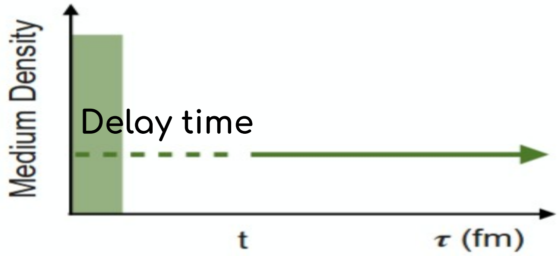
→ Not enough statistics...

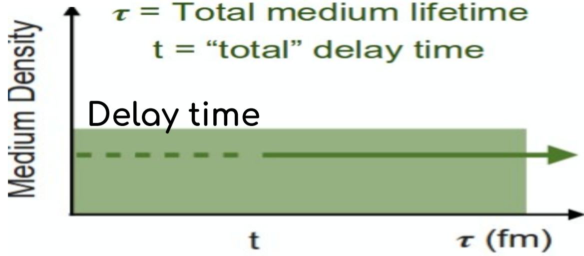
Probe ~ [0.4; 1.2] fm

$\Delta E/E = [(\tau - t)/\tau] * 0.1$

τ = Total medium lifetime

t = "total" delay time

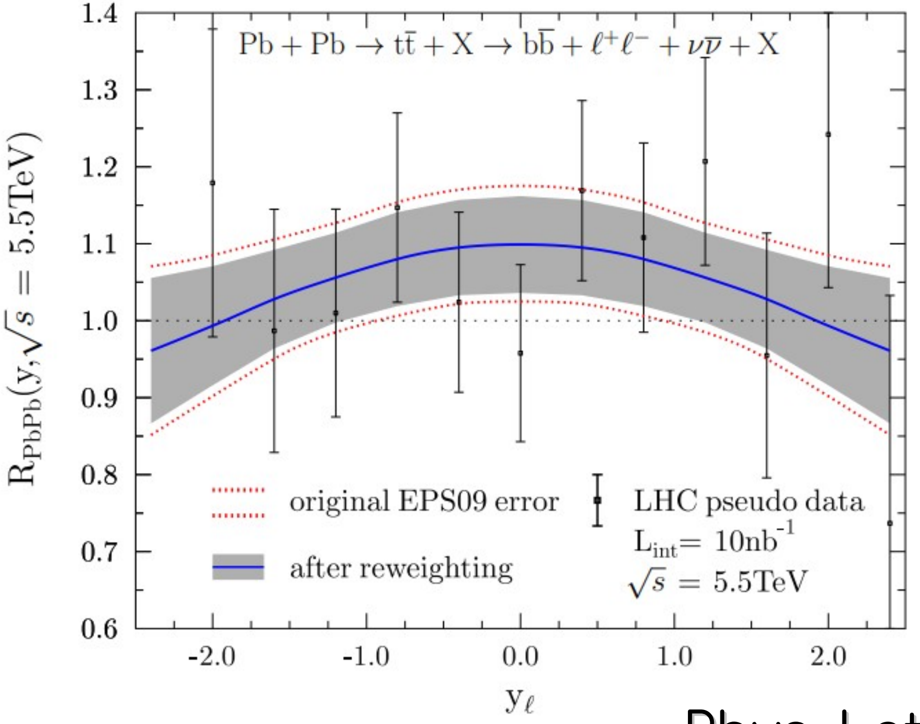


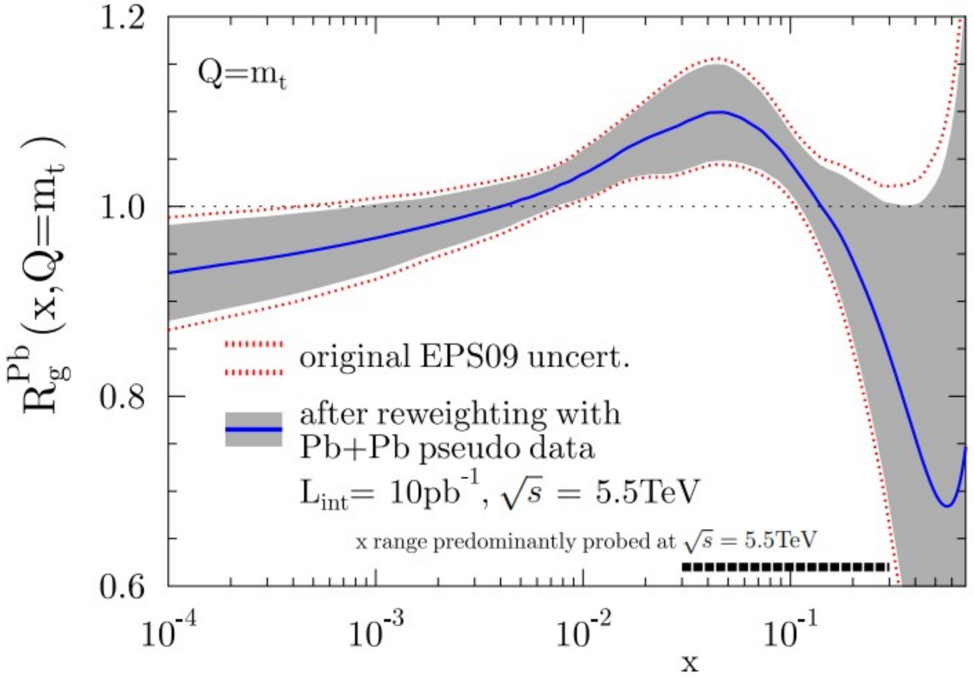


Depending on the chosen p_T, the antenna may still lose some energy.

Knowing the energy loss, it is possible to build the density evolution profile of the medium!

The R_{PbPb} differentially





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- Nuclear modification factor R_{PbPb} for tt production in the dilepton channels with the central PDF sets of CT10+EPS09 as a function of lepton rapidity