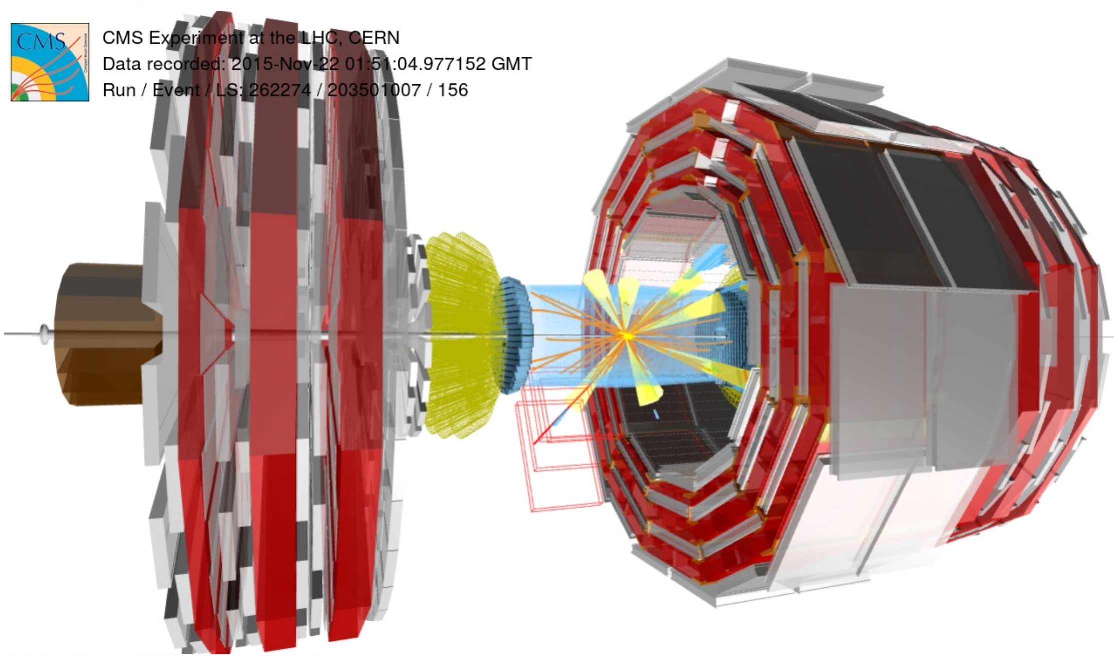
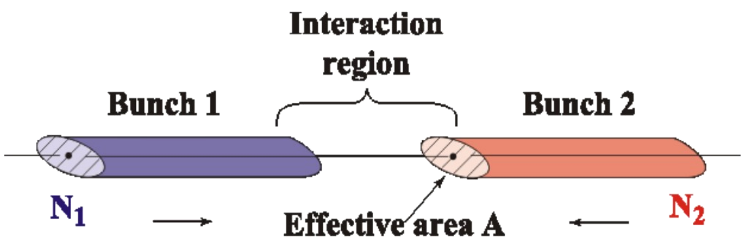


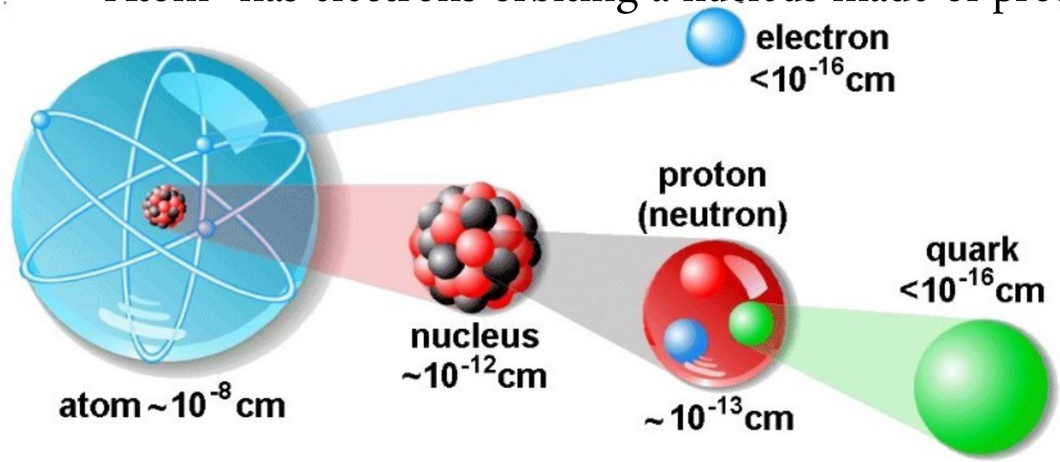
First measurements of the *tt* cross section in LHC pp and pPb collisions at 5.02 and 8.16 TeV and determination of the absolute luminosity in the CMS experiment



G.K. Krintiras
A. Giammanco (Doctoral advisor)

Structure of matter

- It depends on the **resolution scale** (Q) at which it is observed
  - “Atom” has electrons orbiting a nucleus made of protons and neutrons



Unit for energy E (and mc^2): *electron-volt*, eV	
Chemical reactions, per atom	1 to few eV
Rest energy mc^2 of proton	billion eV GeV (Giga)

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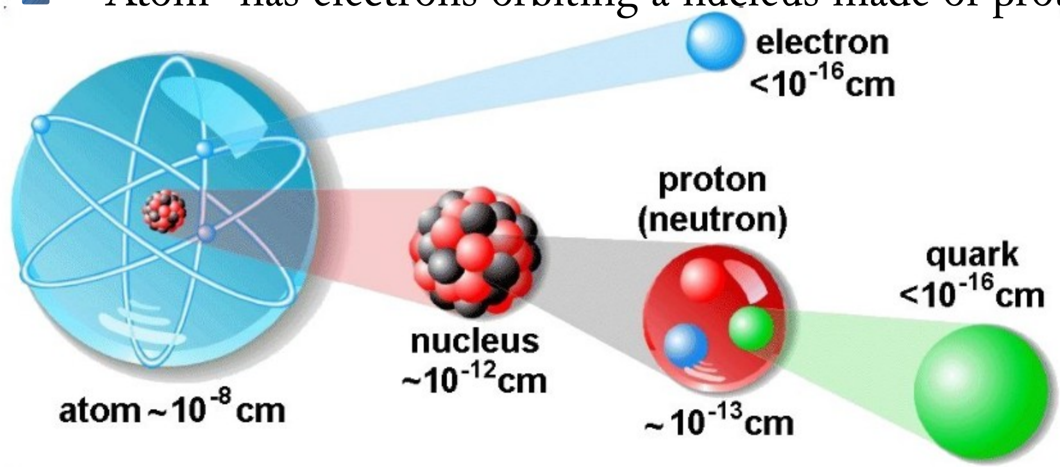
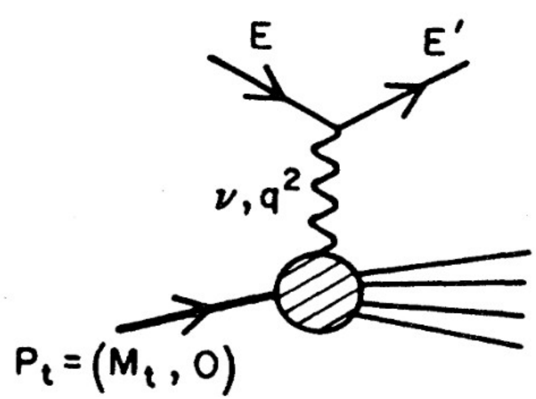
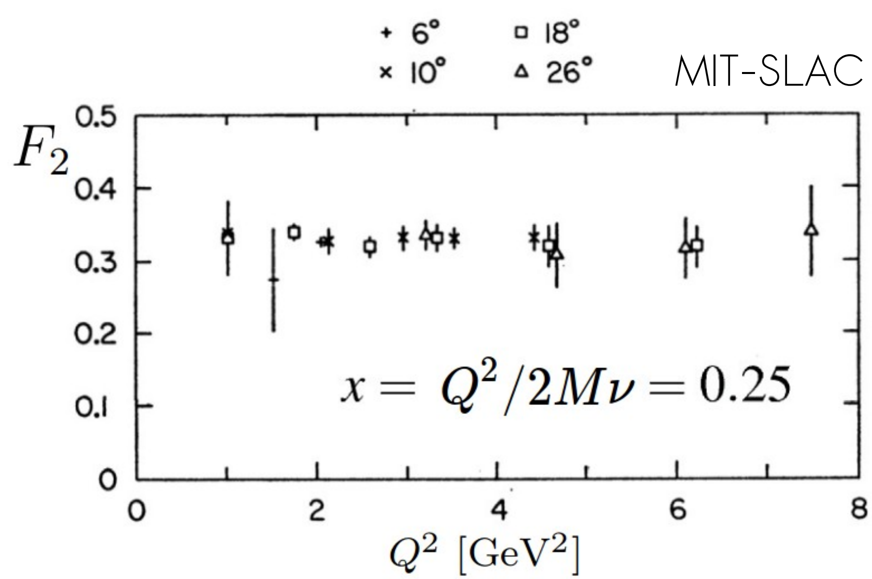


Unit for energy E (and mc^2): *electron-volt*, eV	
Chemical reactions, per atom	1 to few eV
Rest energy mc^2 of proton	billion eV GeV (Giga)

- **Observation**: e+p interaction becomes independent of Q → proton is made up from point-like particles
  - Harbinger of the theory of quarks and gluons, in which a mild violation of scaling would be allowed

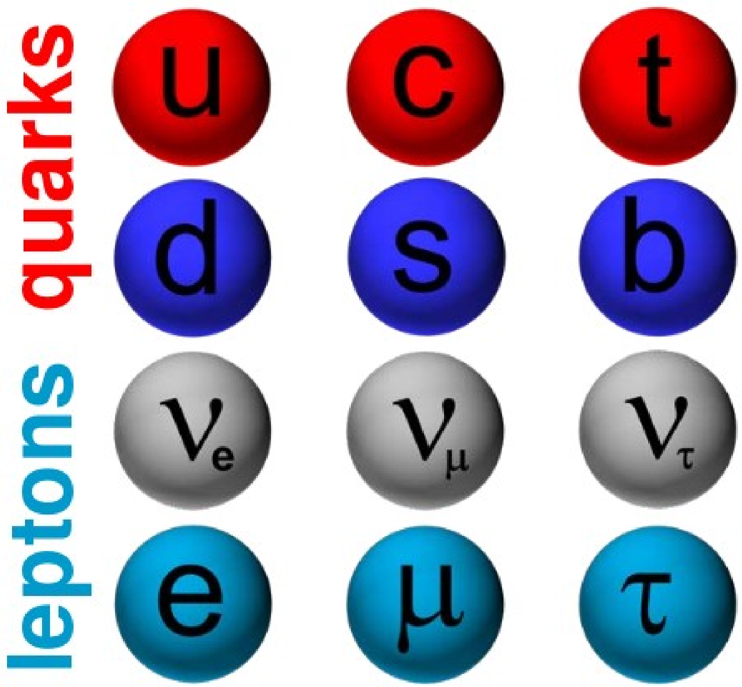


"Feynman" diagram of "deep inelastic scattering"



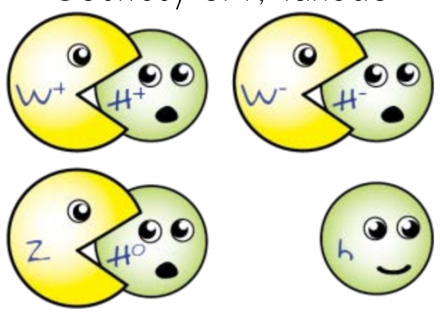
Elementary Particle Physics, aka High Energy Physics

- What are smallest building blocks of matter?
  - Over time, two more massive "copies" identified but otherwise identical to the first set



- What are the forces between them?
  - Four quanta for the combined "electroweak force": a history of unification
  - Quantum chromodynamics: theory of quarks and gluons, and their "strong" interactions
    - built on the concept of "colour": only color-neutral states exist

Courtesy of F. Tanedo



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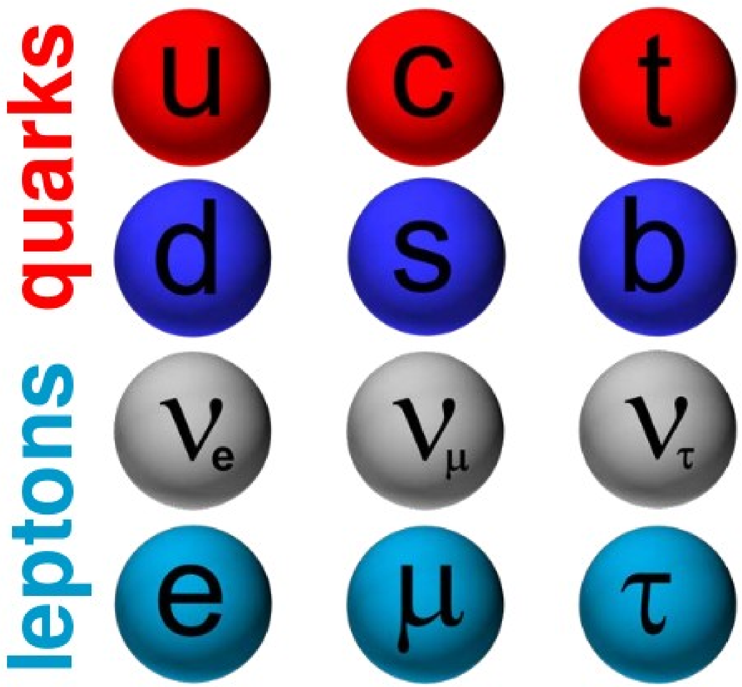

