Top quark evidence in PbPb collisions at $\sqrt{(s_{NN})}$ = 5.02 TeV in CMS

Inna Kucher

Laboratoire Leprince-Ringuet

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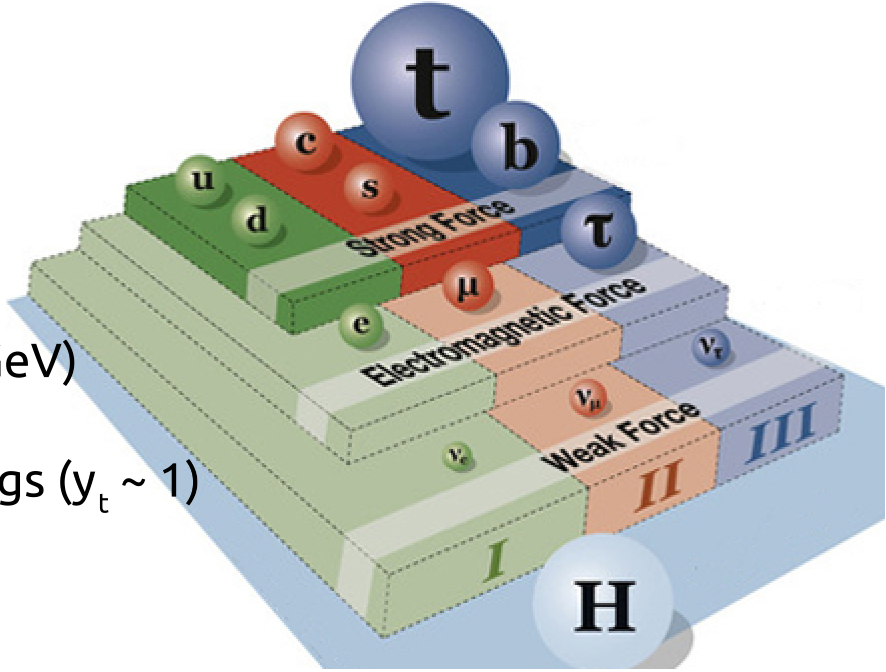
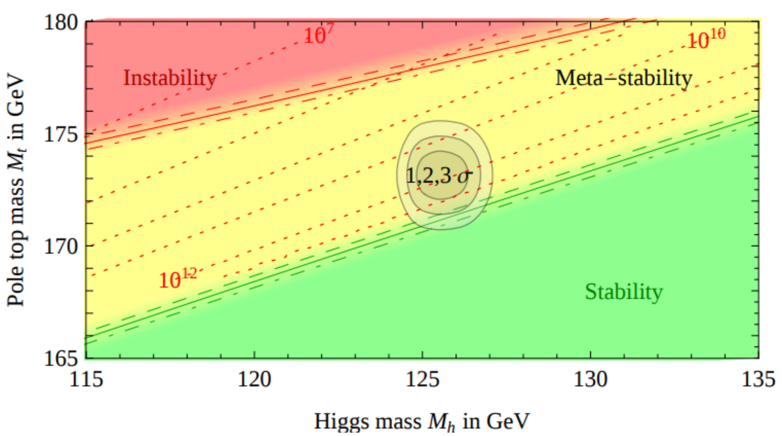
Top quark

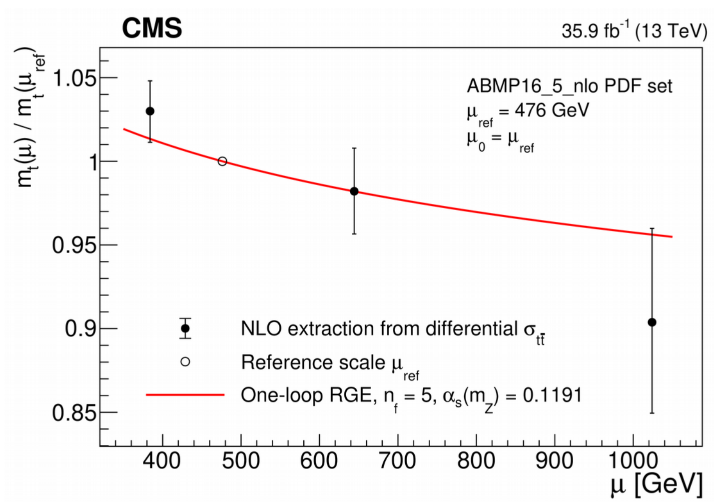
- $SU(2)_L$ partner of the bottom quark
- discovered at Tevatron in $p\bar{p}$ collisions in 1995
- the heaviest known fundamental particle (m_t ~ 173 GeV)
- the only quark with the “natural” coupling to the Higgs (y_t ~ 1)
- the only quark which decays before hadronization

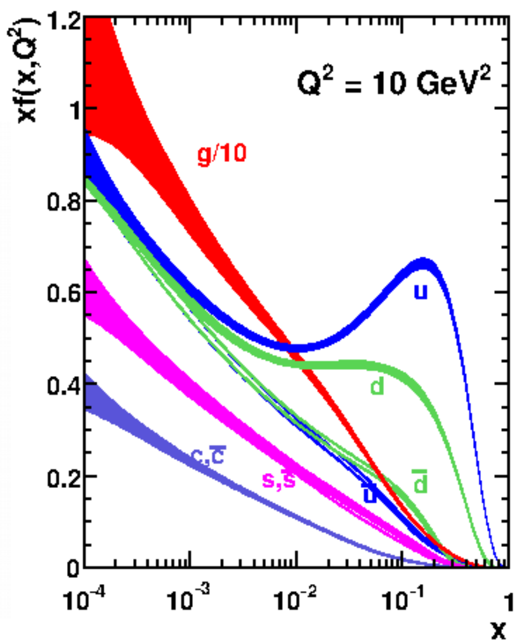


Why do we care about top quark?

- probe the smallest space-time distances (2-3 orders smaller than QCD processes)
- SM tests : e.g. EWK vacuum stability, top quark “running” mass, top Yukawa coupling, …
- gluon parton distribution functions (PDFs) with the large Bjorken x
- popular portal for new physics searches, as it is the largest contributor to loops





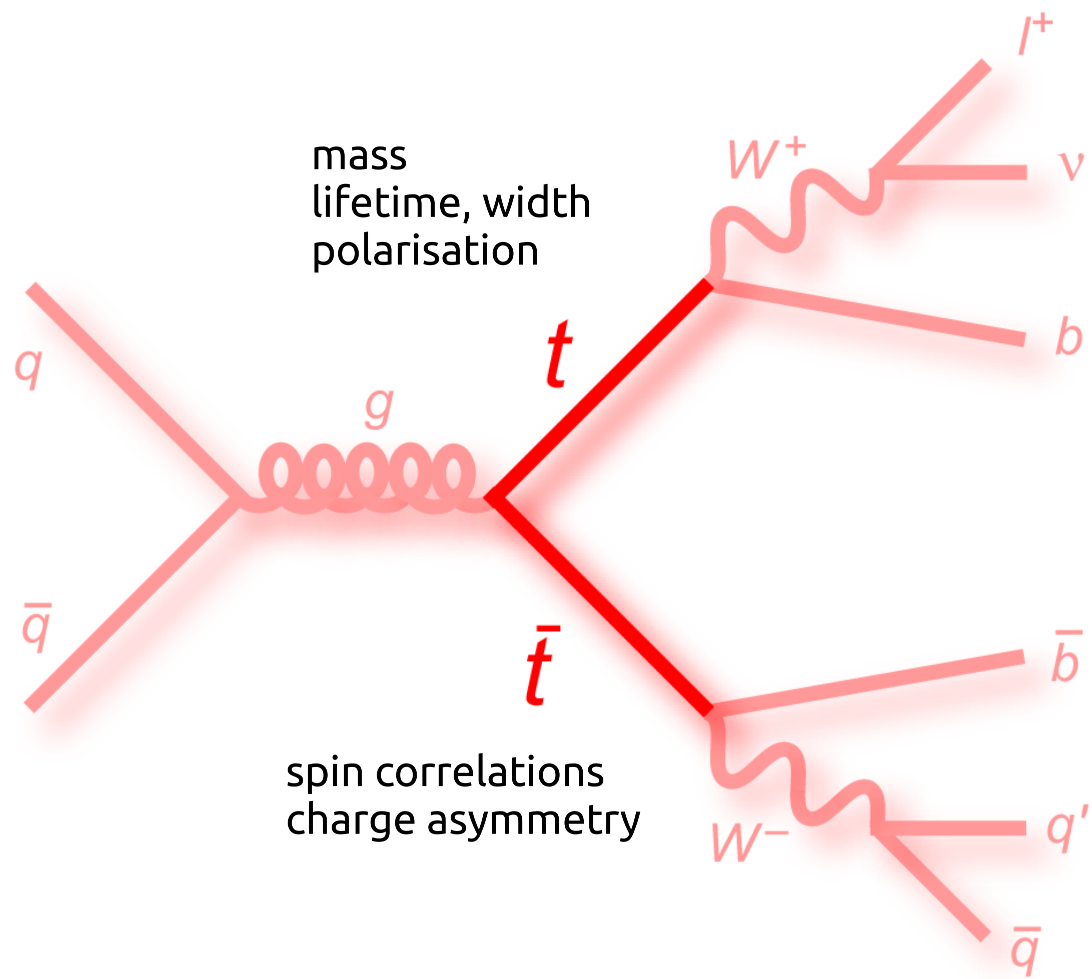


Top quark production in p$\bar{p}$/pp collisions

W helicity

mass
lifetime, width
polarisation

production cross section
production kinematics
resonances, new particles



spin correlations
charge asymmetry

BR(tWb)/BR(tWq)
new decays

Tevatron : $q\bar{q} \rightarrow t\bar{t}$ (~85%) + $gg \rightarrow t\bar{t}$ (~15%)

LHC : $q\bar{q} \rightarrow t\bar{t}$ (~15%) + $gg \rightarrow t\bar{t}$ (~85%)

BR ($t \rightarrow Wb$) ~ 100%

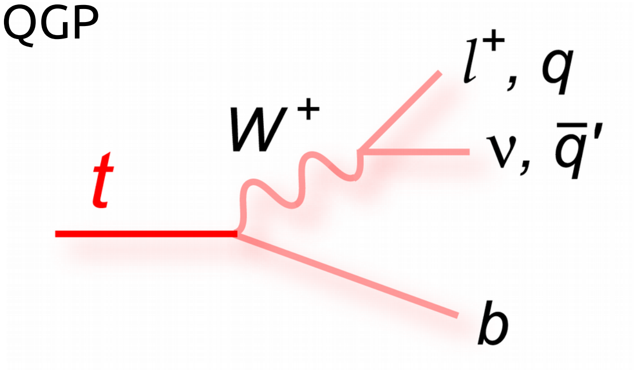
Why do we care about top quark in Heavy Ions?

- Heavy Ion collisions : tool to investigate nuclear matter at extreme energy density – Quark Gluon Plasma (QGP)
- nuclear PDFs (nPDFs) [link] : constraints from pPb collisions at LHC (along w/ W,Z, dijets)
- top cτ ~10^{-24}s , QGP lifetime ~10^{-22}s → top decays within the QGP
- LHC timeline :

  → partons traversing the QGP lose their energy :

  jet energy loss with b-jets

  → $t\bar{t}$ is very important process for precise b-tagging calibrations (as in pp collisions)

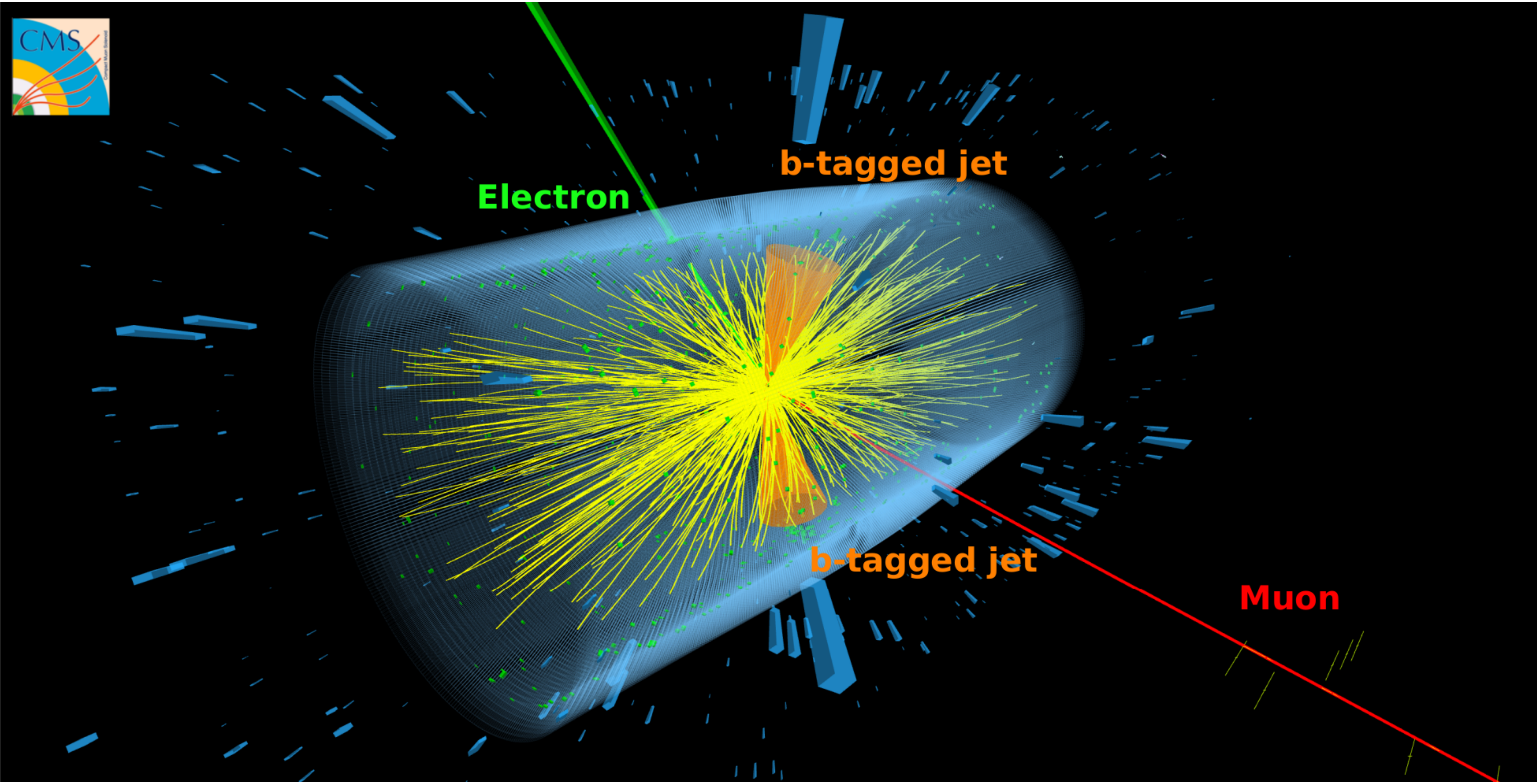


- FCC prospects [link] :

  → top quarks "at rest" decay before the QGP is formed

  → boosted top quarks live longer than formation time → scan QGP space-time evolution