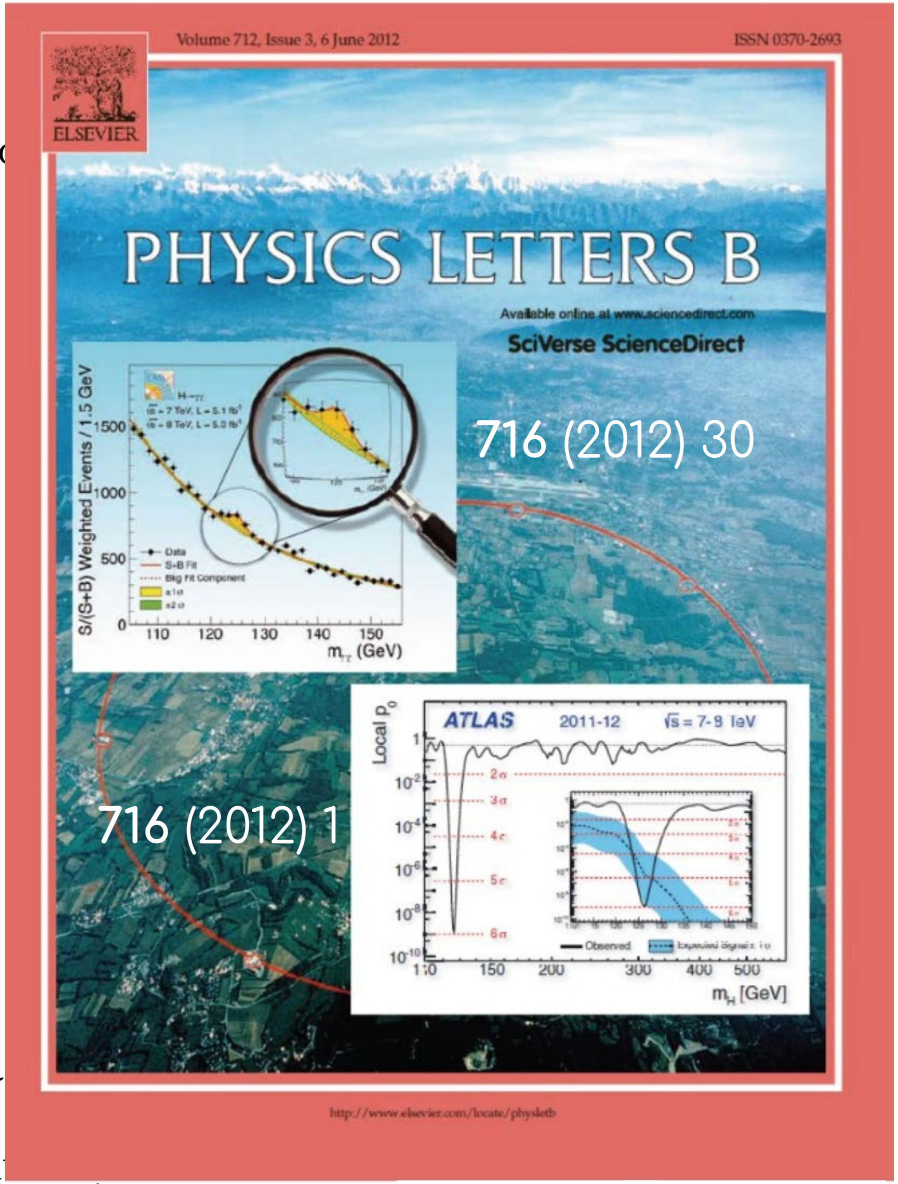

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Top quark: The heaviest elementary particle known today

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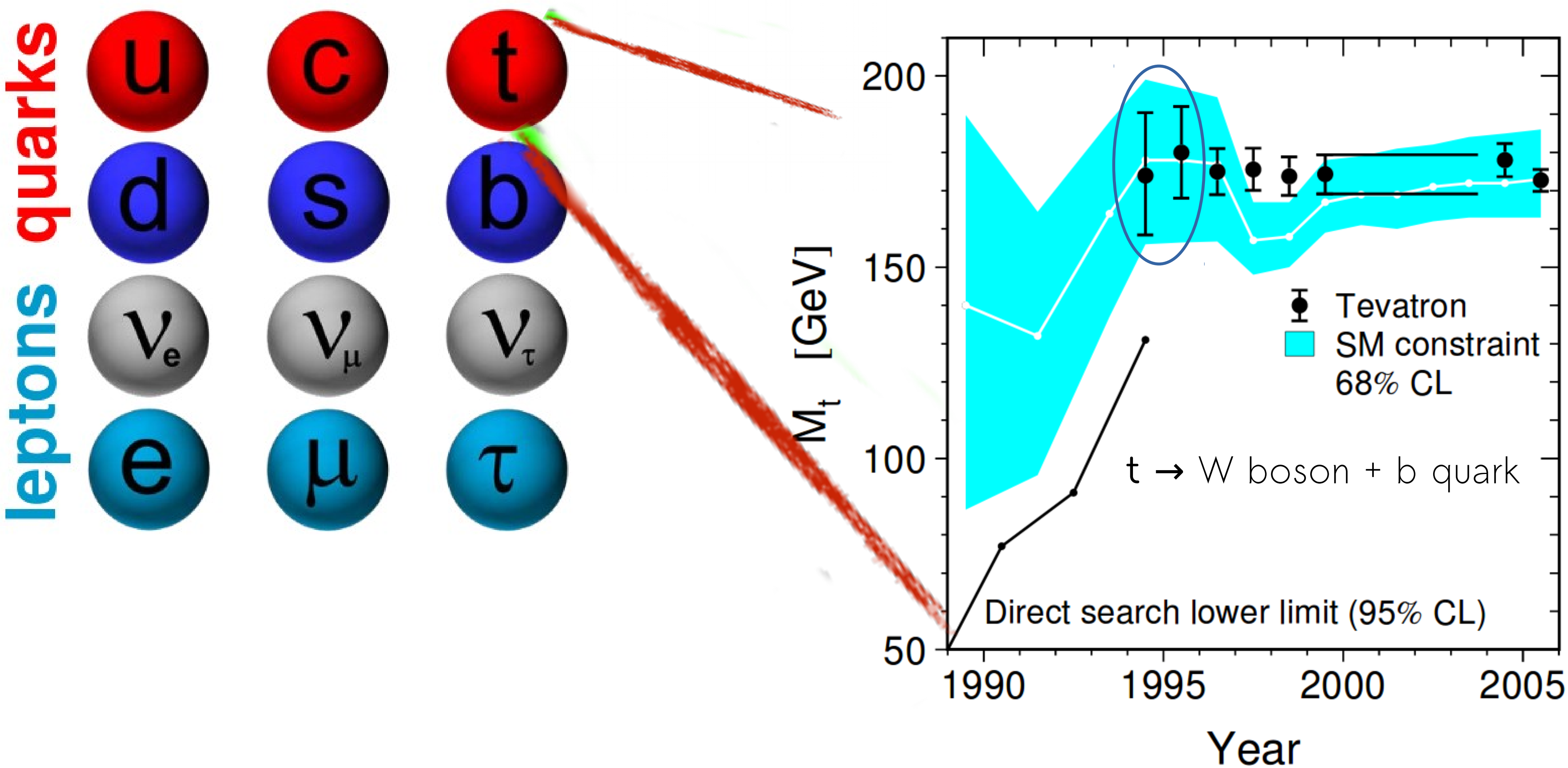
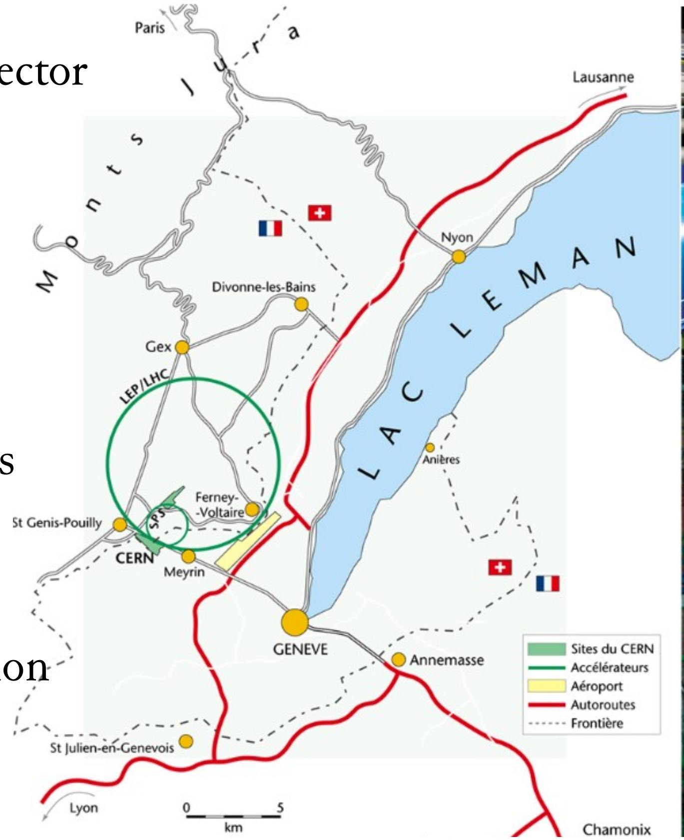


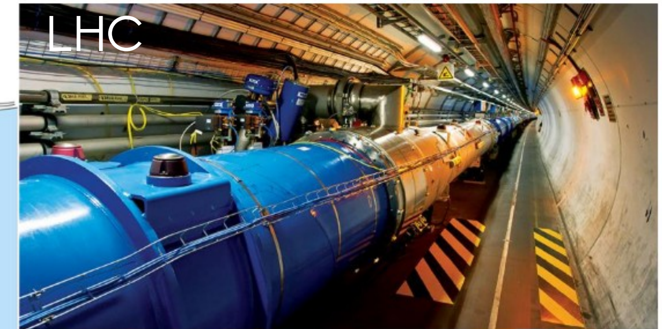
- Indirect, e.g., in LEP, and direct searches hinted to >> 50 GeV
  - The first evidence and observation at Tevatron → top quark **established** with *a* mass of 178.0(4.3) GeV

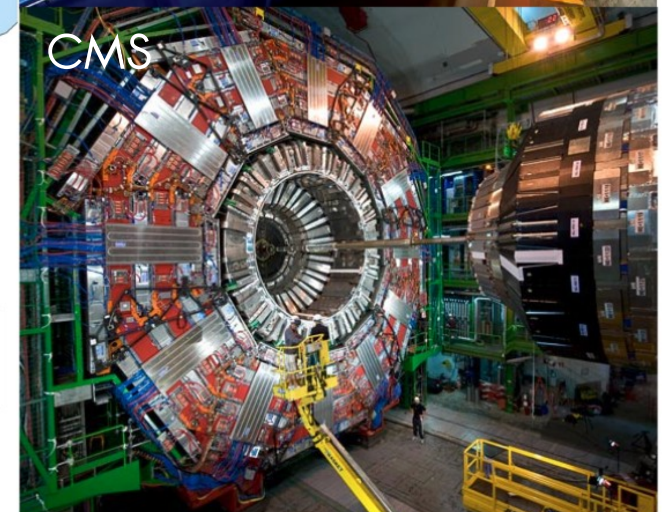
Phys Rev Lett. **74** (1995) 2626
Phys Rev Lett. **74** (1995) 2632
hep-ex/0404010

The Large Hadron (& Ion) Collider (>2009)

- CERN accelerator complex acts as injector
- A two ring-like accelerator
- Straight sections intercepted by the experimental caverns
  - Two “high-”luminosity insertions
    - IR1 & **5**
  - One “medium-” & “low-” insertion
    - IR2 & 8



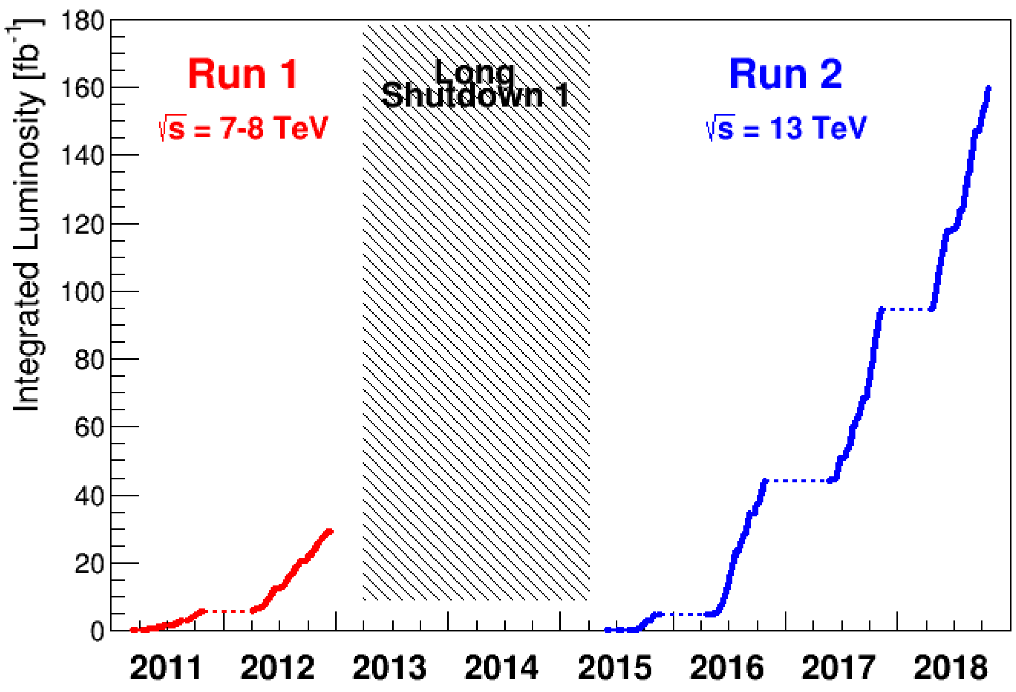




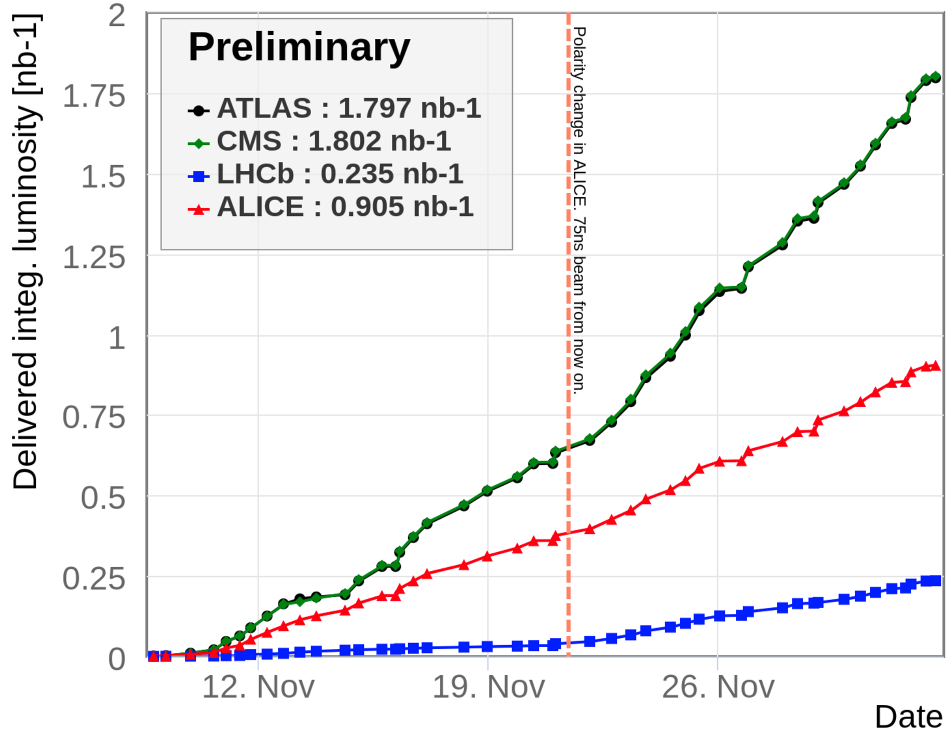
Parameter	LHC	LEP2	Tevatron
Colliding species	p,p	e^+,e^-	$p,\bar{p}$
Dipole field at top energy (T)	8.33	0.11	4.4
Momentum at collisions (TeV)	$\boxed{7}$	0.1	0.98
Number of bunches per beam	2 808	4	36
Particles per bunch ($\times 10^{11}$)	1.15	4.2	2.9, 0.8
Typical beam size in the ring (μm)	200-300	1 800/140 (H/V)	500
Beam size at IP (μm)	16	200/3 (H/V)	24
Peak luminosity ($cm^{-2}s^{-1}$)	$\boxed{10^{34}}$	10^{32}	4.3×10^{32}