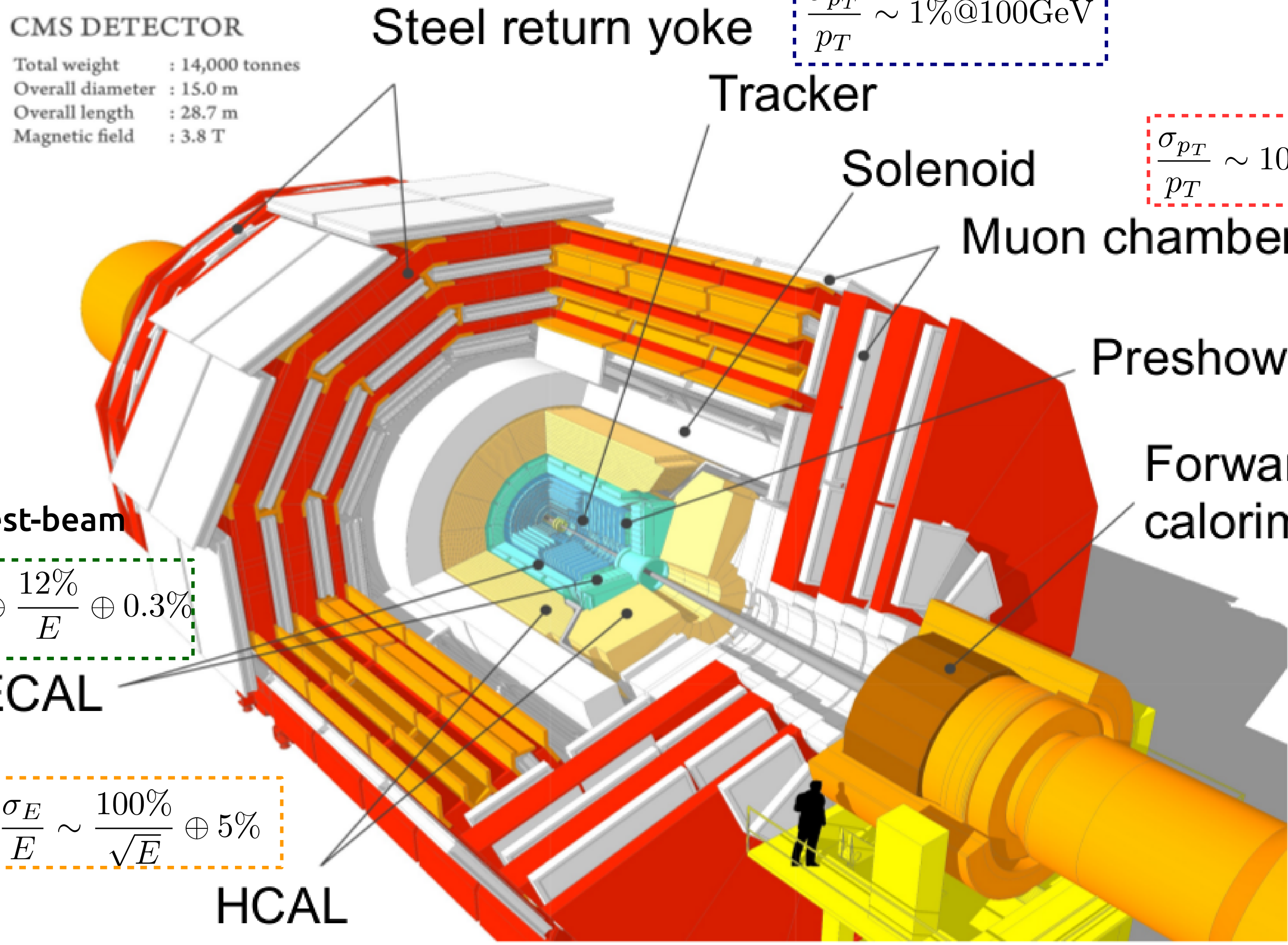
Top quark candidate in PbPb 2018 collisions



PbPb environment is much busier than pp one

(track multiplicity is ~ 10k in PbPb vs pp ~ 750)

CMS detector



$$\frac{\sigma_{p_T}}{p_T} \sim 1\%@100\mathrm{GeV}$$

$$\frac{\sigma_{p_T}}{p_T} \sim 10\%@1\mathrm{TeV}$$

From the test-beam

$$\frac{\sigma_E}{E} \sim \frac{2.8\%}{\sqrt{E}} \oplus \frac{12\%}{E} \oplus 0.3\%$$

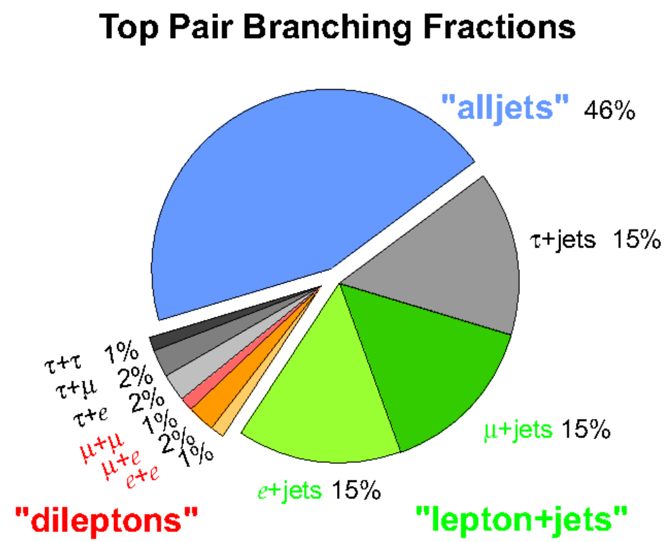
$$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 5\%$$

Pseudorapidity:

$$\eta = -\ln\left[\tan(\frac{\theta}{2})\right]$$

All subsystems are necessary to detect top quark decay particles

Analysis strategy



Fully leptonic decays of $t\bar{t}$ pair : $\mathbf{t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}}$

→ highest purity
→ small BR

Two analysis approaches :

1) Only lepton information : $\mathbf{t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}}$
2) Lepton + b-jet information : $\mathbf{t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}}$

Lepton only analysis : insensitive to b-jet quenching

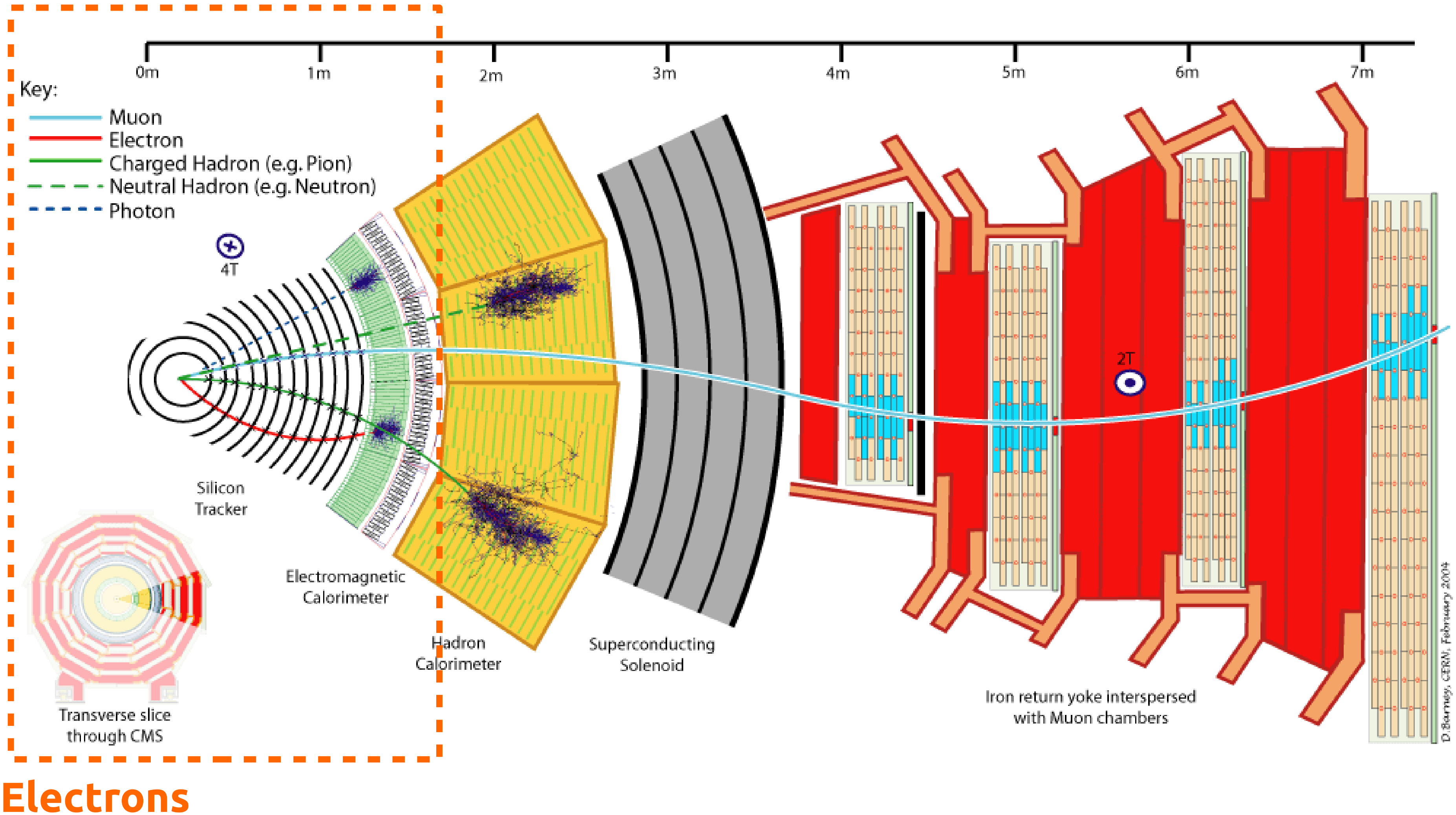
Backgrounds :

- ee/μμ : DY+jets (DY = ll' pairs coming from Z or γ*)
- eμ: Z→ ττ, W+jets, QCD multi-jets with heavy flavor decays
- Small contributions from tW, ZZ, WW

Analysis was blinded to the mass region of interest in data

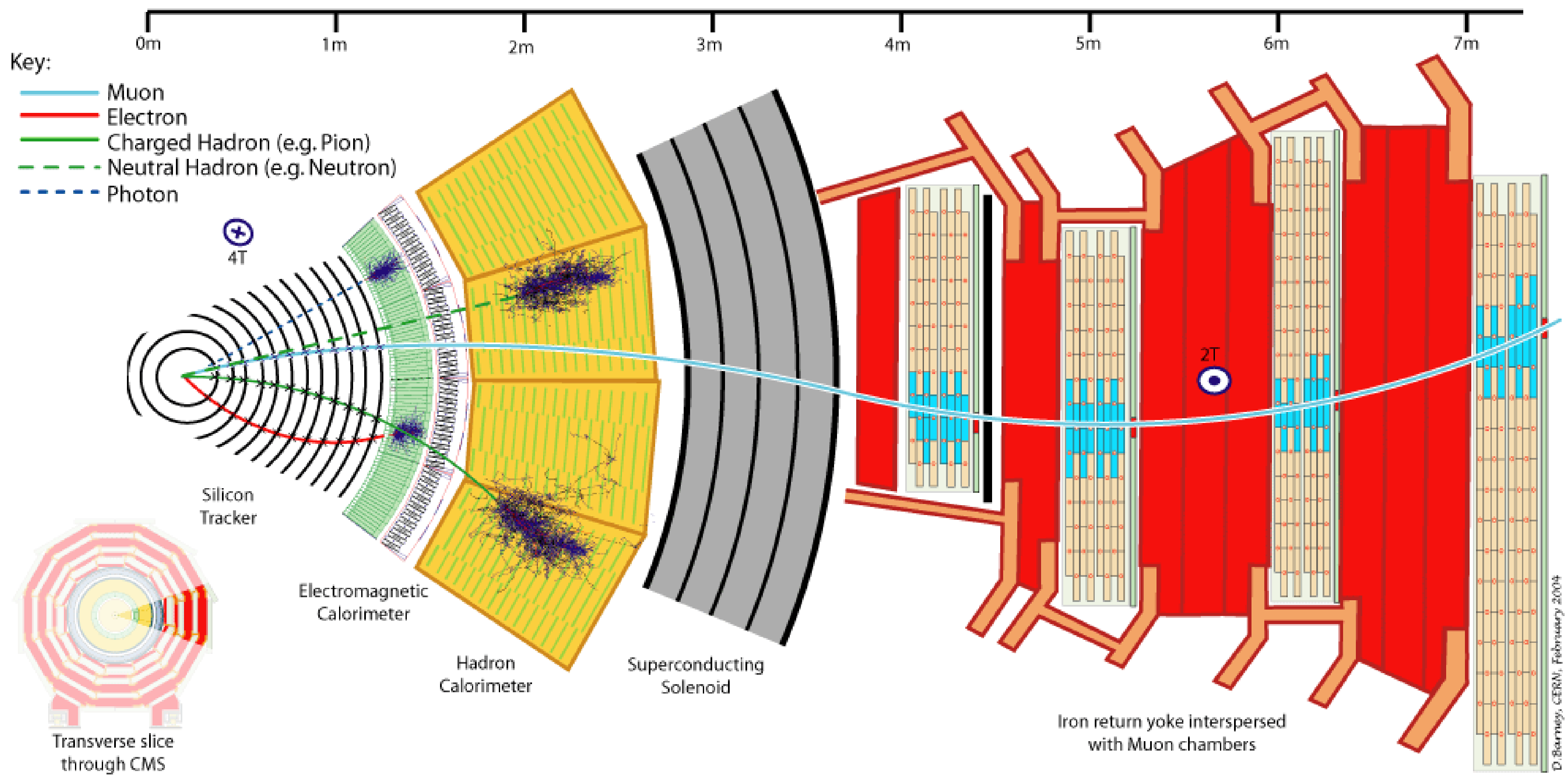
Electron reconstruction

Electron (e) reconstruction : combines tracker and ECAL information



Muon reconstruction

Muon (μ) reconstruction : combines tracker and muon stations information



Muons

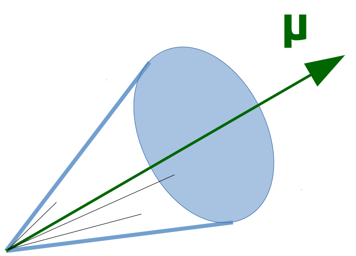
Lepton reconstruction and identification

Muon (μ) reconstruction : combines track and muon stations information

Electron (e) reconstruction : combines track and ECAL information

μ/e identification and selections :

→ identification criteria were optimized for PbPb environment



→ isolation criteria :

$I_{rel} = [I - UE(\rho)]/p_T$; $I - p_T$ sum of all particles inside the cone around the μ/e direction
$UE(\rho)$ - median energy density of the underlying event

$I_{rel} < 0.08$ (-0.06) for μ(e)

→ kinematic selections : $p_T > 20$ (25) GeV and $|\eta| < 2.4$ (2.1) for μ(e)
→ μ and e are opposite charged