A lot of progress in the accelerator forefront

Number of **proton-proton** collisions



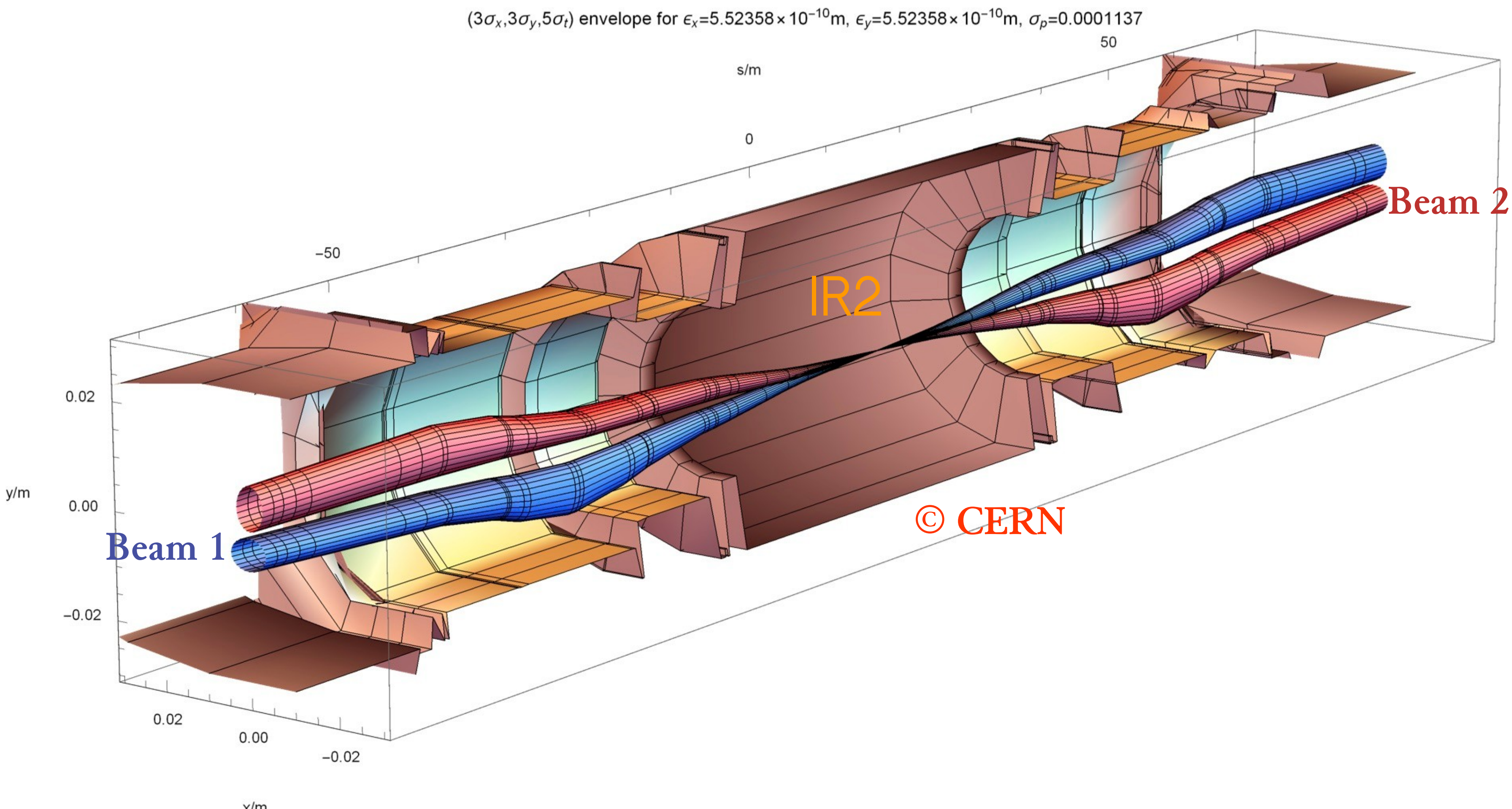
Number of **lead-lead** collisions (in 2018)



- Luminosity is a collider **FOM** for delivering statistically significant (“large”) data samples
  - We have about 2000 times **less** nuclear (lead-lead or proton-lead) than proton-proton data
  - Mainly due to acceleration limitations and partly due to running time: 4 months **vs** > 4 years!

How we know its scale? The "lumi" calibration

$\mathfrak{L}$ measures how many particles can be **squeezed** through a given space at a given time

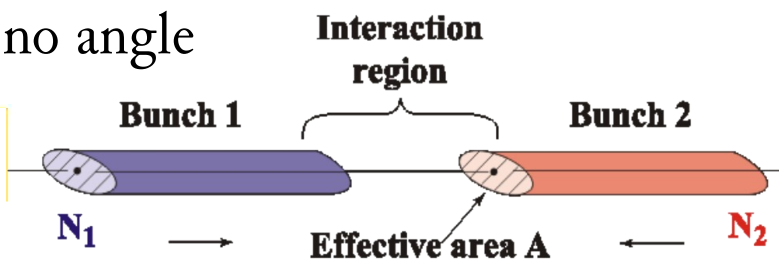


CMS-PAS-**LUM-16-001**
CMS-PAS-**LUM-17-002**
CMS-PAS-**LUM-17-004**

In practice, how the $\mathcal{L}$ calibration is performed (*)?

- Luminosity depends on **beam intensity, beam size,** and **optics** ("β-function")
  - let's take the simplest case of
    - equal intensity, circular beams, full overlap and no angle

$$\mathcal{L} = f_{rev} N^2/4\pi A_{eff}$$



(*) focus only on methods from machine parameters

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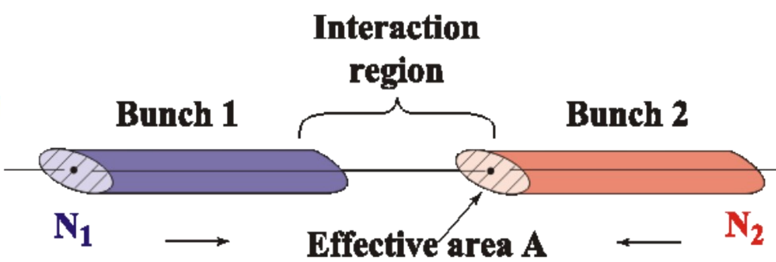
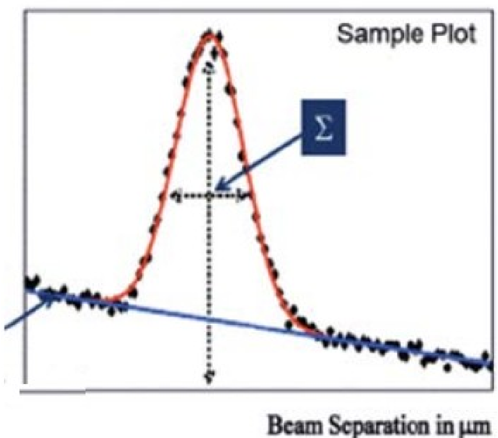
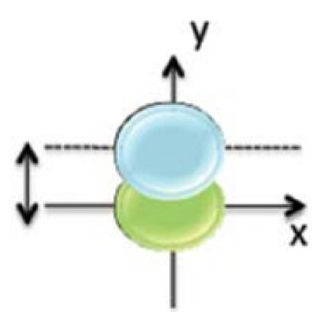


  - N is measured with **accelerator instrumentation**
    - with less than 0.5% unc
    - not the tricky part; at least not anymore (2011 @ ~3%)
  - **Idea**: Indirectly measure the effective area
    - by recording the **interaction rate** as a function of the **beam separation**





$$A_{eff} = 2\,\pi \boxed{\sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}}\ \boxed{\sqrt{\sigma_{y1}^2 + \sigma_{y2}^2}} = 2\,\pi\, \sigma_{xeff}\, \sigma_{yeff}$$

The beam-separation scan technique

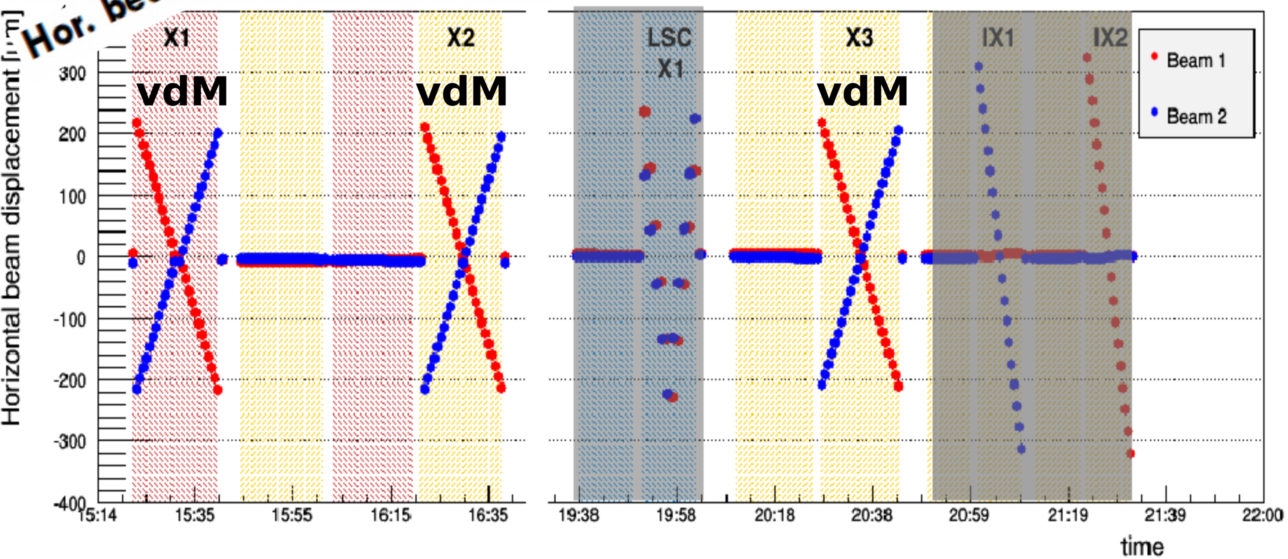
Principle: $\sigma_{eff} = R_{collisions} / \mathcal{L}$ (beam parameters)

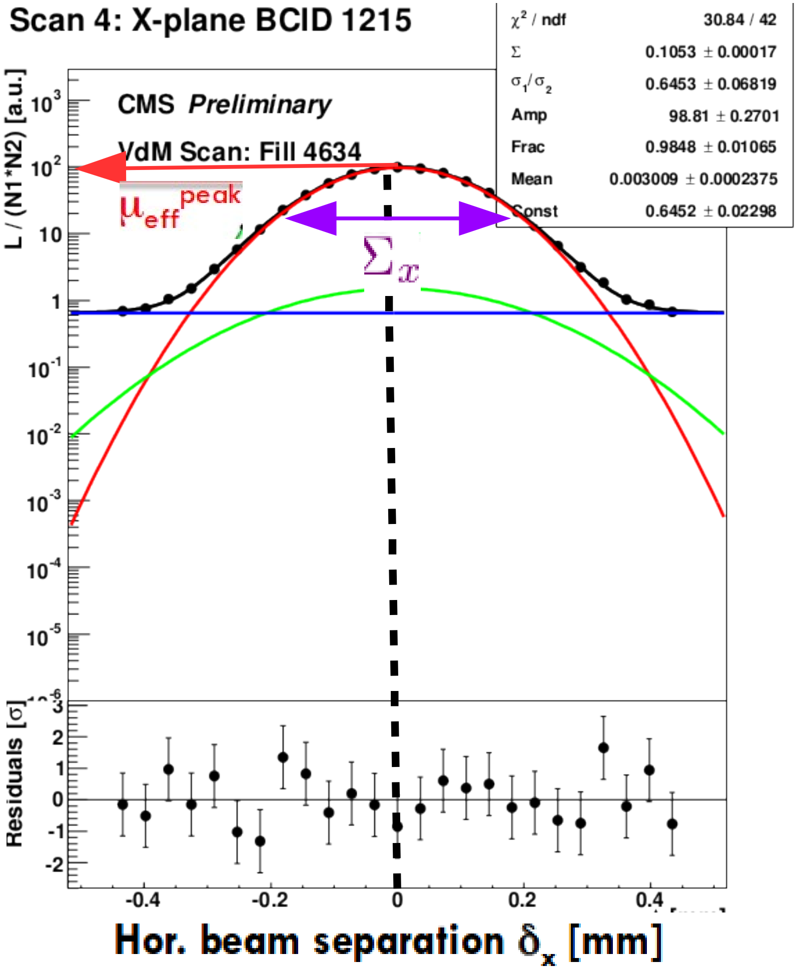
- van der Meer (**vdM**) scans: $\Sigma_{x,y}$ from R vs. beam sep. (δx, δy) LUM-16-001
  - σ_{eff} for each luminosity detector

$$\boxed{\sigma_{\text{eff}}} = \boxed{\mu_{\text{eff}}^{\text{peak}}} \frac{2\pi \boxed{\Sigma_x \Sigma_y}}{\boxed{n_1 n_2}}$$

effective cross-section — peak rate — scan widths — bunch populations

Hor. beam separation δ_x





LHC Fill 4634 (5.02 TeV)

What is the attained precision?