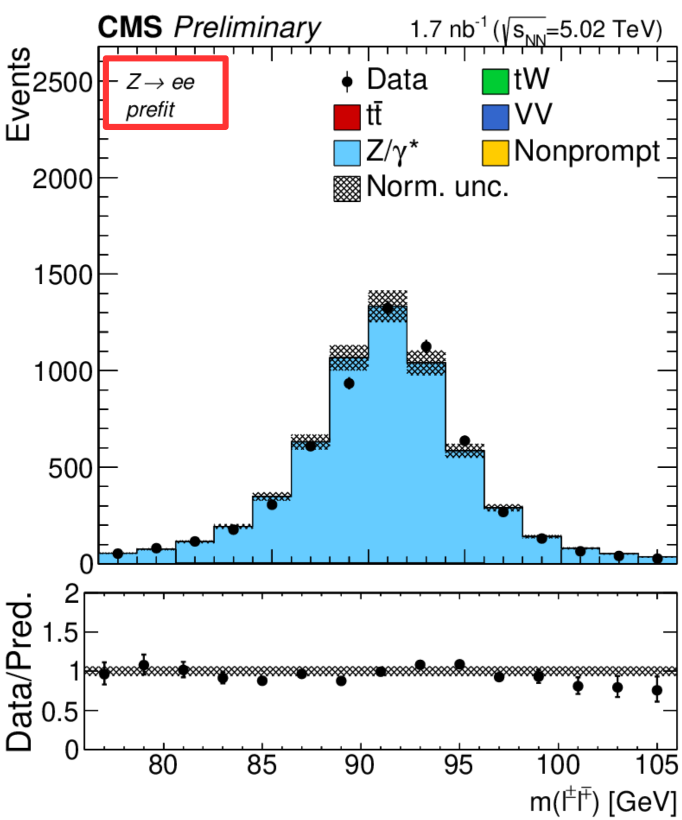
Dilepton mass

$t\bar{t} \to l\nu_l b \; l'\nu_{l'}\bar{b}$

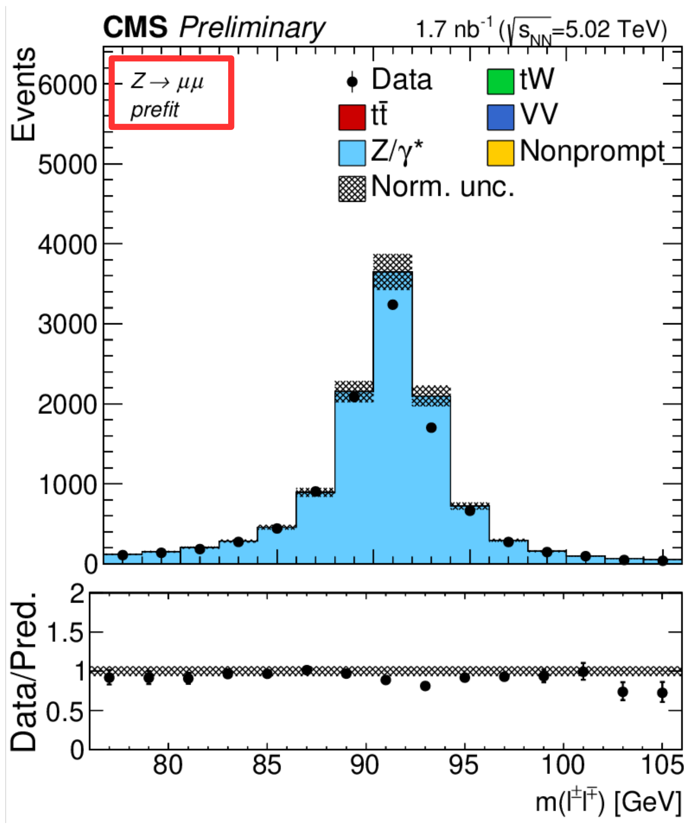
Three dilepton combinations are possible : ee, μμ, eμ

Distributions are **prefit** : MC represents the **expected** yields

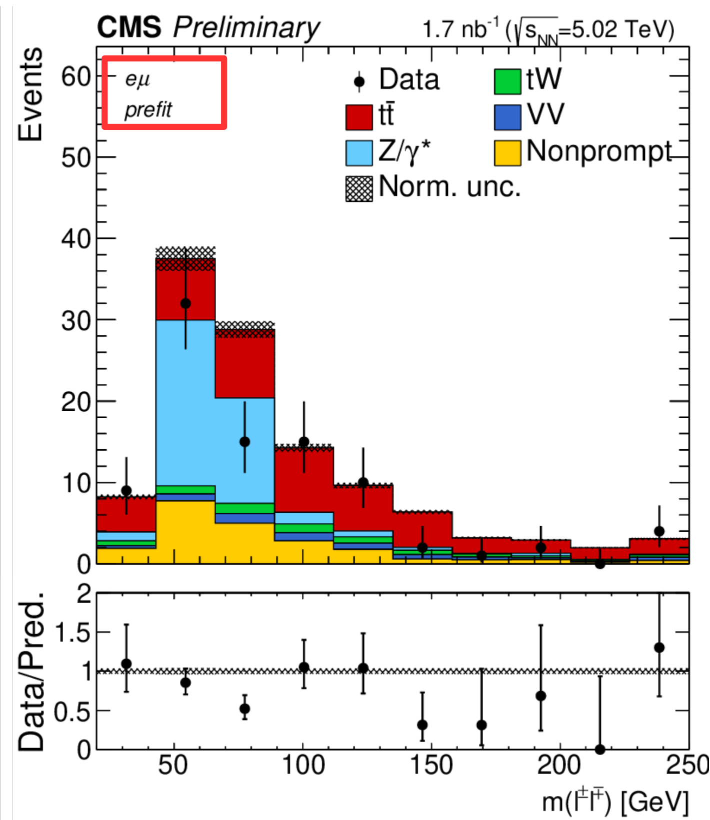
ee



μμ



eμ



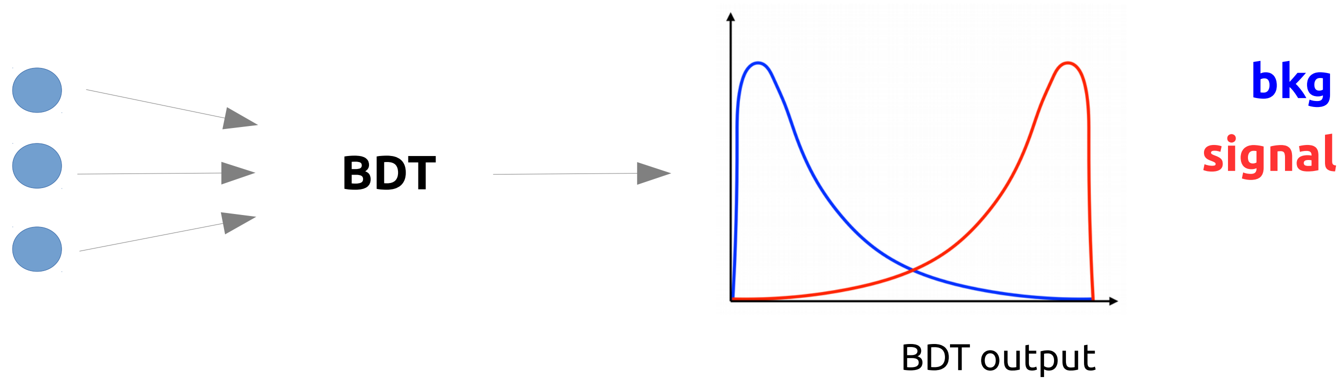
ee, μμ are dominated by Z boson production
To suppress Z : discard events with (76 < $m_{ll'}$ < 106 GeV)

eμ – the cleanest channel to extract $t\bar{t}$

BDT discriminant

$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}$

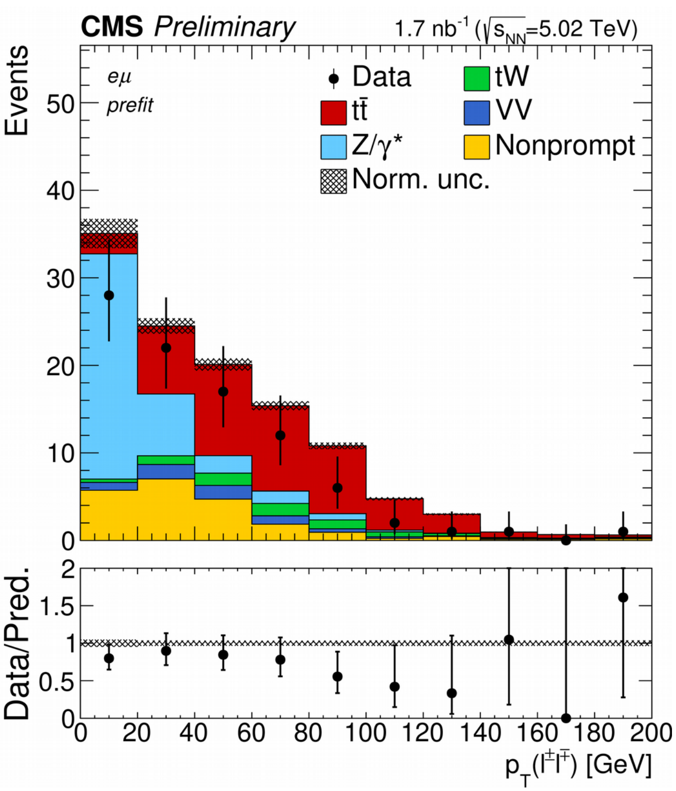
Boosted decision tree (BDT) algorithm - combines lepton information in one discriminant



Trained with signal = $t\bar{t}$ vs background = DY

Lepton information :

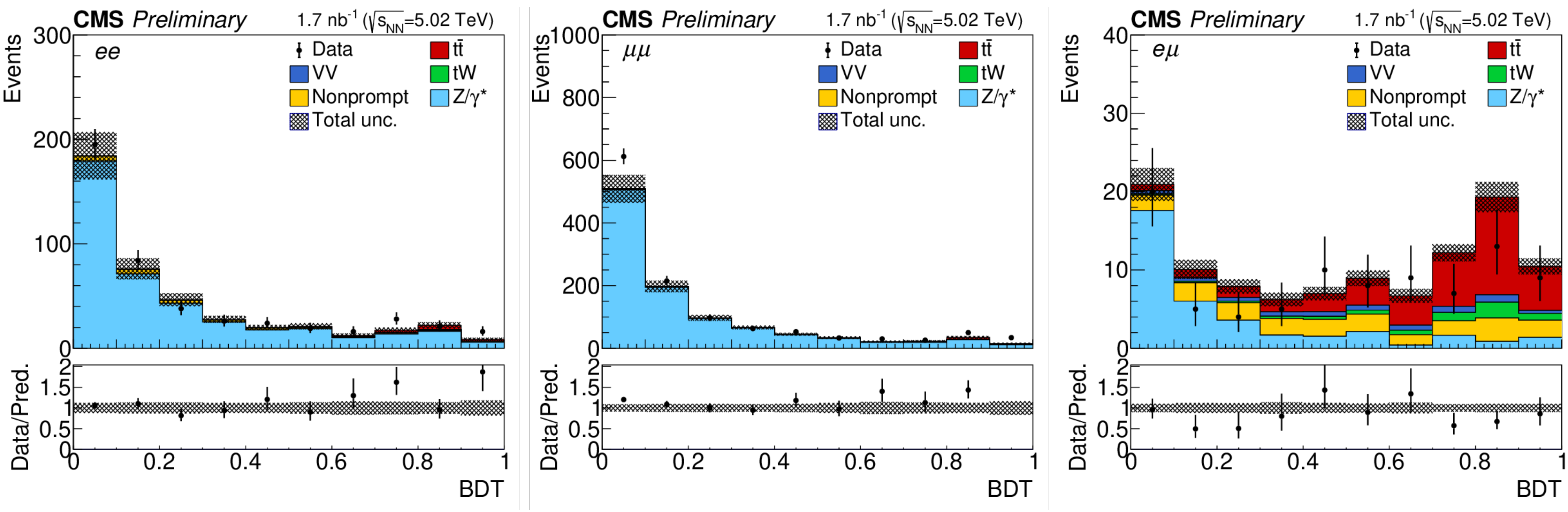
- leading lepton p_T
- momentum imbalance between leptons
- dilepton system p_T
- dilepton system $|\eta|$
- absolute azimuthal separation of the leptons
- scalar sum of the $|\eta|$ of the two leptons



BDT discriminant : pre-fit

$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'} \bar{b}$

ee μμ eμ

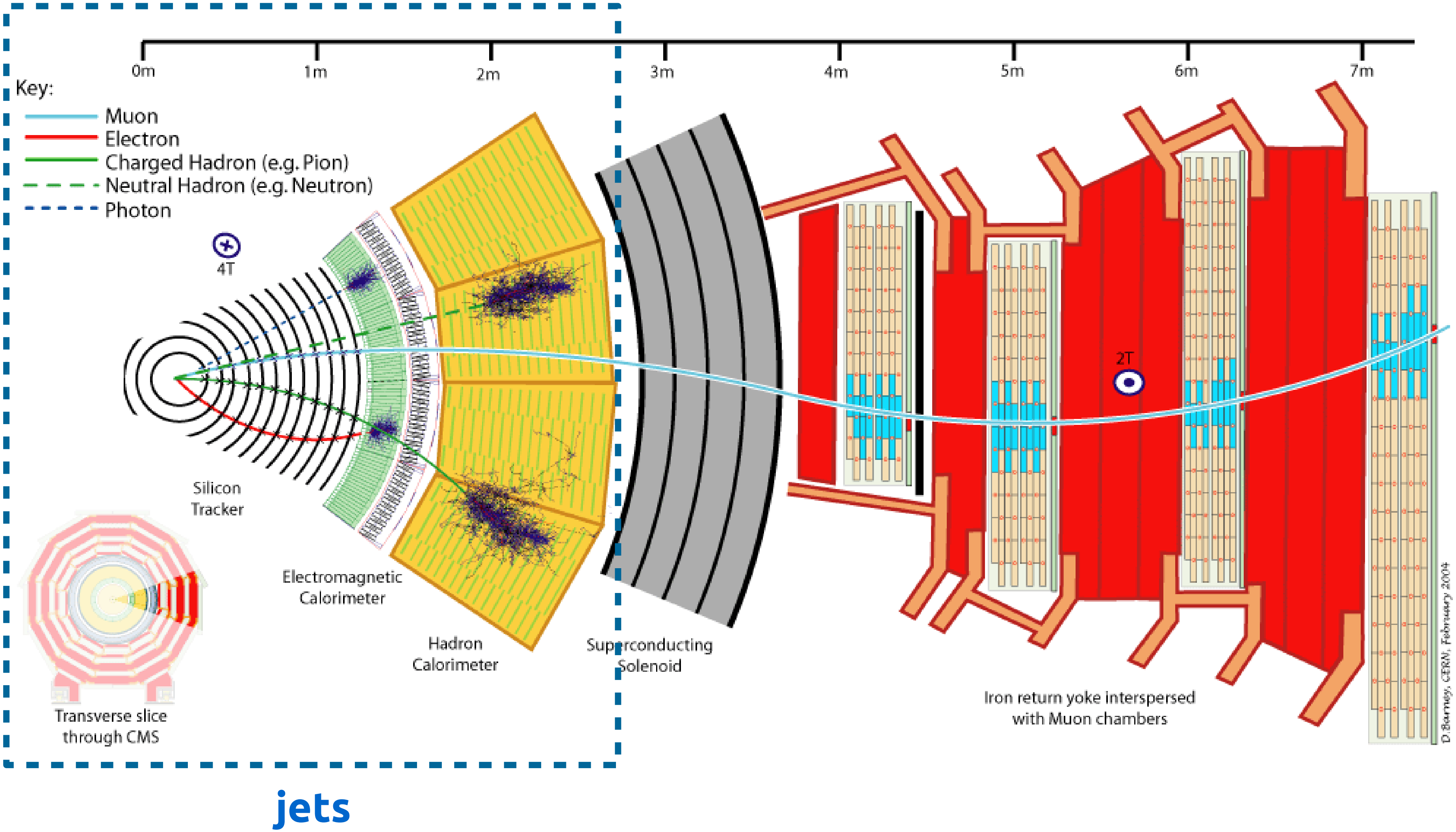


BDT discriminant : $t\bar{t}$ peaks at higher values of BDT ~ 0.8-1.0, DY peaks ~ 0

eμ channel : data points are lower than expectation

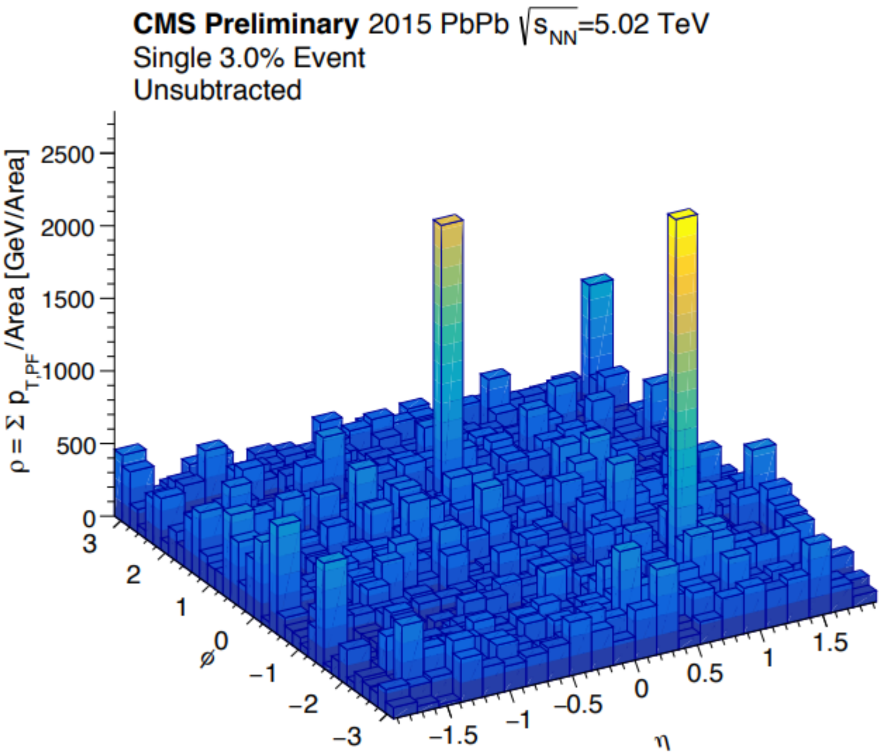
Jets in CMS

Jet reconstruction : combines tracker, ECAL and HCAL information

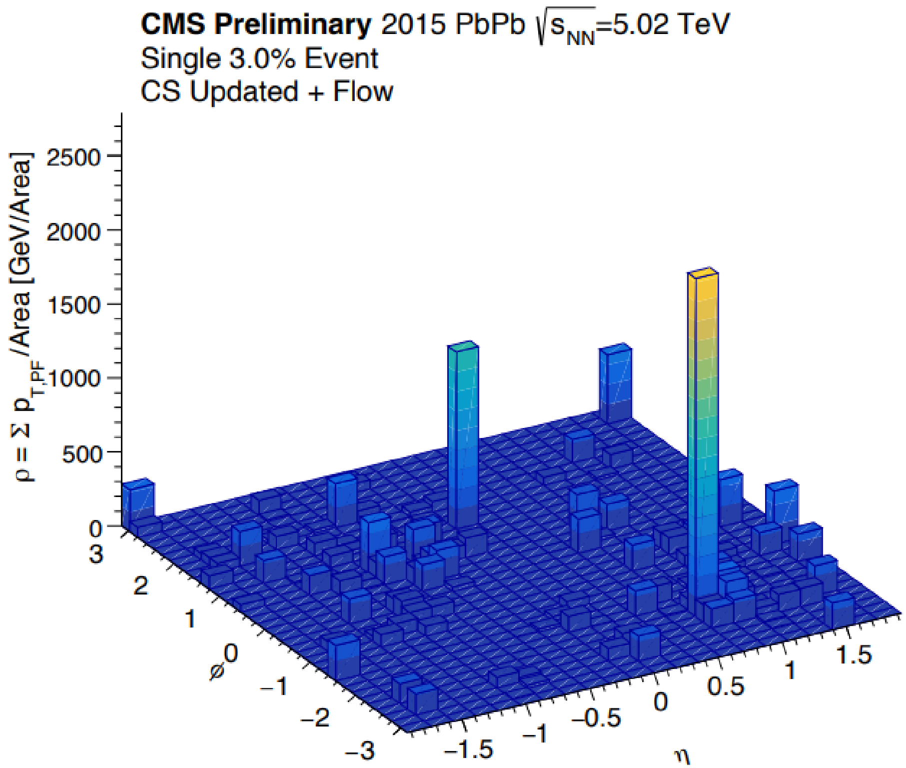


Jets in PbPb collisions

Before UE subtraction



After UE subtraction



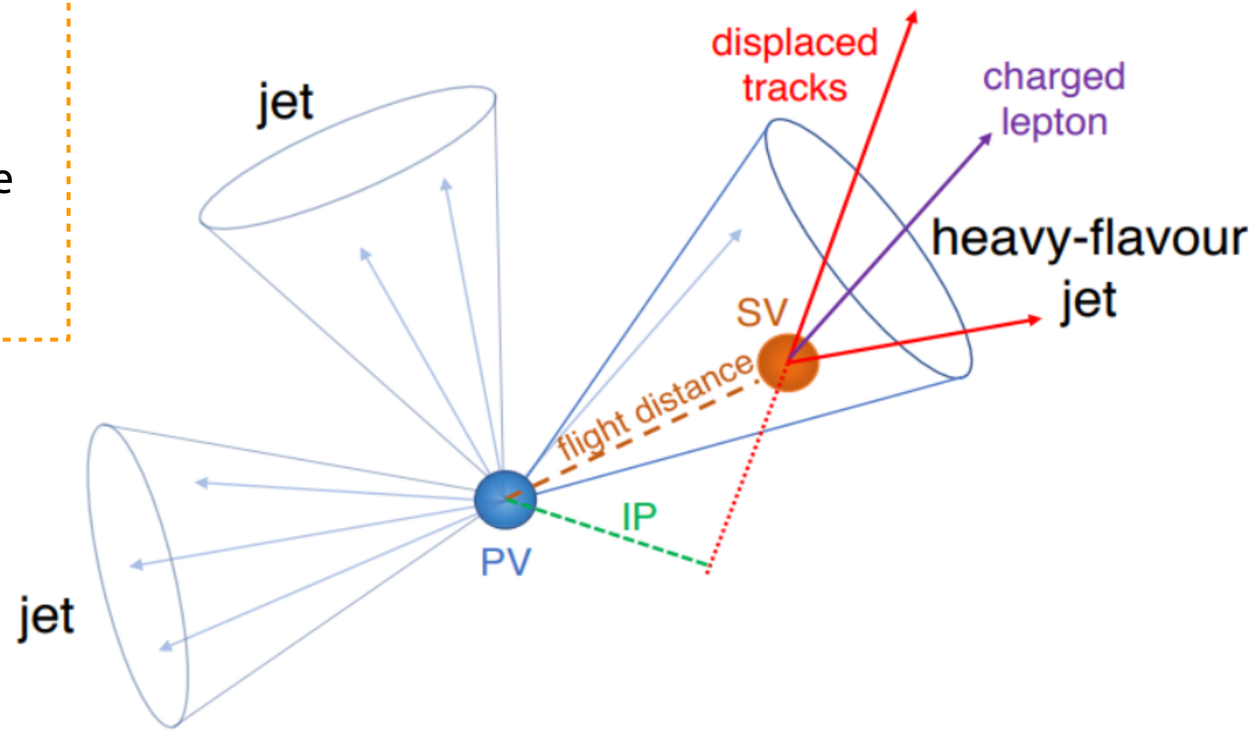
What amount of UE to subtract? How?

Particle-by-particle: correct the 4-momentum of a jet and substructure

b-jet identification

<u>B-hadrons</u>

- Fragment hard, zb ~ 0.7 – 0.8
- Large decay multiplicity, $\langle n_{ch} \rangle \sim 5$
- Long-lived hadrons cτ ~ 500 μm → mm – cm displacement in lab frame
- Tend to decay semi-leptonically (20% for μ and e)



Method : exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays

Method was re-optimized for PbPb environment

Lepton + b-jet analysis

$t\bar{t} \rightarrow l\nu_l b\ l'\nu_{l'}\bar{b}$

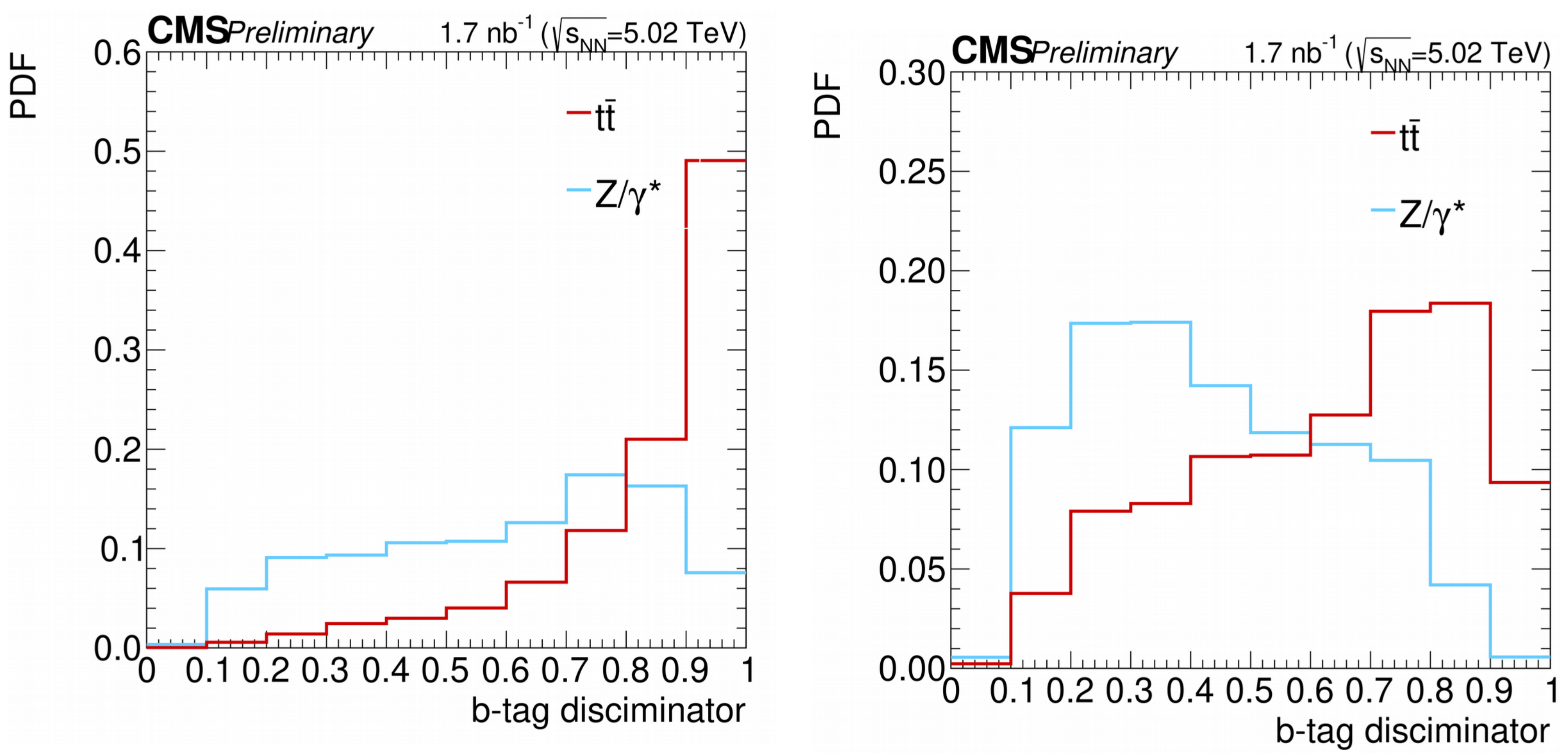
Requiring b-jets in the analysis improves expected $t\bar{t}$ significance.

b-jet treatment :

- all jets with p_T > 30 GeV and $|\eta|$ < 2.0 are sorted by b-tag discriminant values
- only two jets with the highest discriminant value are kept in the analysis
- events events are categorized in 0b, 1b,2b (all original events are kept)

Leading jet

Sub-leading jet

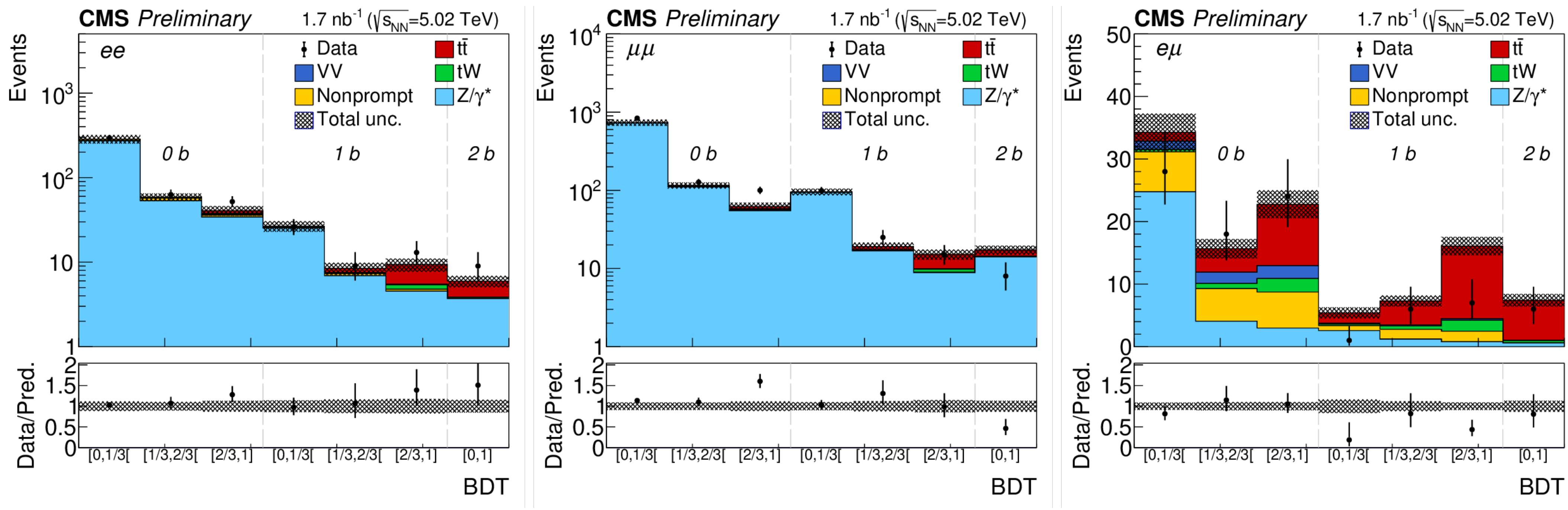


BDT pre-fit in lepton+bjet analysis

$t\bar{t} \rightarrow l\nu_l b\ l'\nu_{l'}\bar{b}$

BDT discriminant for 0b, 1b and 2b jets categories

ee μμ eμ



eμ channel : data points are lower than expectation
in the 1b and 2b categories, which have the highest S/B