- No tailored beam conditions for reference or ion runs; commissioning time is **prohibitively** large
  - tracker resolution mostly **lower** than the beam effective size at IP
    - Extreme region for the **applicability** of the applied technique in CMS
- However, for both studied conditions number of simultaneous interactions ("pileup") is low
  - Nonlinear response of luminometers not a limitation

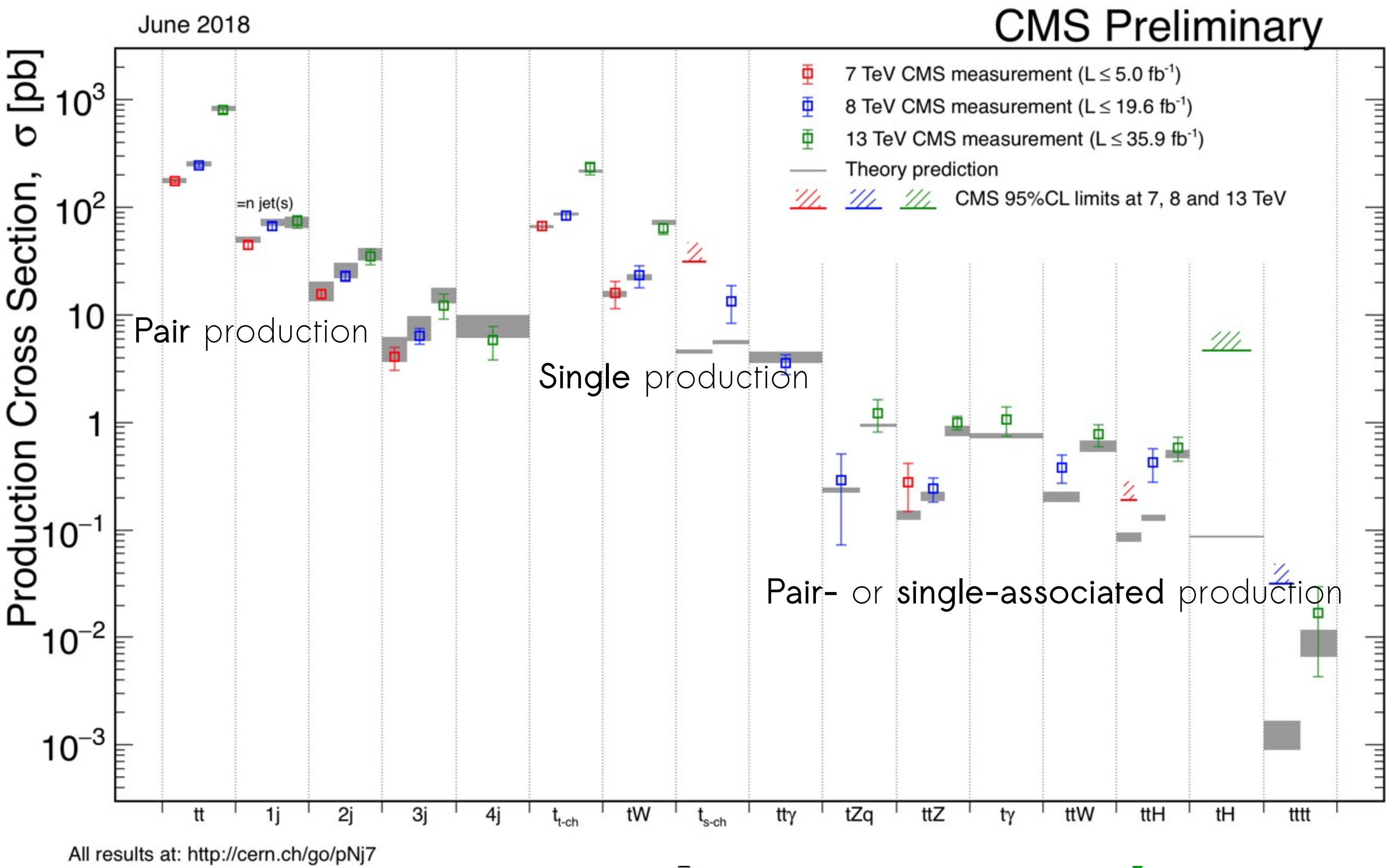
LUM-16-001, 17-002

Complex mix of unc sources

some examples:
Length scale calibration
Bunch population products
Bunch-by-bunch σ_{vis}
Beam-beam effects
Factorisation
Long-term drifts
μ-dependence
....

	Source	Correction (%) pp	Pbp	pPb	uncertainty (%) pp	Pbp	pPb
Normalization	Beam nonfactorizability	-	-	-	1.4	2.3	2.9
	Bunch-to-bunch variation	-	-	-	-	1.4	1.5
	Scan-to-scan variation	-	-	-	-	0.6	1.0
	Length scale	1.0	-	-	0.2	0.7	0.7
	Ghosts and satellites	1.8	1.3	1.2	0.2	0.7	0.6
	Orbit Drift	-	-	-	0.4	0.5	0.5
	$\Sigma_{x,y}$ compatibility	-	-	-	-	0.5	0.2
	Dynamic-β	-	-	-	0.5	0.5	0.5
	Beam-beam deflection	1	0.3	0.3	0.2	0.3	0.3
	Beam current calibration	-	-	-	0.3	0.3	0.3
Integration	Cross-detector stability	-	-	-	1	0.9	0.7
	Type 1/2	7	-	-	1	-	-
	DAQ deadtime	-	-	-	0.5	0.5	0.5
	Dynamic inefficiency	-	-	-	0.4	-	-
	Total				2.3	3.2	3.7

It works spectacularly good: the top quark paradigm



$$\sigma_{h_1h_2\to X} = \sum_{a,b}\int_0^1 dx_1 dx_2\, \underbrace{f_{h_1/a}(x_1,\mu_F^2)\, f_{h_2/b}(x_2,\mu_F^2)}_{\text{PDFs}} \times \underbrace{\hat{\sigma}_{a,b\to X}\left(x_1,x_2,\alpha_s(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2}\right)}_{\text{partonic cross section}} \underbrace{\left[+\mathcal{O}\left(\frac{1}{Q^2}\right)\right]}_{\text{power corrections}}$$

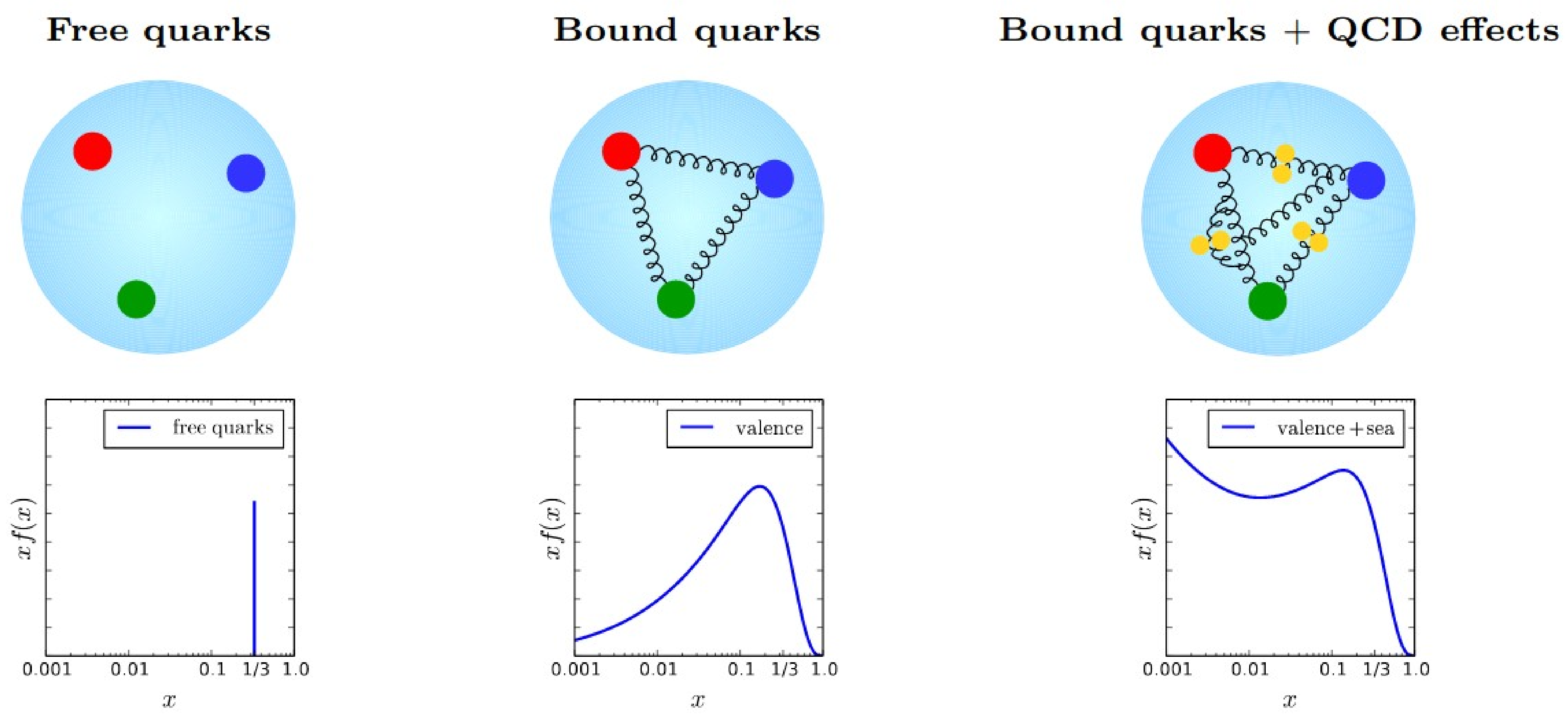
e.g., LO, NLO, NNLO, ...

Q – characteristic energy scale, e.g., DIS: 4-momentum transfer, DY/tt: mass of the Z boson/top quark, etc.

μ – factorization scale: Naturally set to be of order Q (the same as the renormalization scale)

Parton distribution functions

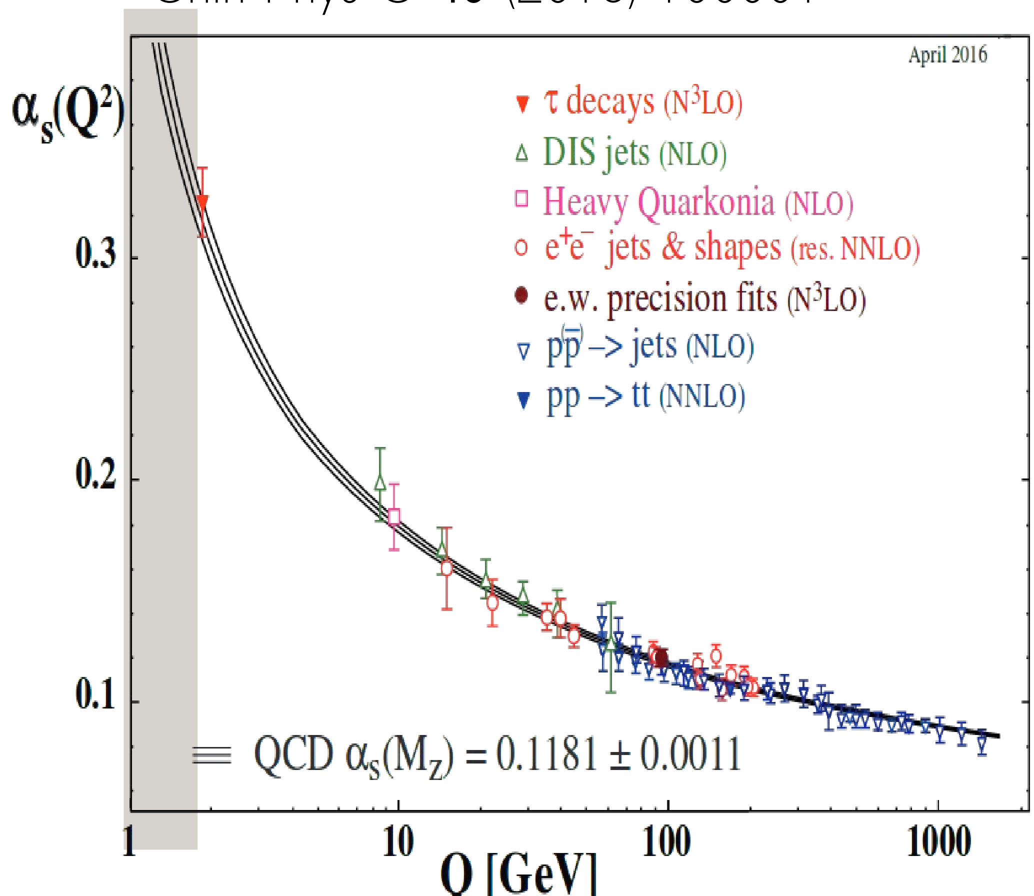
PDF $[f_{a/p}(x,\mu)]$:"probability"that a parton a carries fraction x of proton's momentum (valid at leading-order of QCD).



- The x dependence cannot be predicted in the perturbative QCD
- PDFs at certain (x,Q_0) are determined from "global" analyses, i.e., a wide range of hard scattering measurements

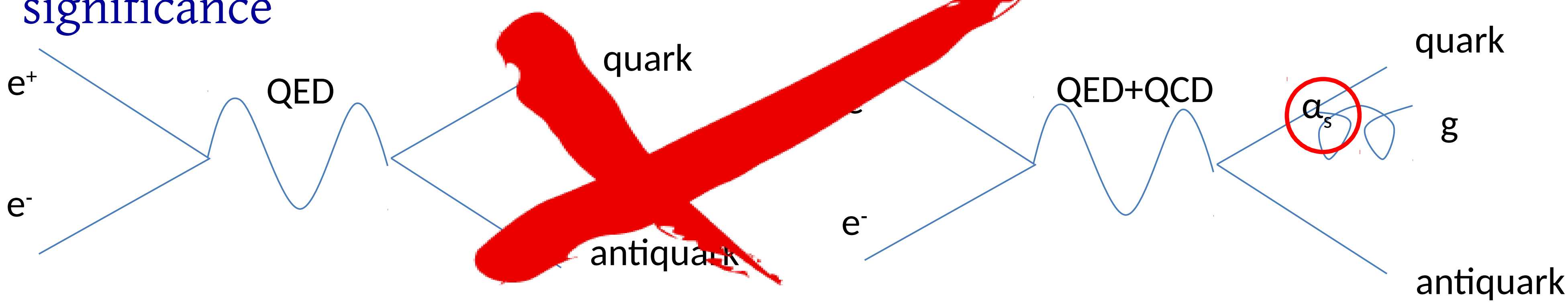
But why QCD is called the strong interaction?