BDT discriminant is an input for a statistical test : likelihood fit

Maximum likelihood method

Likelihood function: how theoretical assumption is compatible with observed data

Maximum likelihood method estimates the best values of the parameters to describe data

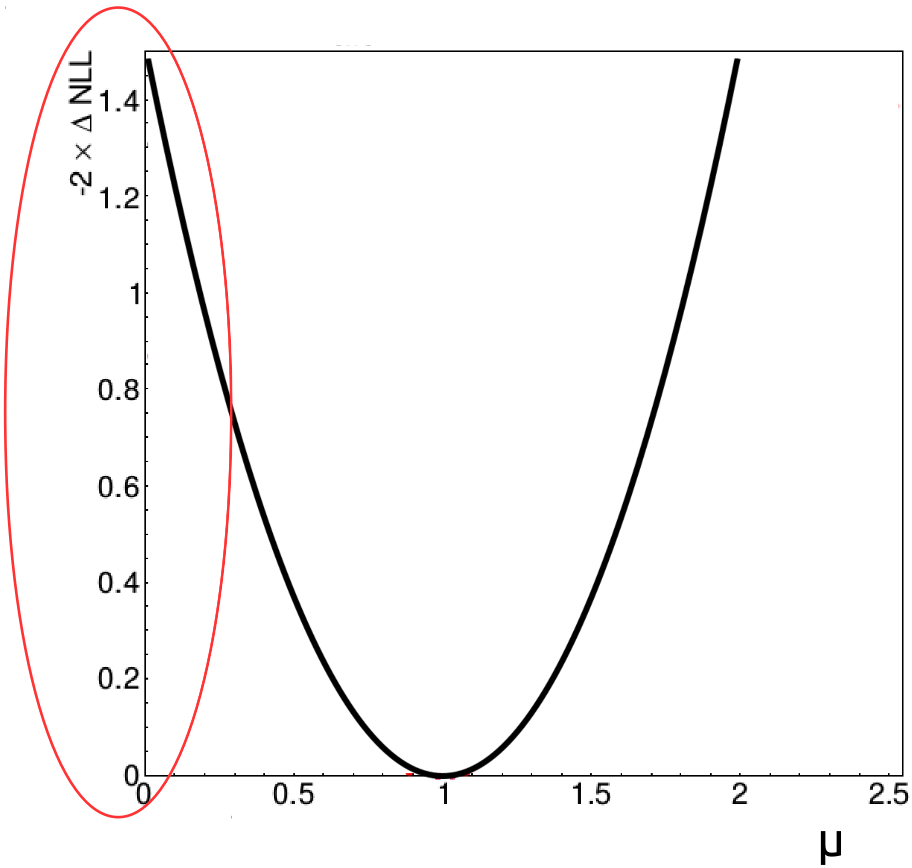
Parameters :

- Signal strength (μ)
- Signal contribution
- Background contribution
- Nuisance parameters

Significance (σ) of an excess over the background-only expectation : ratio at μ = 0

Expected : μ = 1 and $\sigma = \sigma_{exp}$

Profile likelihood ratio



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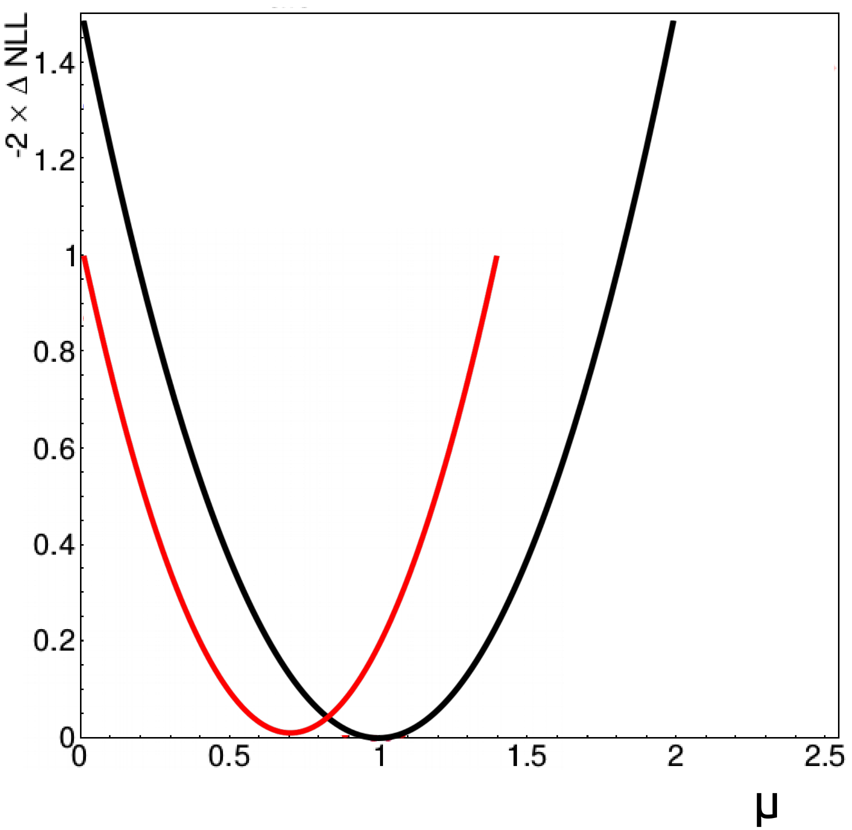
Significance (σ) of an excess over the background-only expectation : ratio at μ = 0

Expected : $\mu = 1$ and $\sigma = \sigma_{exp}$

Observed less signal than expected : $\mu < 1$ and $\sigma_{obs} < \sigma_{exp}$

Profile likelihood ratio



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Parameters :

- Signal strength (μ)
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- Background contribution
- Nuisance parameters

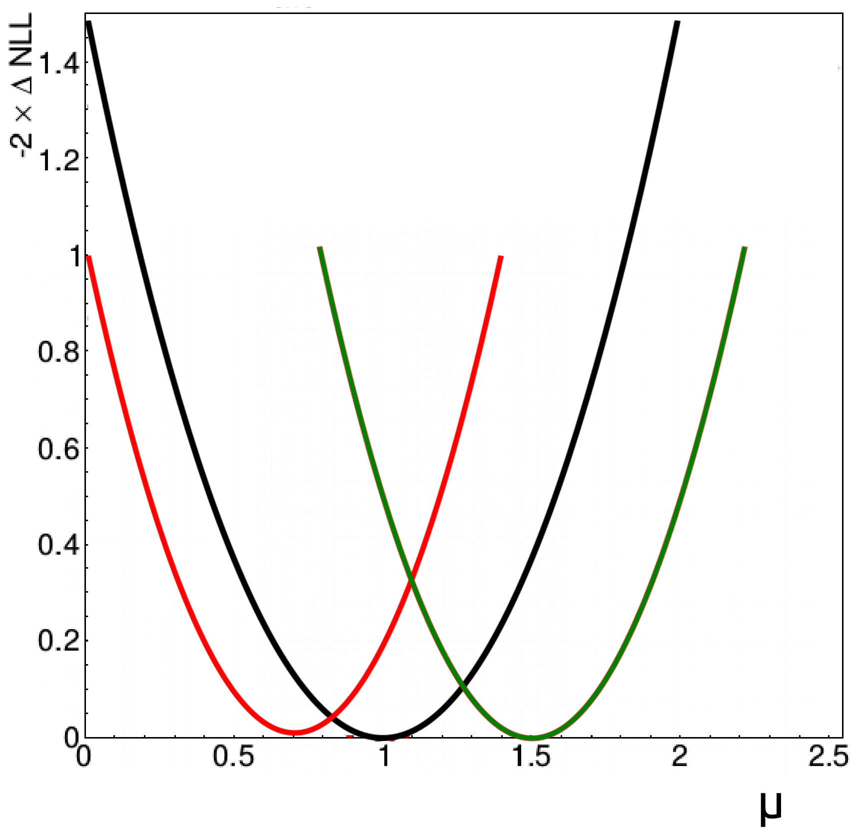
Significance (σ) of an excess over the background-only expectation : ratio at μ = 0

Expected : μ = 1 and $\sigma = \sigma_{exp}$

Observed less signal than expected : μ <1 and $\sigma_{obs} < \sigma_{exp}$

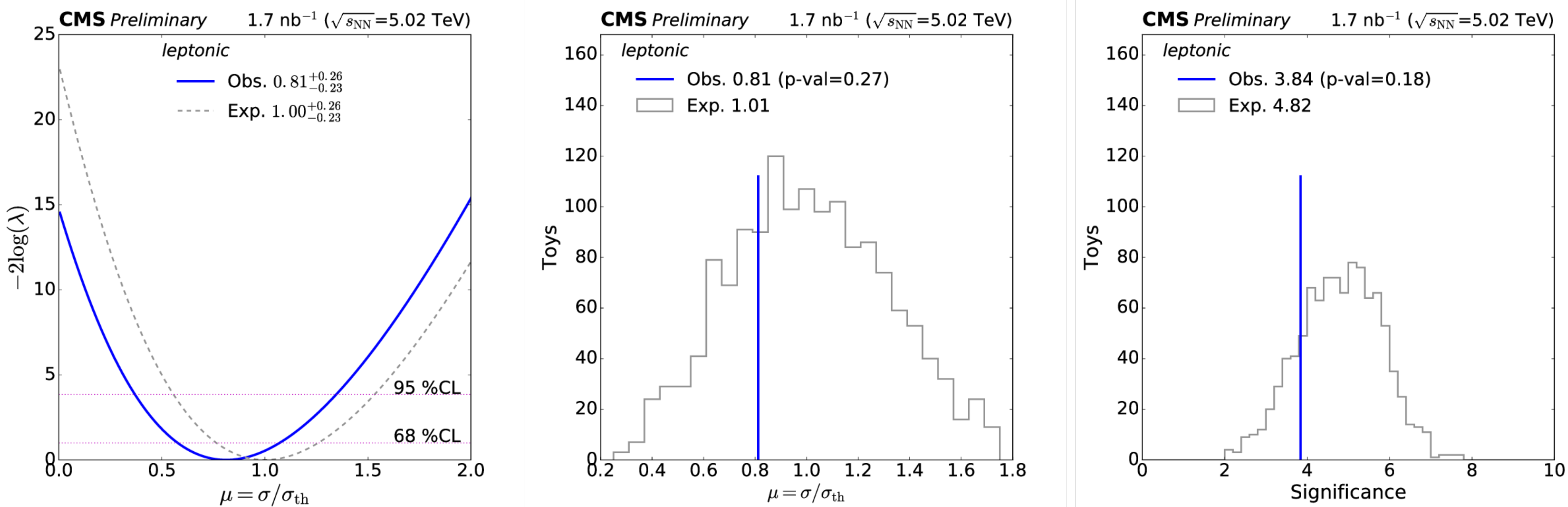
Observed more signal than expected : μ >1 and $\sigma_{obs} > \sigma_{exp}$