Chin Phys C **40** (2016) 100001

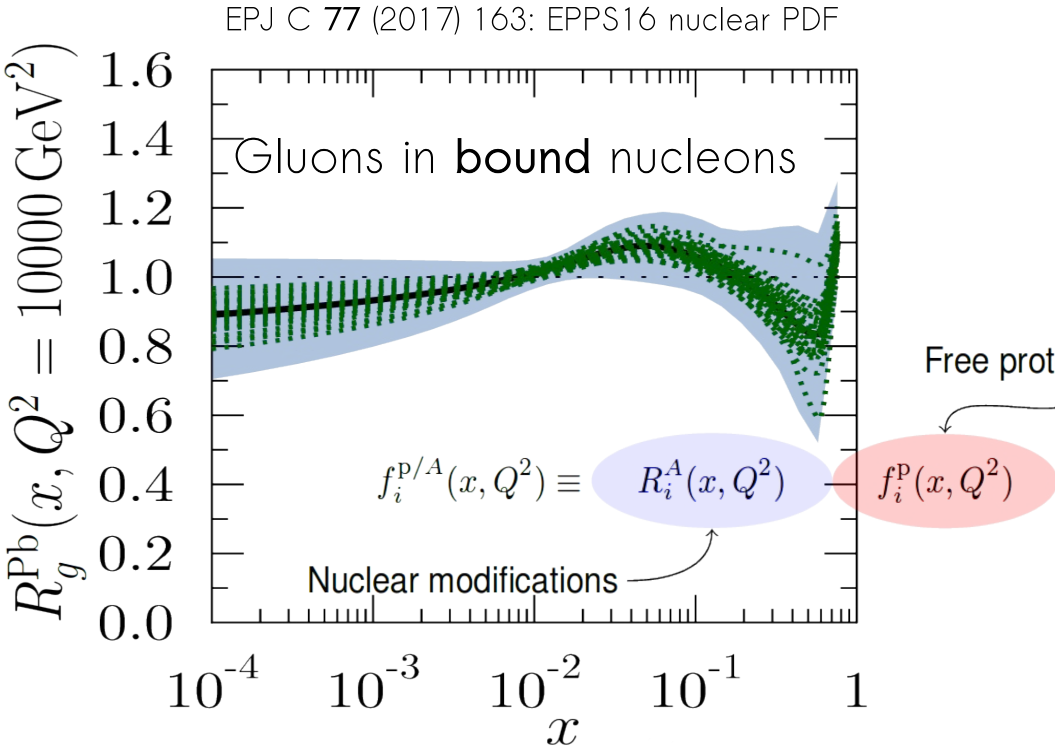


- Hard scattering cross sections calculable
  - **provided** the scale μ is chosen large
- Does the large-distance behavior of QCD implies
  - a transition region where "color" degrees of freedom dominate?
  - I.e., a **deconfinement** phase exists?

Large coupling → we cannot verify by sequentially adding terms of lower significance

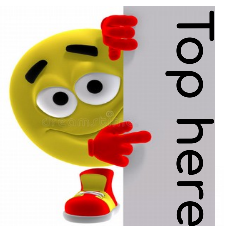


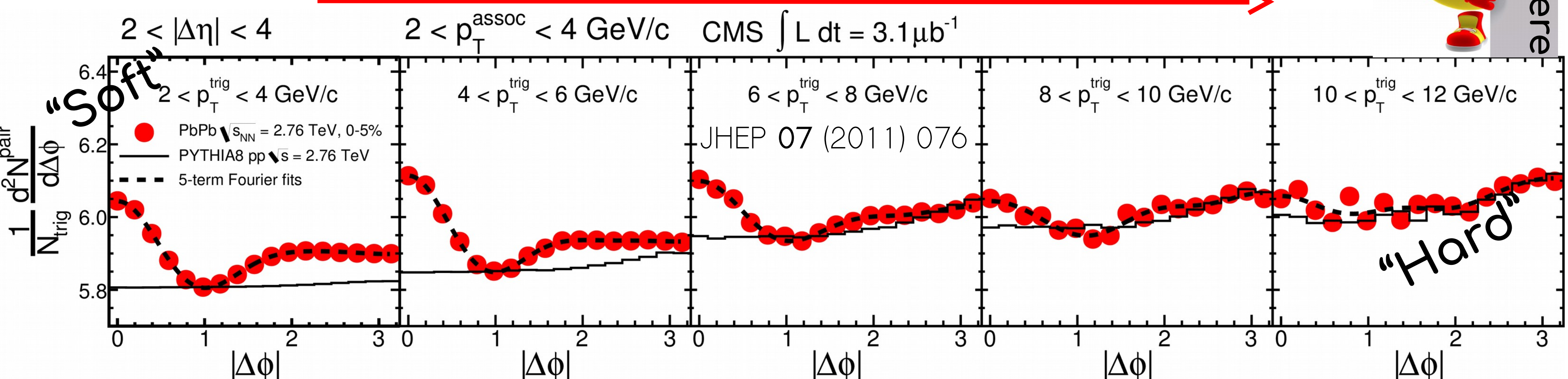
What is the primordial form that early Universe existed in?



- It was very much in the state of a "soup"
- Disproving the liquid hypothesis is **easy**
- Validating the liquid hypothesis is **tricky**
  - What happens to bound nucleons?

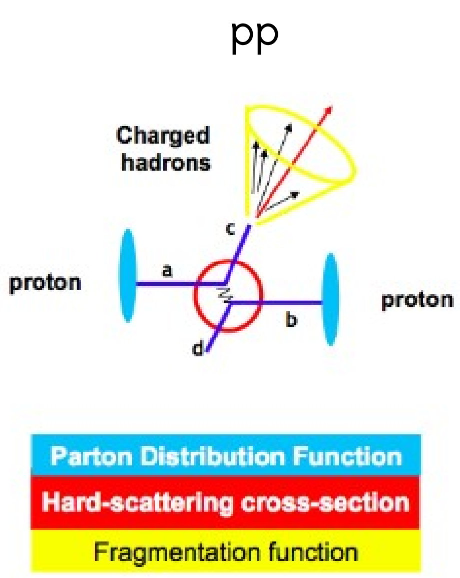
A fluid that retains its QCD **asymptotic freedom** character!

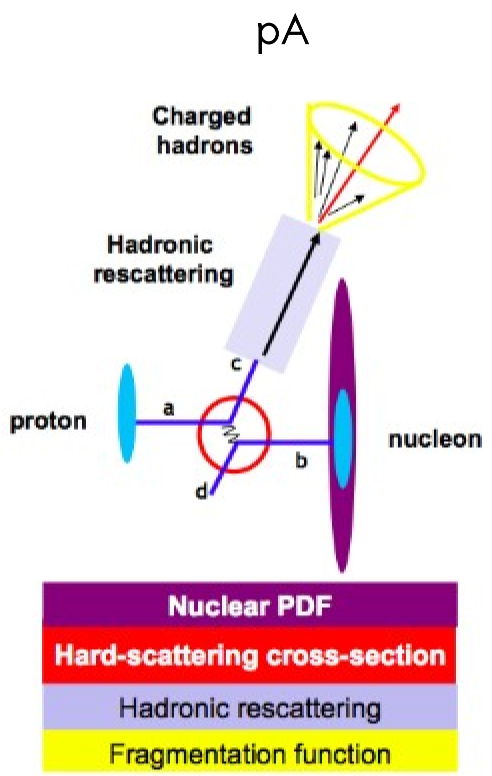


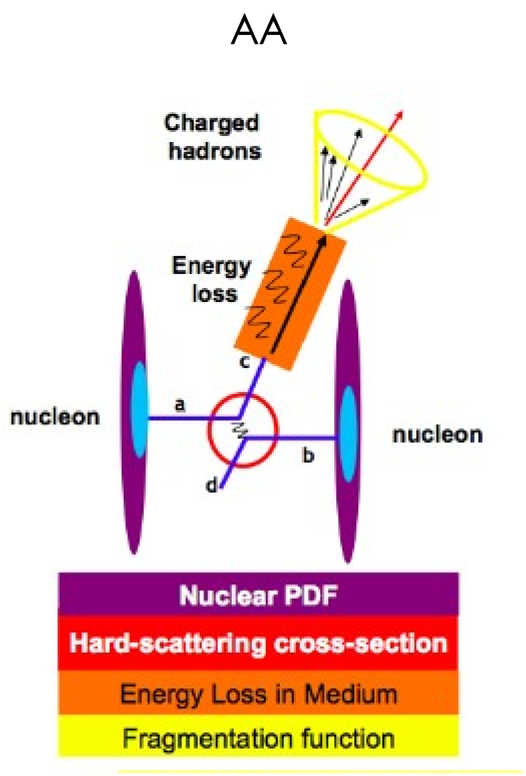


Experimental search for “interesting” phenomena

- Look at elementary pp and pA collisions
  - Measure an observable, e.g., “hard” probes such as Z/W boson, jet production
- Look at heavy ion (AA) collisions
  - Measure the very same observable as in pp, pA collisions
- Compare them: Is there something new, e.g., **incompatible to** the A scaling?

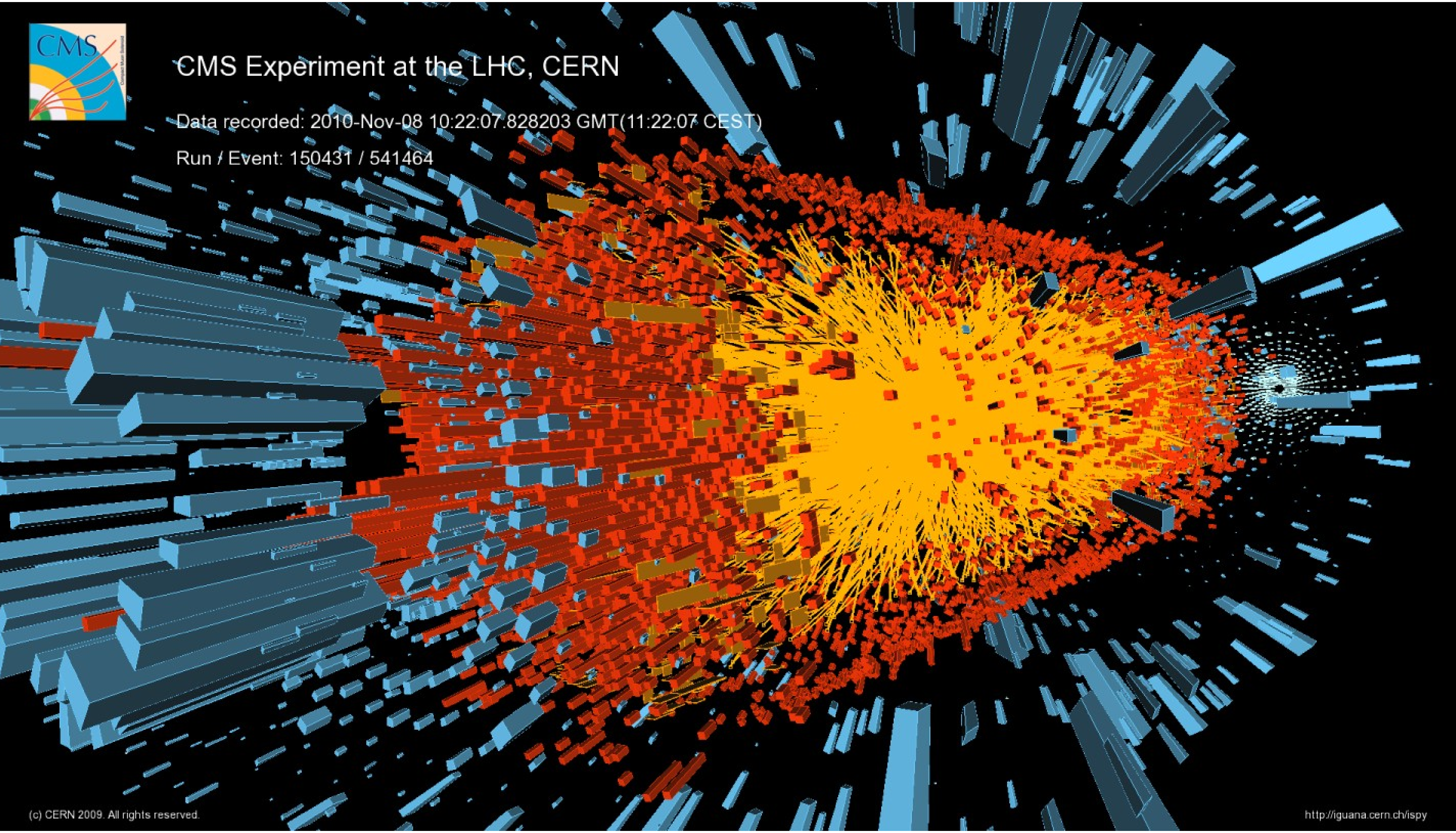






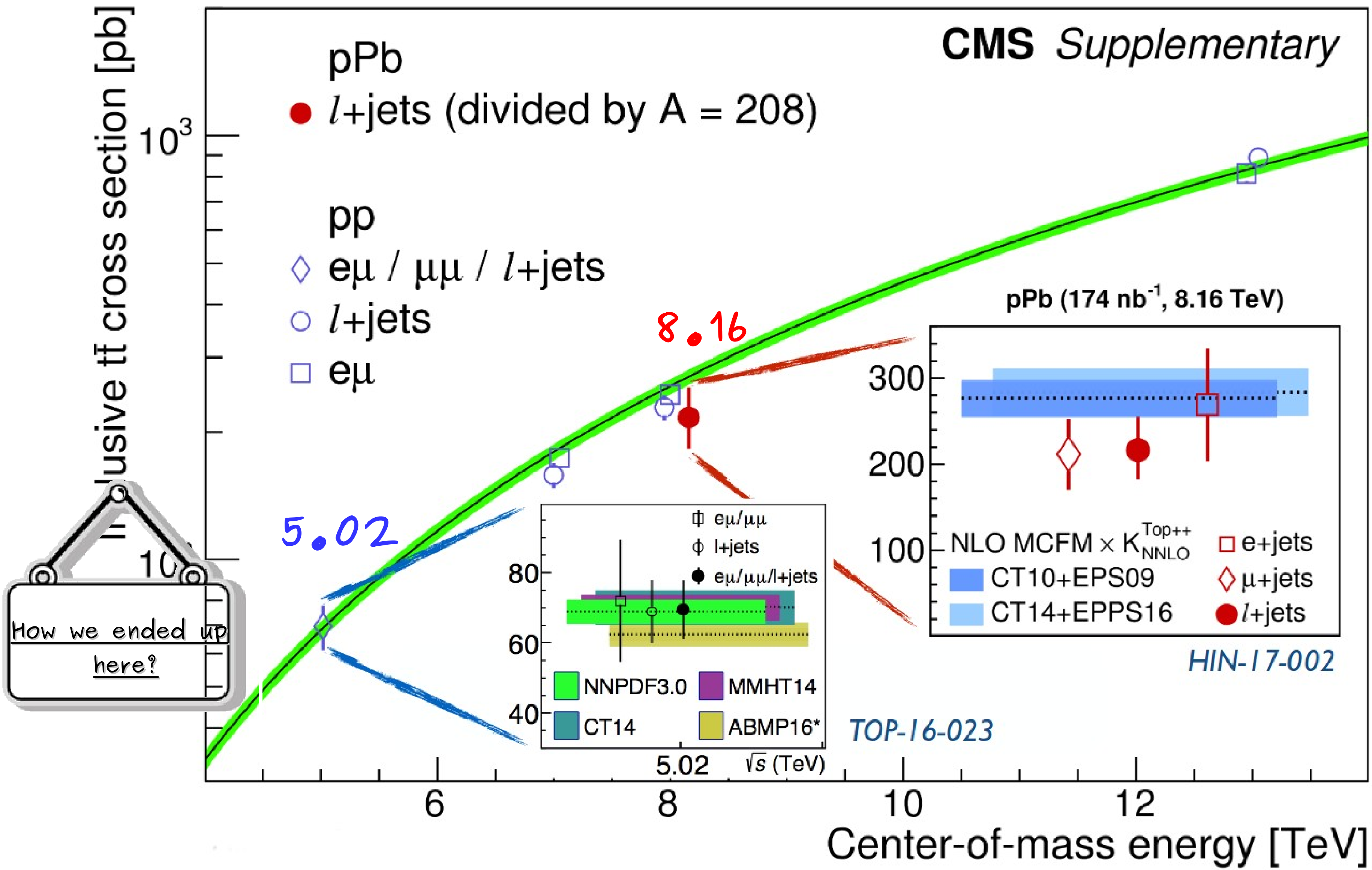
That's a mess ☺

CMS-PHO-EVENTS-2010-002-51



- We search for **distinct** event signatures, characteristic of particle production of some type