Profile likelihood ratio

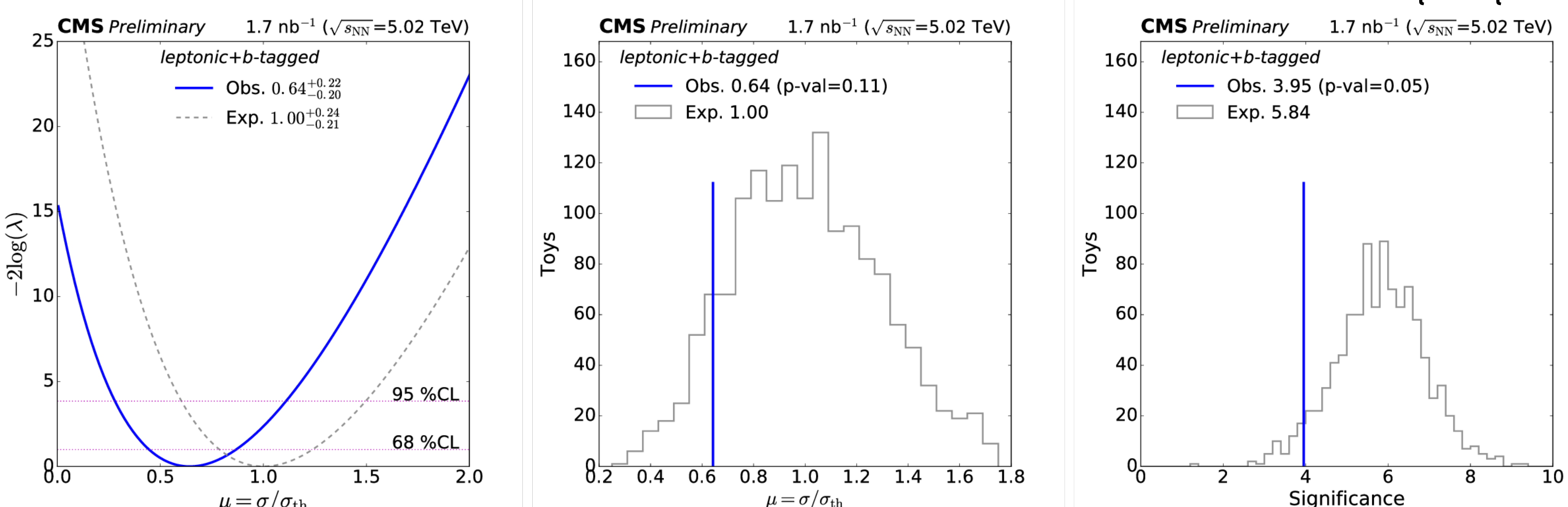


Likelihood fit and significance

$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}$

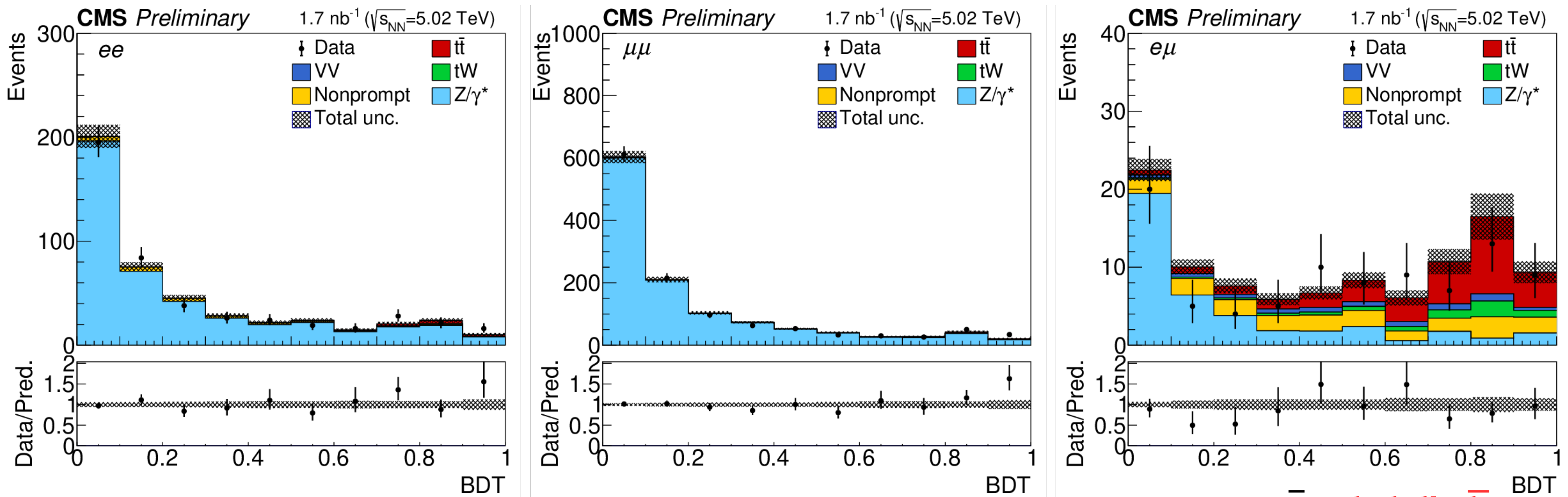


$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}$

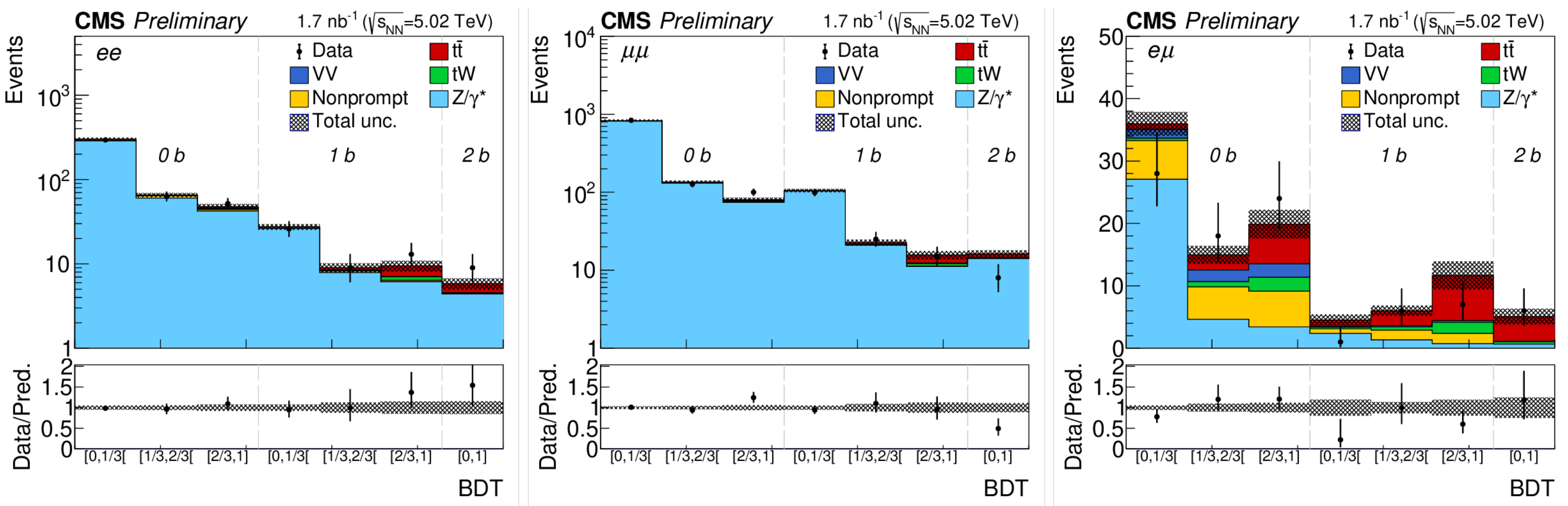


Post-fit BDT distributions

$t\bar{t} \rightarrow l\nu_l b\ l'\nu_{l'}\bar{b}$



$t\bar{t} \rightarrow l\nu_l b\ l'\nu_{l'}\bar{b}$



Event yields

In total **1768** events were observed in the data :

→ of which **43.2 ± 11.1 $t\bar{t}$** events extracted from the likelihood fit

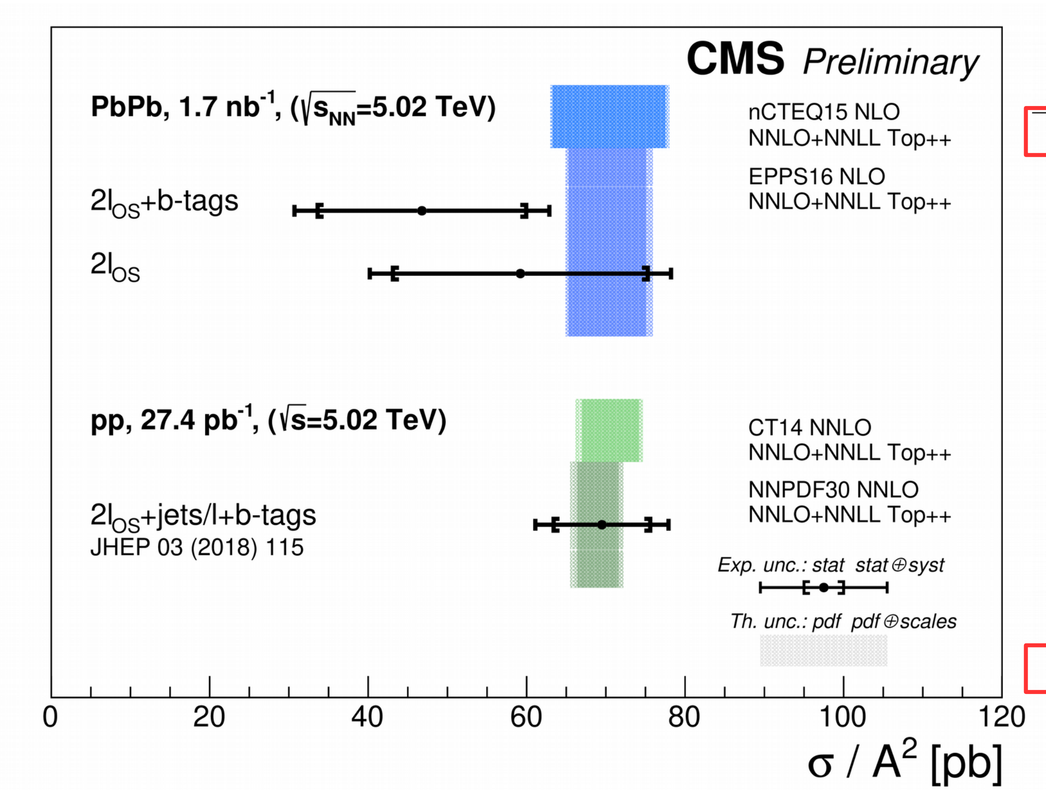
Process	Final state e^+e^- 0b	e^+e^- 1b	e^+e^- 2b	$\mu^+\mu^-$ 0b	$\mu^+\mu^-$ 1b	$\mu^+\mu^-$ 2b	$e^\pm\mu^\mp$ 0b	$e^\pm\mu^\mp$ 1b	$e^\pm\mu^\mp$ 2b
Z/γ^*	389.8±15.4	40.4±2.7	4.4±0.8	1027.5±27.3	136.1±5.7	14.1±1.7	35.1±1.7	4.4±0.9	0.7±0.2
Nonprompt	17.3±2.2	1.4±0.2	$\leq$ 0.1	7.6±1.0	0.8±0.1	$\leq$ 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

- best S/B in eμ channel
- ee/μμ only matters in 1b and 2b categories
- very high purity in 2b category

$t\bar{t}$ signal strenght and cross-section

$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}$: $\mu = 0.81 \pm 0.25$; 3.8σ (4.8σ exp.)

$t\bar{t} \rightarrow l\nu_l b\, l'\nu_{l'}\bar{b}$: $\mu = 0.64 \pm 0.21$; 4.0σ (6.0σ exp.)



Source	$\Delta\mu/\mu$ leptonic-only	$\Delta\mu/\mu$ 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
btagging 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

Two analyses yield consistent cross-sections

Statistical uncertainty dominates !

Summary

- CMS provide a strong evidence of the top quark production in PbPb collisions :

  $\mu = 0.81 \pm 0.25$; 3.8σ (4.8σ exp.) - in lepton only analysis,
  $\mu = 0.64 \pm 0.21$; 4.0σ (6.0σ exp.) - in lepton +b-jet analysis

- $t\bar{t}$ production cross-section in PbPb collisions :

  2.02 ± 0.69 μb - in lepton only analysis,
  2.56 ± 0.82 μb - in lepton + b-jet analysis

- The results are compatible between 2 analysis, and also with expectation from pp collisions and QCD computations

- First step towards the top quark as a tool to probe the QGP evolution

Backup slides

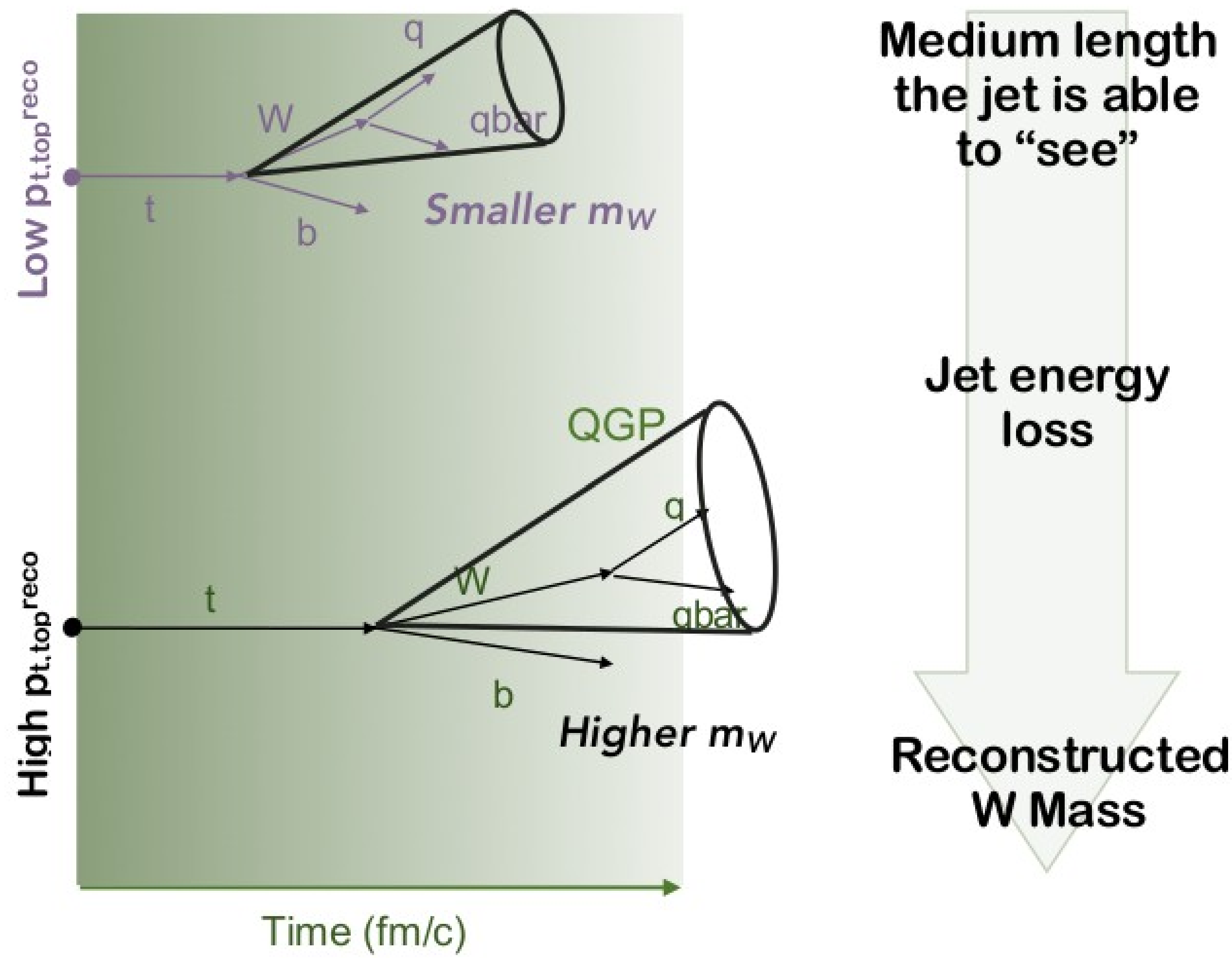
Boosted top in PbPb at FCC

At rest, top quarks decay with a lifetime of about 0.15 fm/c and the W that is produced in the top-quark decay has a lifetime of about 0.09 fm/c.

When the W boson decays hadronically, the resulting $q\bar{q}$ pair is not immediately resolved by the medium. Only after the q and $\bar{q}$ have propagated and separated a certain distance do they start interacting independently with the medium. This delay is called decoherence time, τ_d.

Thus the jets that are produced in the **t → Wb → $q\bar{q}$ b** decay chain do not see the full QGP, but only the part of the QGP that remains after the sum of decay and decoherence times.

That sum of times is correlated to the momentum of the top quark, a feature that may be exploited.