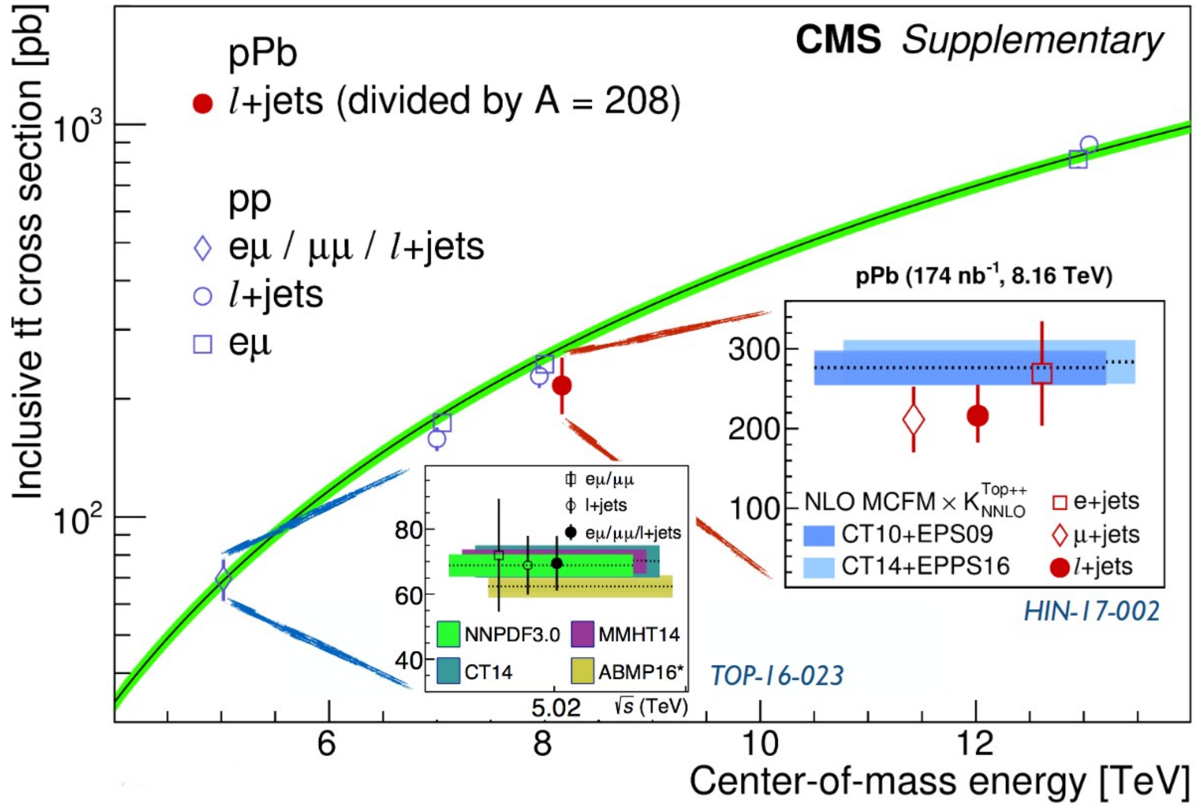
Did we have a probe and dataset never used before?



Probe: Top quark (pair production)

Dataset(s): Actually it turned out not to be one, but **two**!

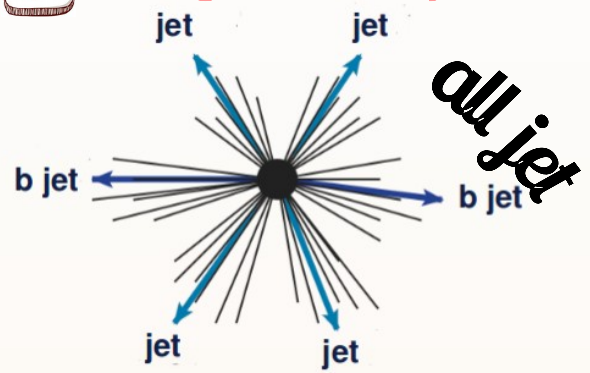
A multifaceted quark!



"Ideal" top-decay channels

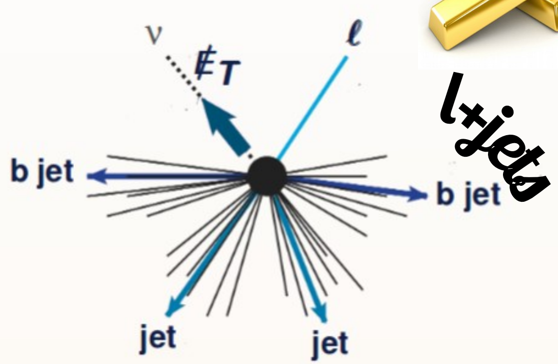
The highest BR

Large multijet bkg



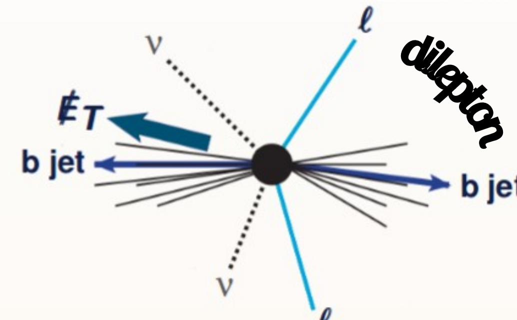
High BR, good S/B

W+jets bkg

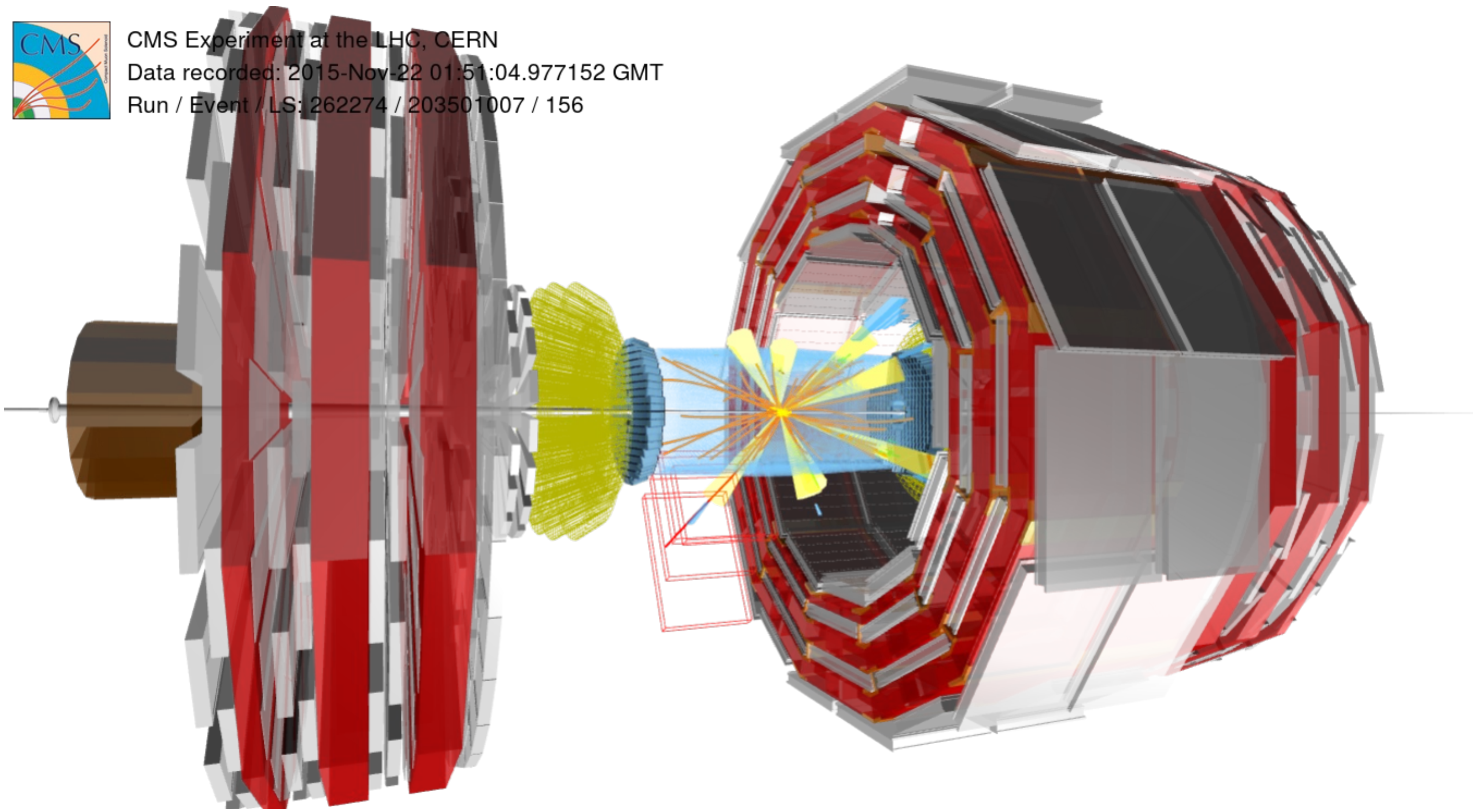


Excellent S/B

The lowest BR



The "top in pp @ 5.02 TeV" measurement



CMS-PAS-**TOP-16-015**
JHEP **03** (2018) 115

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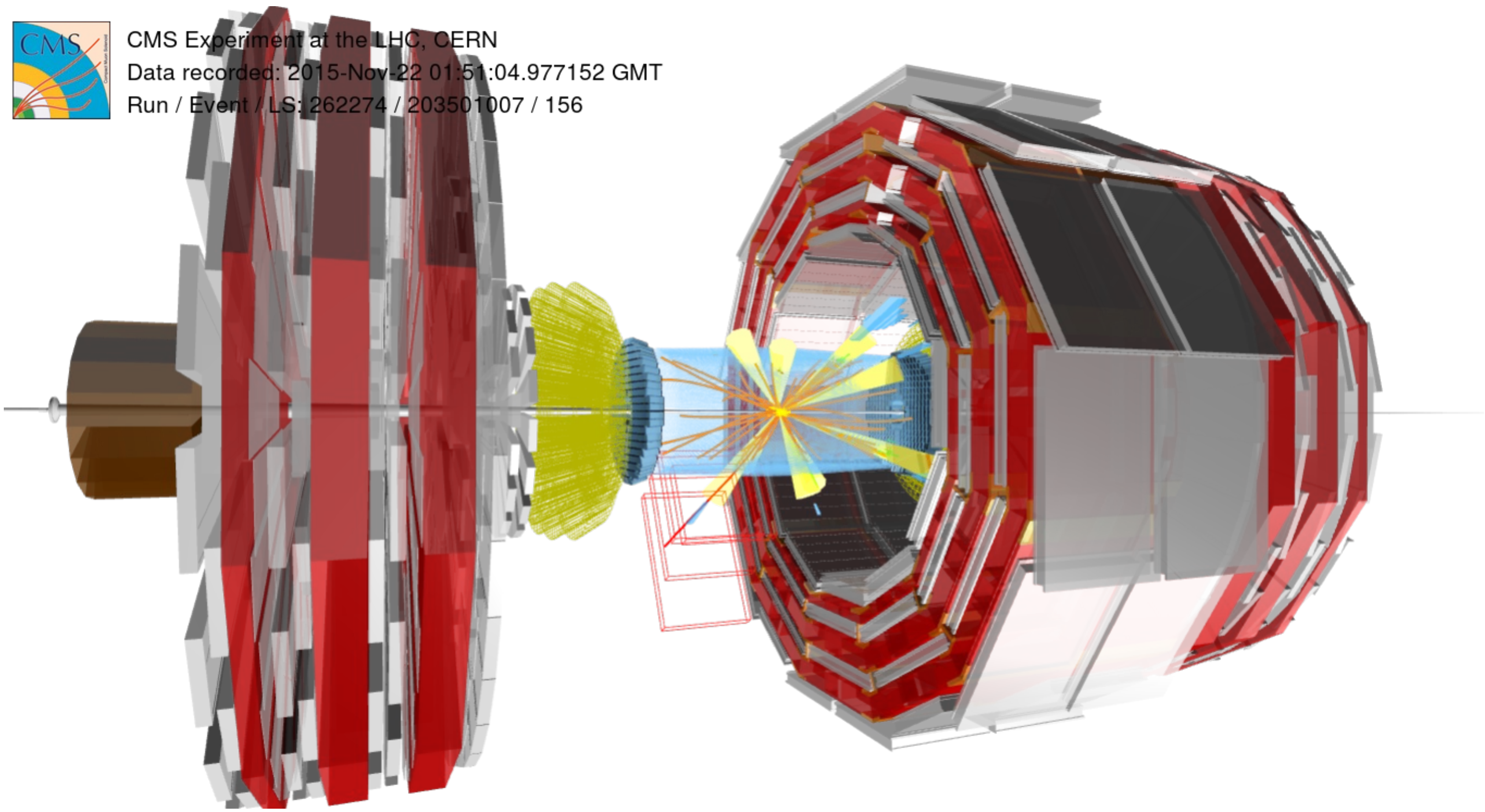
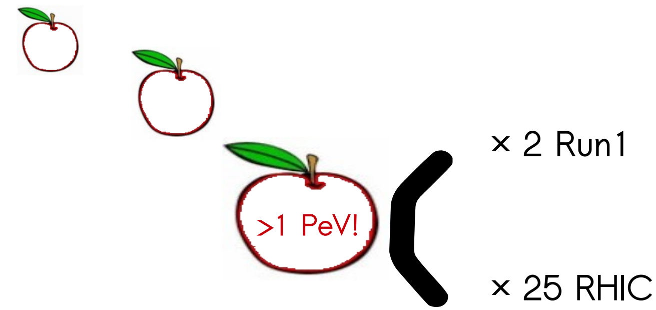
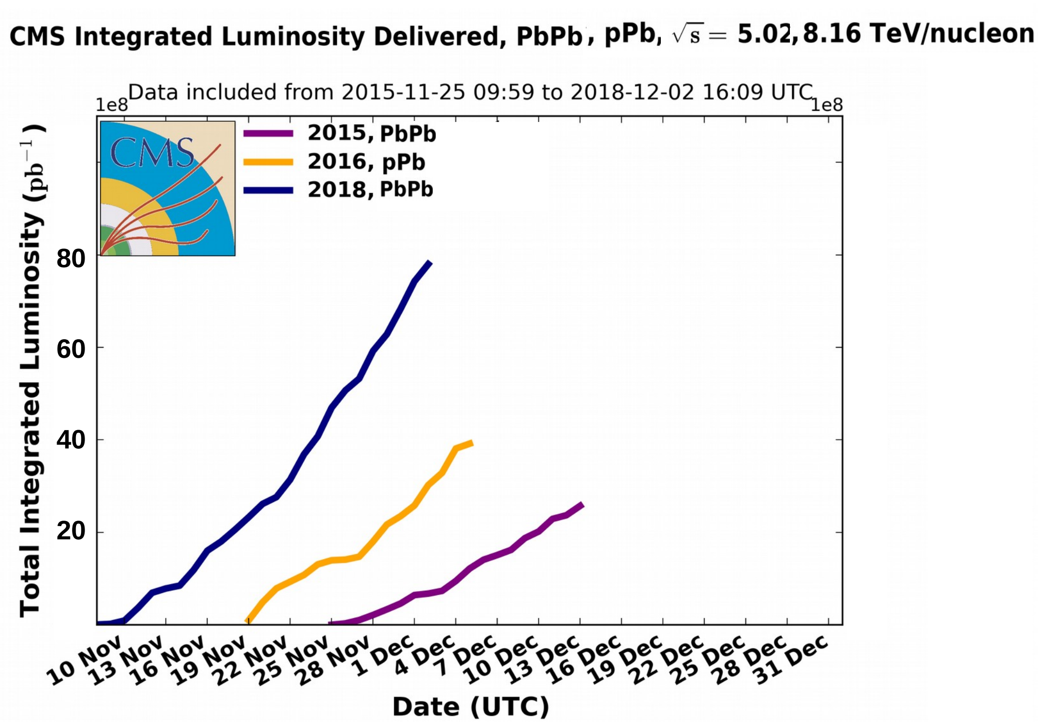


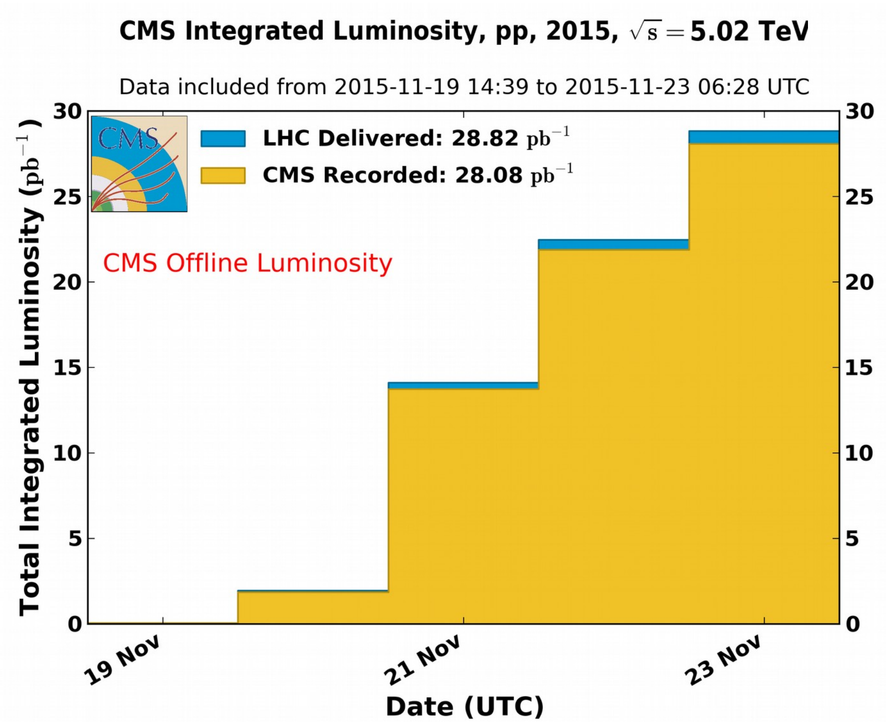
Dilepton event (very clean signature):
electron + muon + “jets” (spray of particles) + missing energy

Why recording collision data @ 5.02 TeV?

- Unique chance to compare **3** colliding species at the **same c.o.m** ($\sqrt{s_{NN}}$)
  - perform measurements in QCD vacuum and nuclear matter with
    - **pp** energy of 2.51 TeV; Nov 2015 (+2017)
    - **pPb** (beam) energy of $4Z$ TeV; Jan-Feb 2013
    - **PbPb** (beam) energy of $6.37Z$ TeV; Nov 2015 (+2018)
  - Price to pay: rapid commissioning between LHC configurations
    - PbPb delivered to **all experiments** for the first time though







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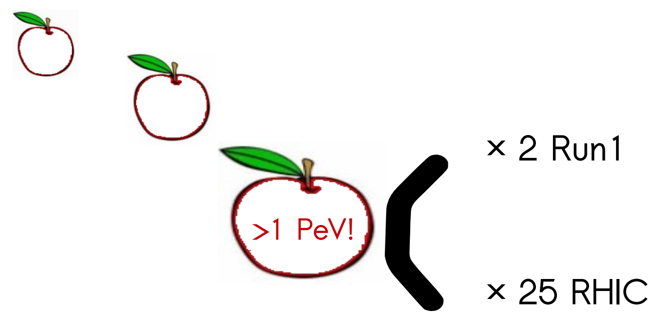
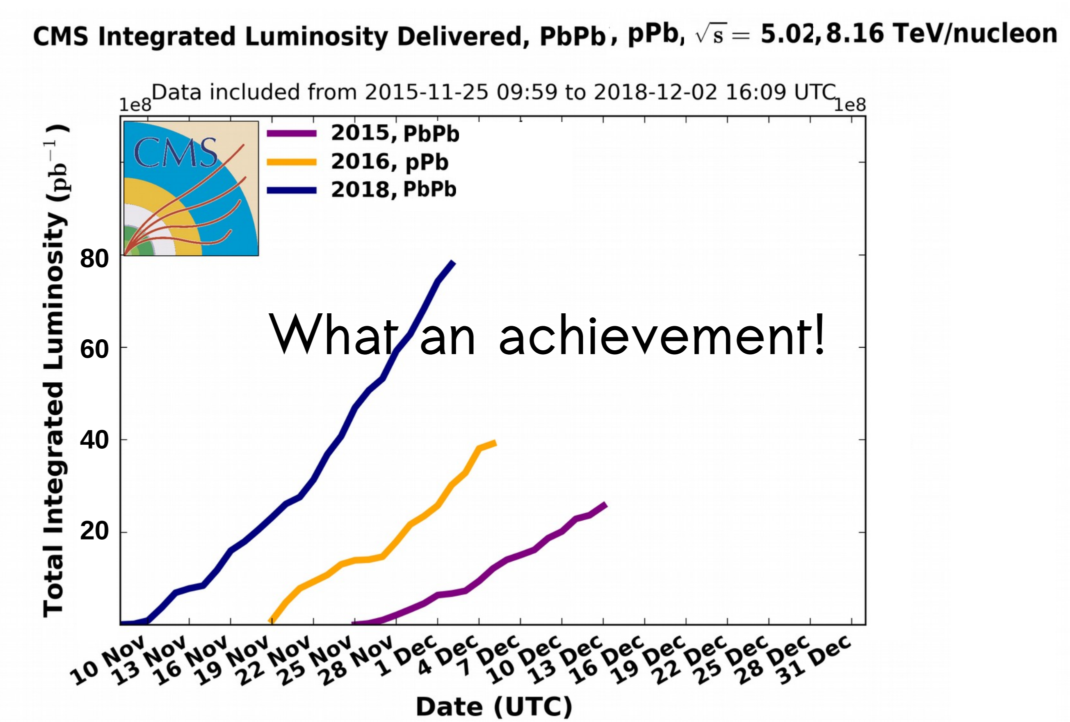
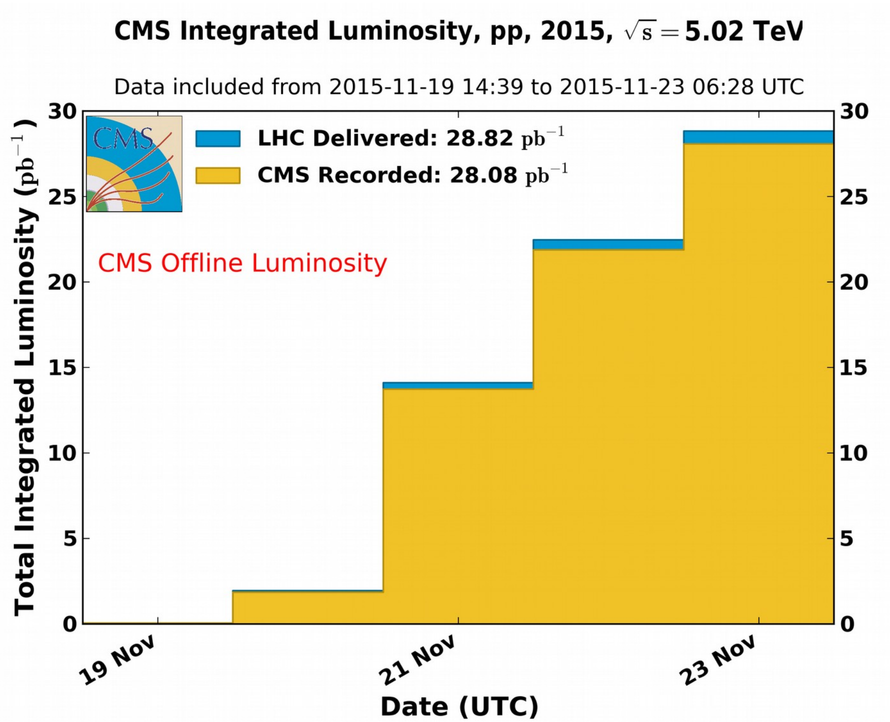
    - PbPb delivered to **all experiments** for the first time though



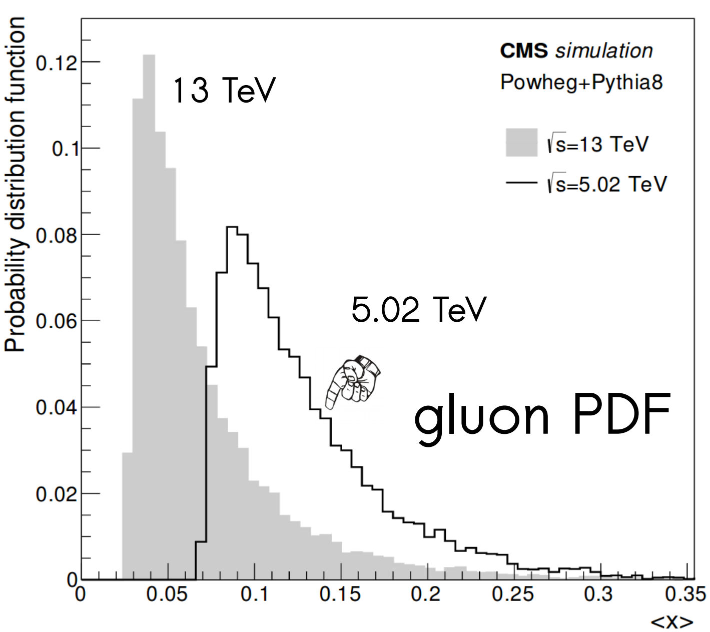


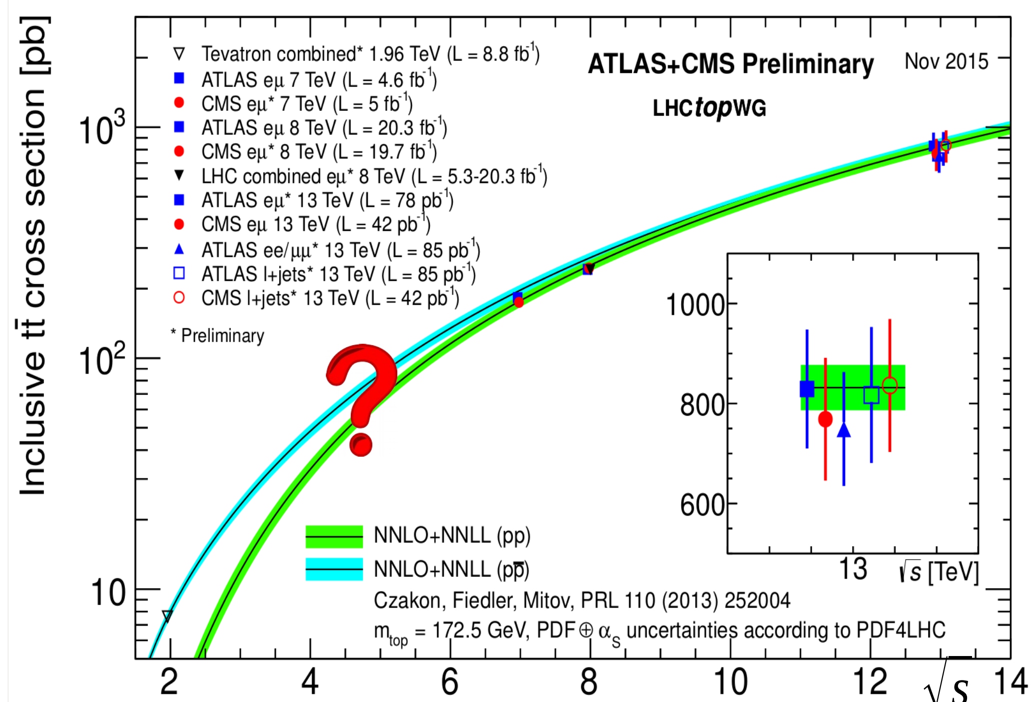


Why TOP @ 5.02 TeV? Any complementarity in place?