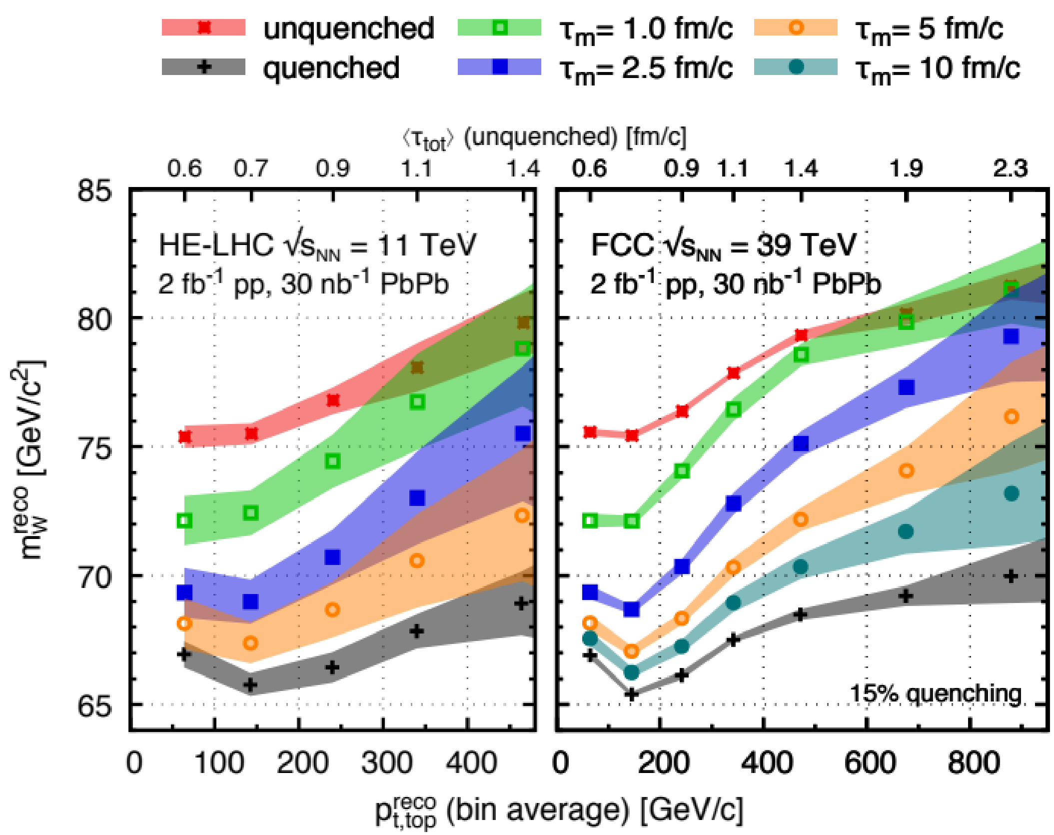
Boosted top in PbPb at FCC

Dependence of the reconstructed W mass on the reconstructed top p_T:

→ Useful probe of the QGP density evolution

FCC: able to scan entire QGP lifetime!

HE-LHC: Limited discrimination between short vs long lived medium.



Dependence of the reconstructed W mass on the reconstructed top p_T for HE-LHC (left) and FCC (right) collisions.

The quenched result corresponds to baseline full modification of the pp results, which would be obtained using knowledge of quenching from other measurements.

Signal strength and significance per channel

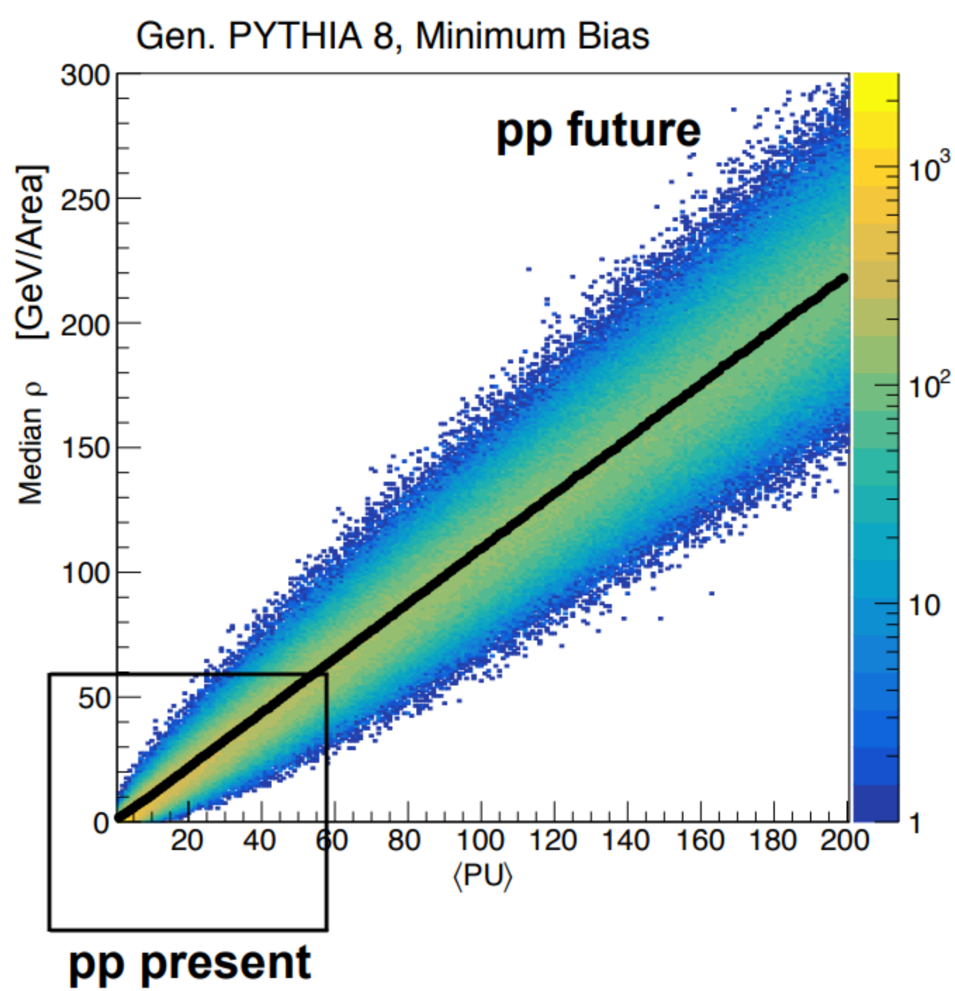
Fit alternative	Signal strength μ	Significance
$e^{\pm}\mu^{\mp}$ (leptonic only)	$0.66^{+0.24}_{-0.22}$ $(1.00^{+0.27}_{-0.25})$	3.3 (4.7)
$e^{+}e^{-}, \mu^{+}\mu^{-}$, and $e^{\pm}\mu^{\mp}$ (leptonic only)	$0.81^{+0.26}_{-0.23}$ $(1.00^{+0.26}_{-0.23})$	3.8 (4.8)
$e^{\pm}\mu^{\mp}$ (leptonic+b-tagged)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

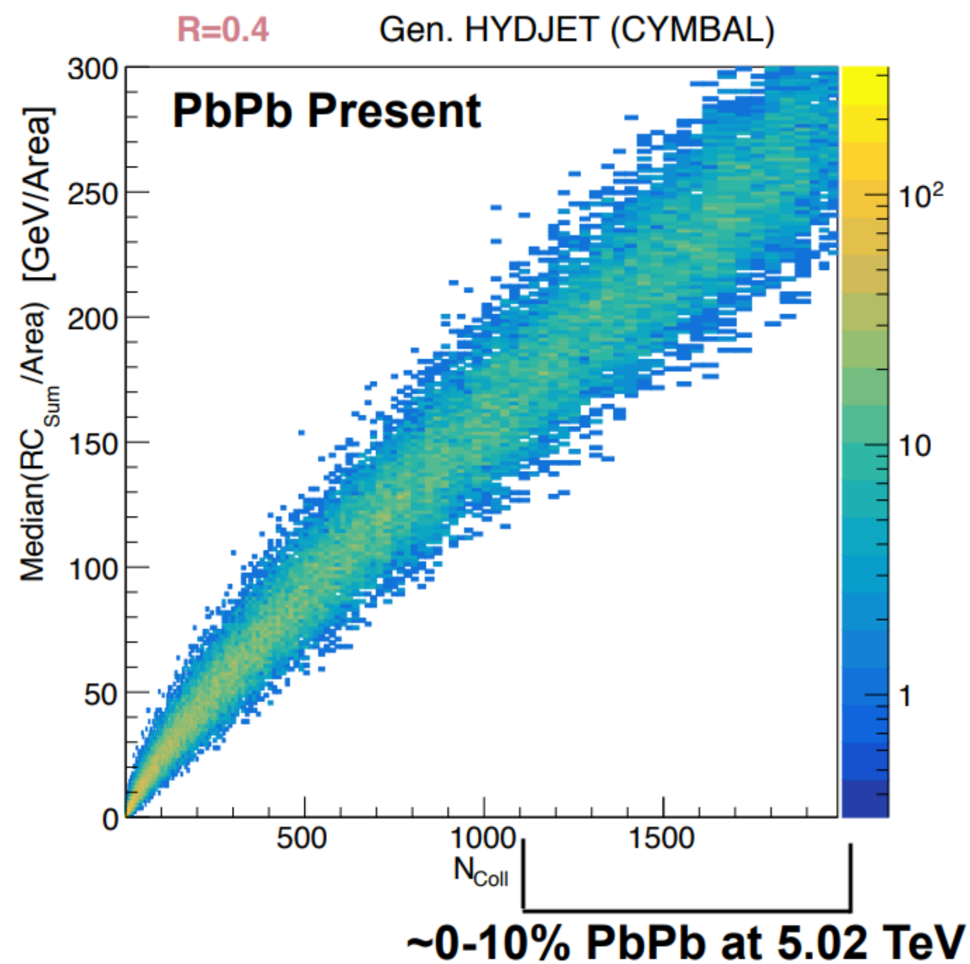
Underlying event in pp and PbPb collisions

Underlying Event (UE) - particles not associated with the hardest parton-parton process quantified as transverse momentum density (ρ)

PileUp (PU) – concurrent interactions coming from the same bunch crossing

BNL jet workshop '18, C.McGinn talk



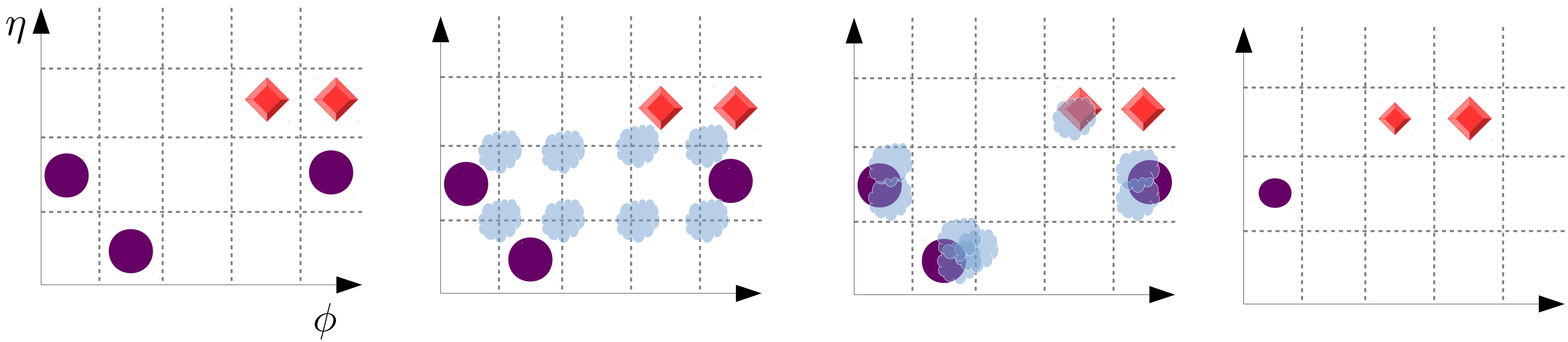


UE in pp with <PU> ~ 200 looks like central PbPb

UE subtraction in CMS : constituent subtraction

Particle-by-particle: correct the 4-momentum of a jet and substructure

- signal   - underlying event   - ghost (artificial particles)



Add ghosts with
$p_T^{ghost} = A_{ghost} \cdot \rho$
in random locations;

A_{ghost} - area occupied

Combine them with the closest real particle

$p_T^{particle} > p_T^{ghost}$

$p_T^{particle} < p_T^{ghost}$

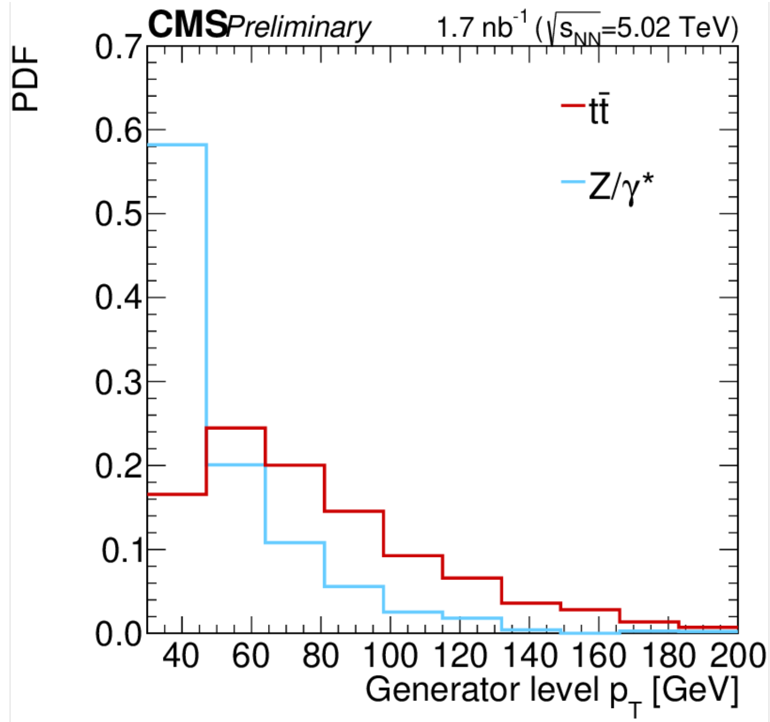
The largest pT particle/ghost survives

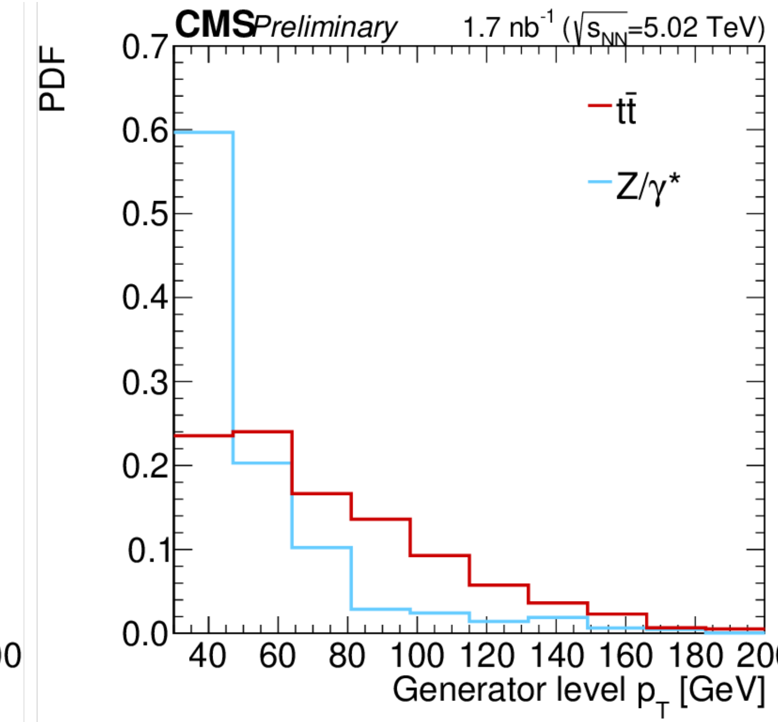
$p_T^{particle} = p_T^{particle} - p_T^{ghost}$

$p_T^{ghost} = p_T^{ghost} - p_{T\,particle}$

Repeat until no ghosts/particles left

Remaining particles get clustered into a jet


CMS Preliminary
1.7 nb-1 (√sNN=5.02 TeV)
PDF
tt̄
Z/γ*
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
40
60
80
100
120
140
160
180
200
Generator level pT [GeV]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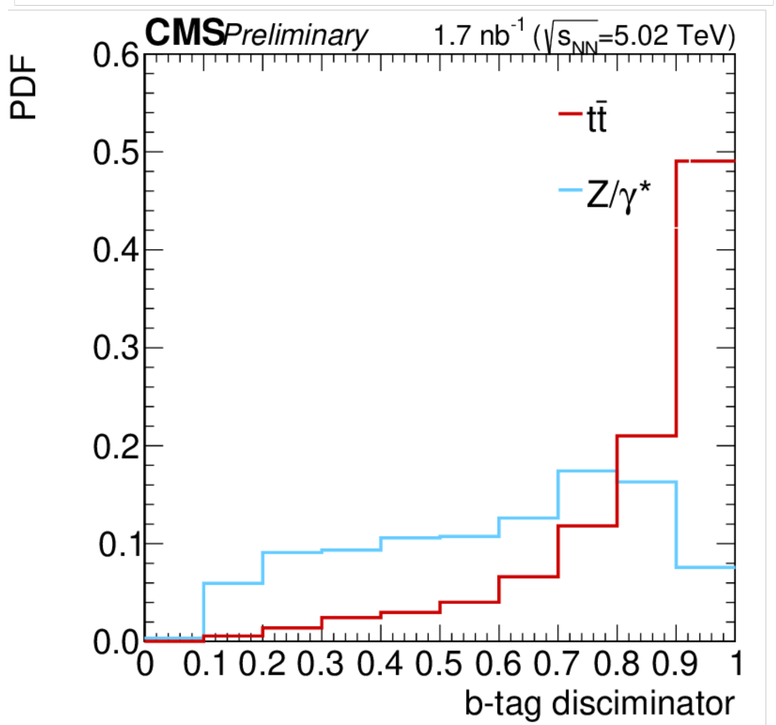
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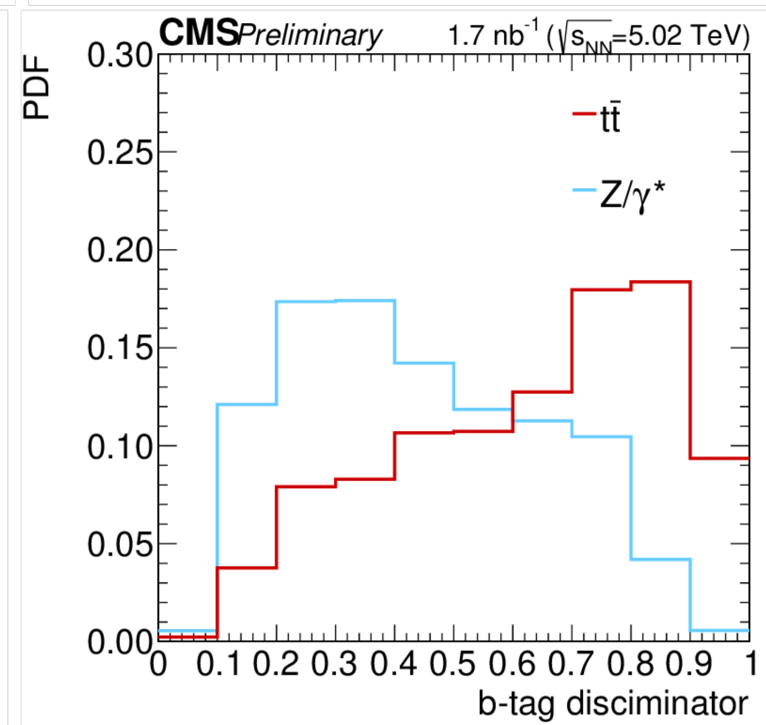
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
b-tag discriminator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0.05
0.10
0.15
0.20
0.25
0.30
0
0.1
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0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
b-tag discriminator

Maximum likelihood method

Likelihood function: how theoretical assumption is compatible with observed data

Maximum likelihood method estimates the values of the parameters

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{M} \frac{(\mu s_i + b_i)}{n_i!} e^{-(\mu s_i + b_i)}$$

- Signal strength = μ
- Signal contribution = s_i (according to a nominal model)
- Background contribution = b_i
- Nuisance parameters = θ

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

$$\lambda(\mu = 0) = \frac{\mathcal{L}(0, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

- $\hat{\hat{\boldsymbol{\theta}}}$ is the value of θ maximizing $\mathcal{L}$ for a certain μ
- $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ correspond to the true global maximum likelihood
- the profile likelihood ratio (λ) :

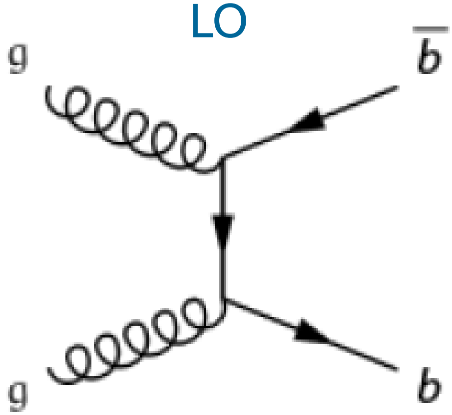
  → λ ~ 1 – data is compatible with signal expectation
  → λ ~ 0 – data is compatible with background-only expectation

$$s = \sqrt{-2Log\lambda(\mu = 0)}$$ - significance of an excess over the background-only expectation

b-jet production channels at LHC

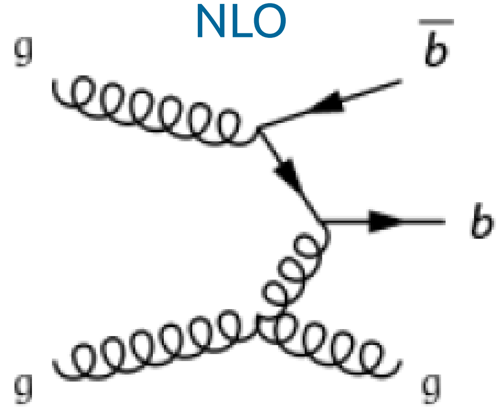
Flavor Creation (FCR)

LO



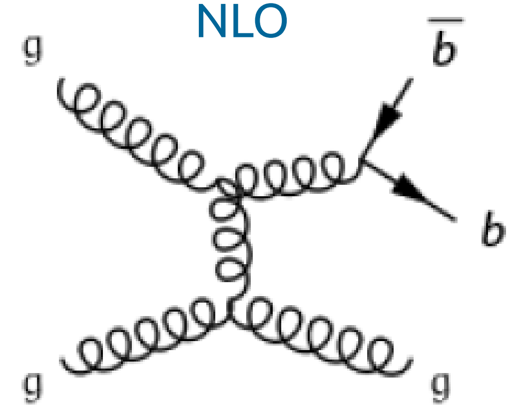
Flavor Excitation (FEX)

NLO



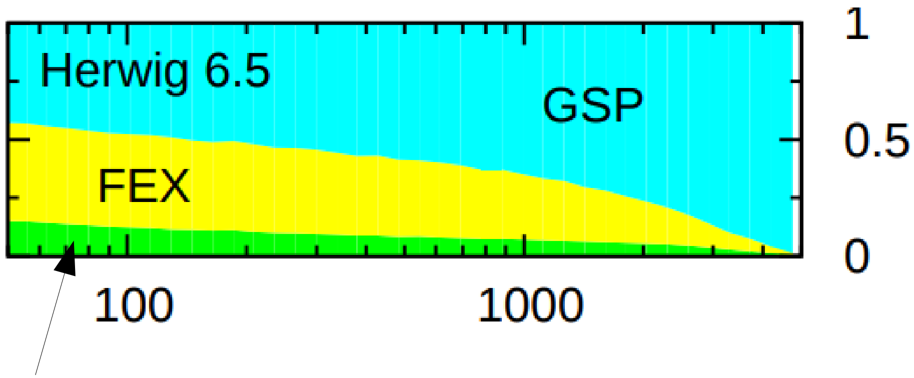
Gluon Splitting (GSP)

NLO



LHC, pp collisions at 14 TeV

JHEP 0707:026,2007



FCR is not dominant process

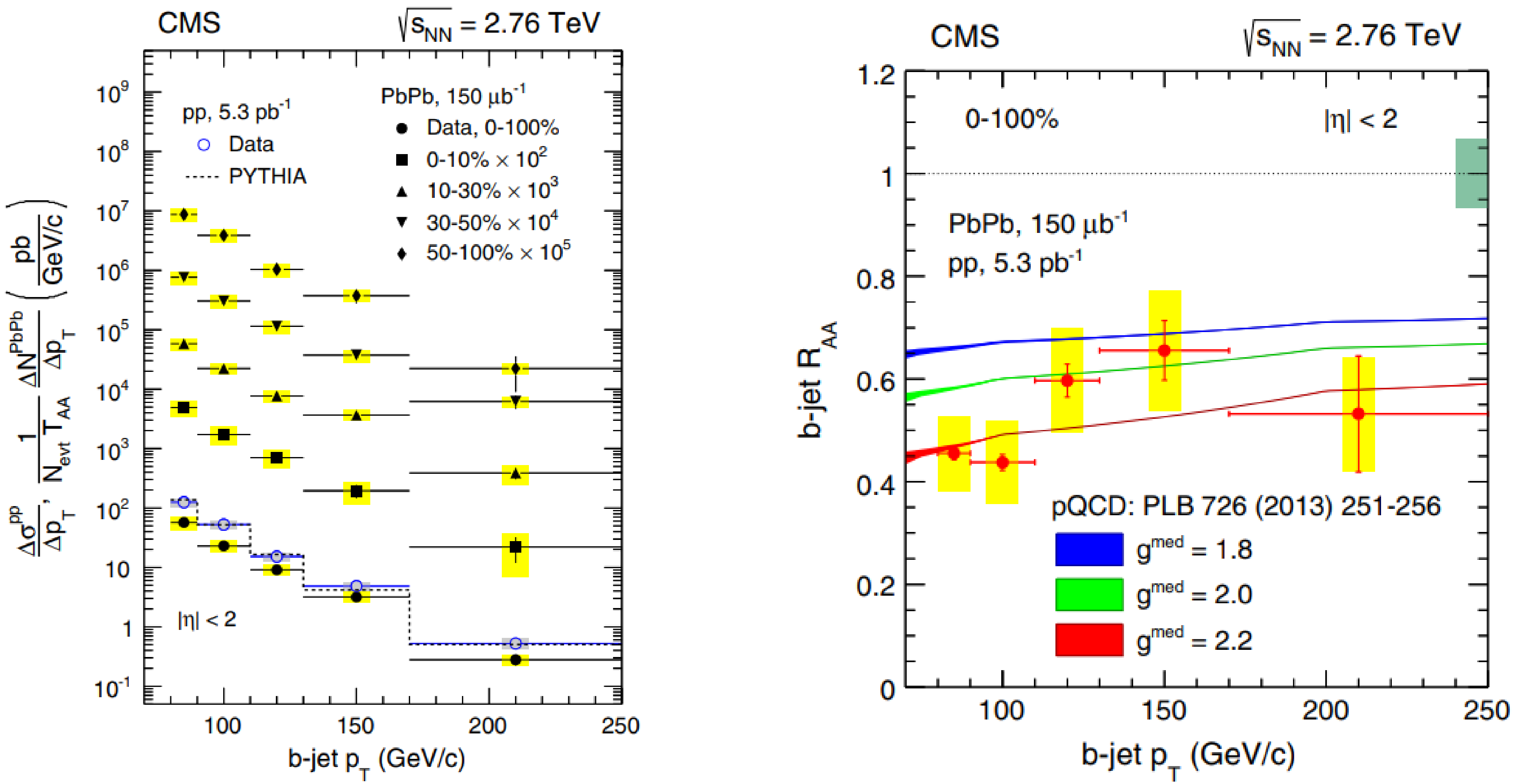
First Heavy Ion measurements convolute large contributions from NLO b-quark production processes

Energy loss is expected to depend on flavor → measure heavy flavor jets suppression

Quenching of b-jets

Jet spectra corrected for detector resolution effects for several centrality selections and pp

CMS, PRL 113 (2014) 132301

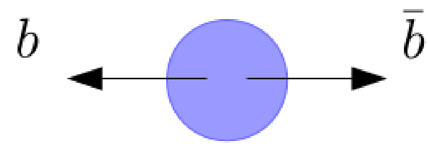


Suppression consistent with the one observed from inclusive jets

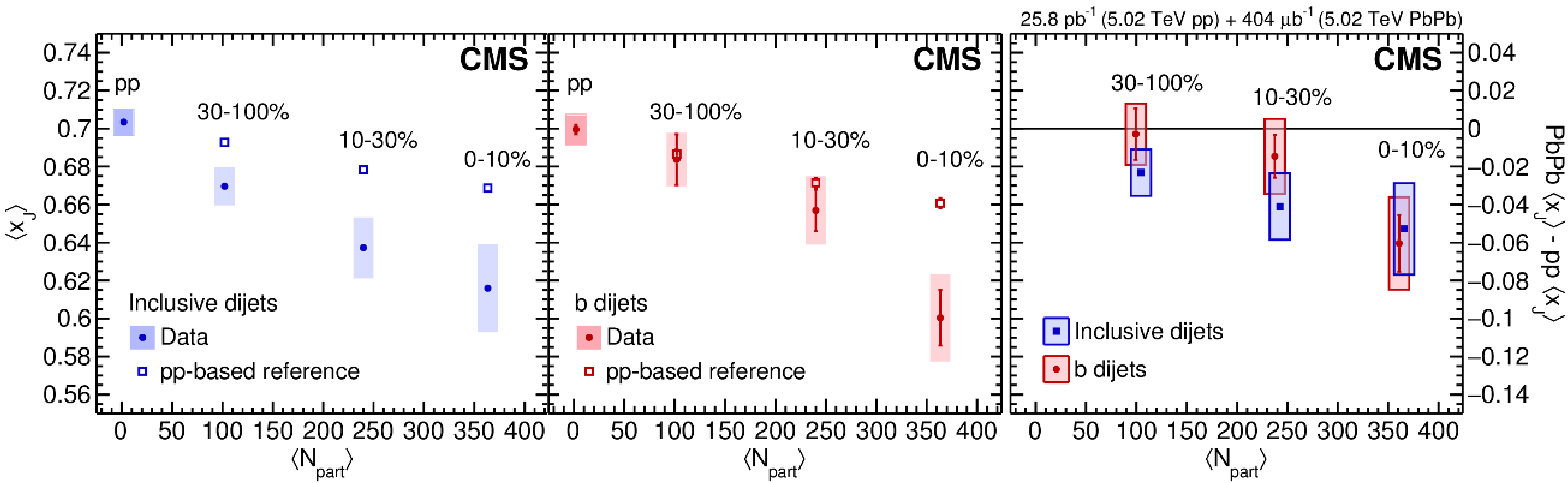
bb correlations

To suppress the contribution of gluon splitting and probe LO b-jet production :
look at pairs of b jets that are back-to-back in azimuth.

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$



CMS , JHEP 1803 (2018) 181



No clear difference between pT balance of inclusive and b-dijets

Data from Run 3 will allow to make a conclusive statement