- Measurement of the $t\bar{t}$ cross section in pp @ 5.02 TeV
  - **tracks** the $\sqrt{s}$ evolution of the theo expectation
    - at an interesting "corner"
  - **probes** the production of large-$\langle x \rangle$ gluons
    - check the impact on gluon PDF and its uncertainty
  - **paves** the way for the first study in nucleus-nucleus collisions
    - no need to extrapolate from different $\sqrt{s}$

Nov 2015

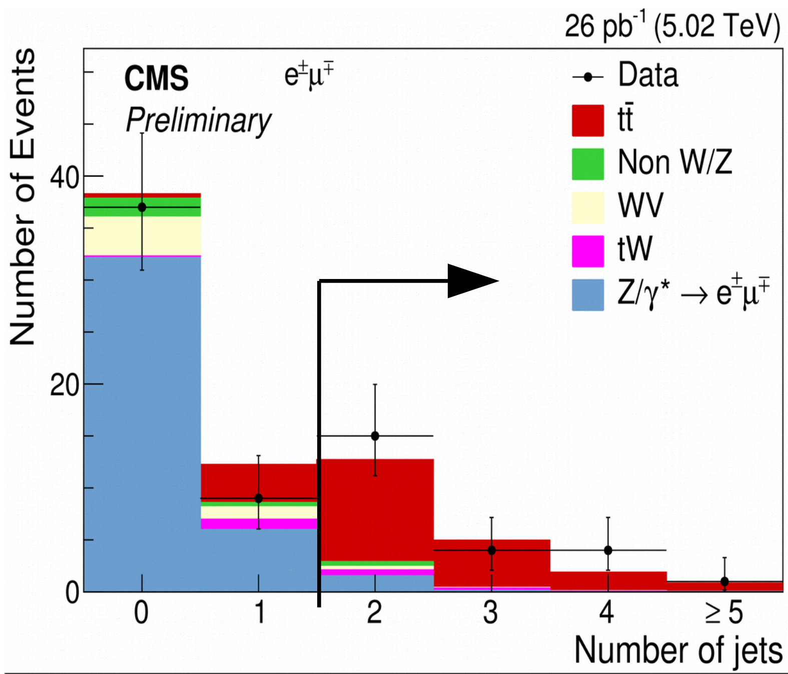


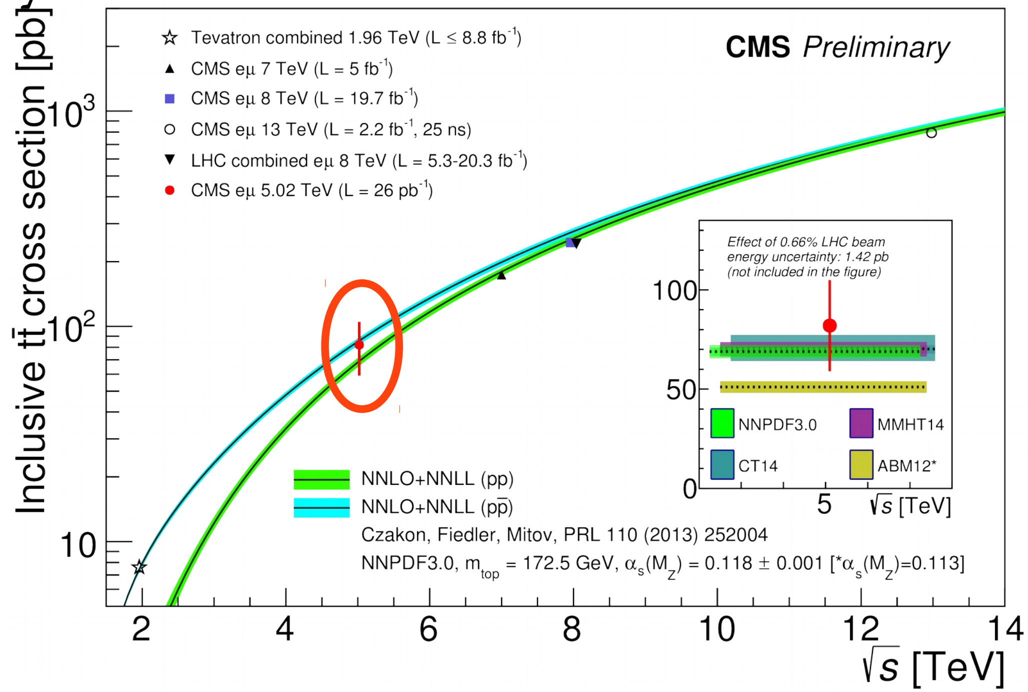


The first preliminary measurement: TOP-16-015

- First measurement using eμ events
  - achieved **only with** six attempts from LHC, resulting in a 28**%** tot unc
    - dominated by stat unc and **luminosity scale**

June 2016





Step	Object	Selection
0	Trigger	one muon candidate, $p_T > 15$ GeV
1	Electrons	"loose"ID, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$, $I_{rel} < 0.09$ (barrel), $I_{rel} < 0.12$ (endcap)
2	Muons	"tight"ID, $p_T > 18$ GeV, $\lvert\eta\rvert < 2.1$, $I_{rel} < 0.15$
3	Jets	$p_T > 25$ GeV, $\lvert\eta\rvert < 3$, $\Delta R(\text{jet, lepton}) > 0.3$
4	Dilepton pair	opposite charge $e^{\pm}\mu^{\mp}$, $m_{e\mu} > 20$ GeV, maximum p_T sum
5	Jet multiplicity	≥ 2

Can we do it better?

- A series of improvements were implemented
  - inclusion of **μ+jets** & **e+jets** channels
    - minimized sensitivity to statistics
  - inclusion of same lepton flavor **(ll)** channels, though more tricky
    - define an additional variable to suppress Drell–Yan; trigger-p_T thresholds
  - **offline calibration** of luminosity scale $\mathfrak{L}$
    - dominant syst unc

TOP-16-015

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Electron efficiencies	1.1	1.4
Muon efficiencies	2.4	3.0
Jet energy scale	1.1	1.3
Jet energy resolution	0.05	0.06
QCD scales of $t\bar{t}$ signal (PS)	1.0	1.2
QCD scales of $t\bar{t}$ signal (ME)	0.2	0.2
Hadronization model of $t\bar{t}$ signal	1.0	1.2
PDF	0.4	0.5
MC statistics	1.2	1.4
t W background	1.1	1.3
WV background	0.5	0.6
DY background	2.1	2.6
Non W/Z background	1.9	2.3
Total systematic (w/o luminosity)	4.6	5.6
Integrated luminosity	9.8	12
Statistical uncertainty	20	24
Total	23	28

How to search for *tt* pairs in l+jets and ll channels?

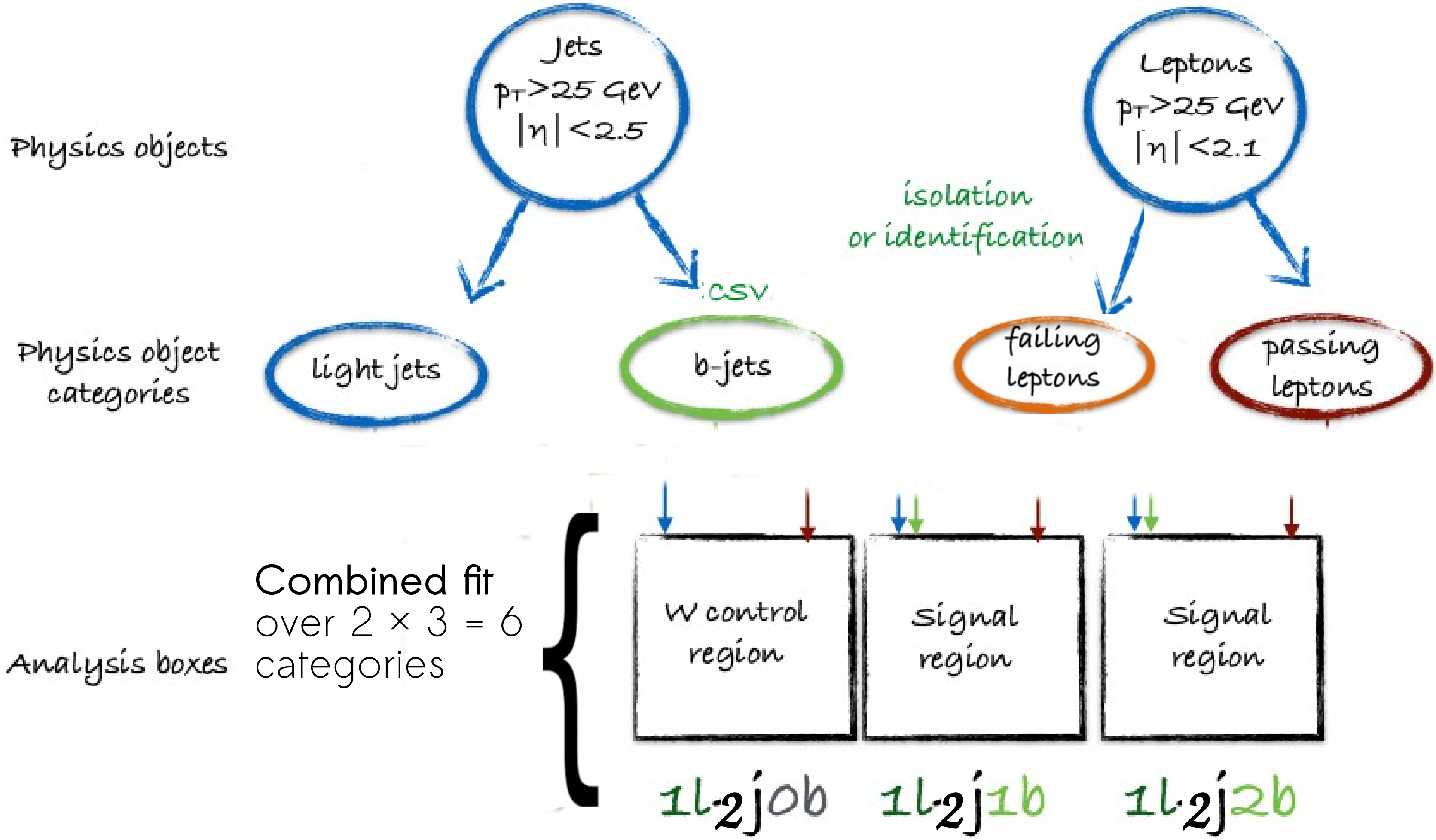
- l+jets : t t → bW bW → b l b jj' (+missing transverse momentum), i.e., crucial to search for the lepton & non-b jets (a.k.a. the light jets j,j')
  - lepton is triggered, then one has to think
  - how to retrieve the j,j' jets

→ to construct variable(s) of interest

Filter or physics object	ℓ+jets	Dilepton	
Trigger	one μ (e) candidate, $p_{\mathrm{T}} > 15$ ($E_{\mathrm{T}} > 40$) GeV	one μ candidate, $p_{\mathrm{T}} > 15$ GeV	
Leptons	exactly 1 μ or e	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
$M_{\ell\ell}$	—	> 20 GeV	
Z veto	—	—	Yes
$p_{\mathrm{T}}^{\mathrm{miss}}$	—	—	> 35 GeV
Jet multiplicity	≥ 2		
b tagging	CSVv2 L (Table 3.5) $\Rightarrow$ $1\ell2j0b$, $1\ell2j1b$, and $1\ell2j2b$		

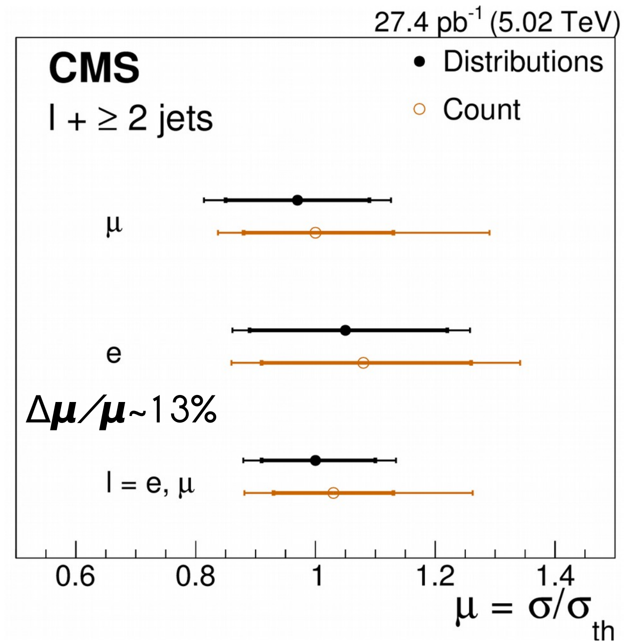
Overview of the event categories in l+jets

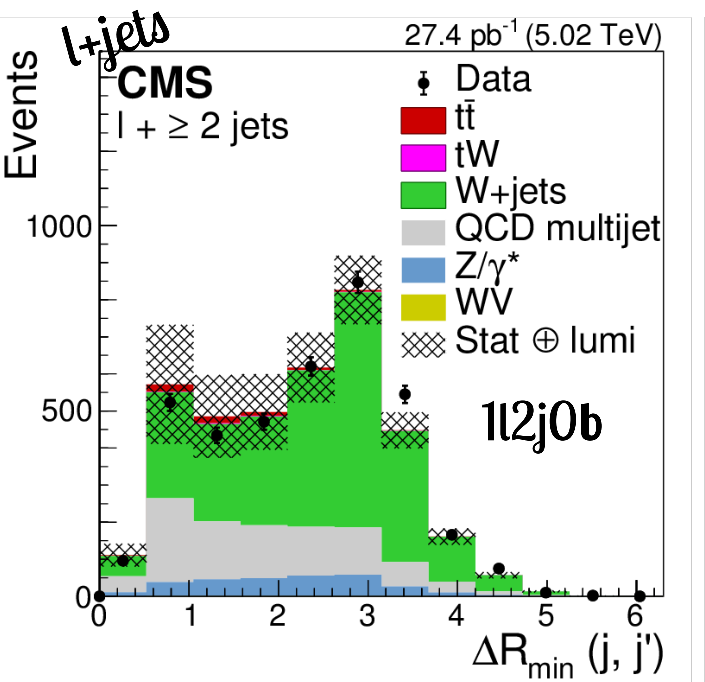
- l+jets : $t\bar{t} \to bW\ bW \to b\ l\ b\ jj'$ (+missing transverse momentum), i.e., crucial to search for the lepton & non-b jets
  - lepton is triggered, then one has to think
  - how to retrieve the j,j' jets → to construct variable(s) of interest

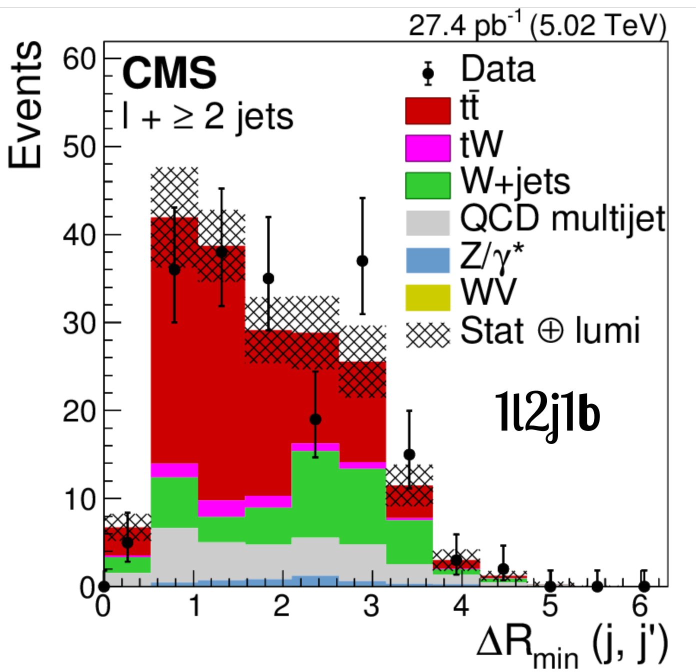


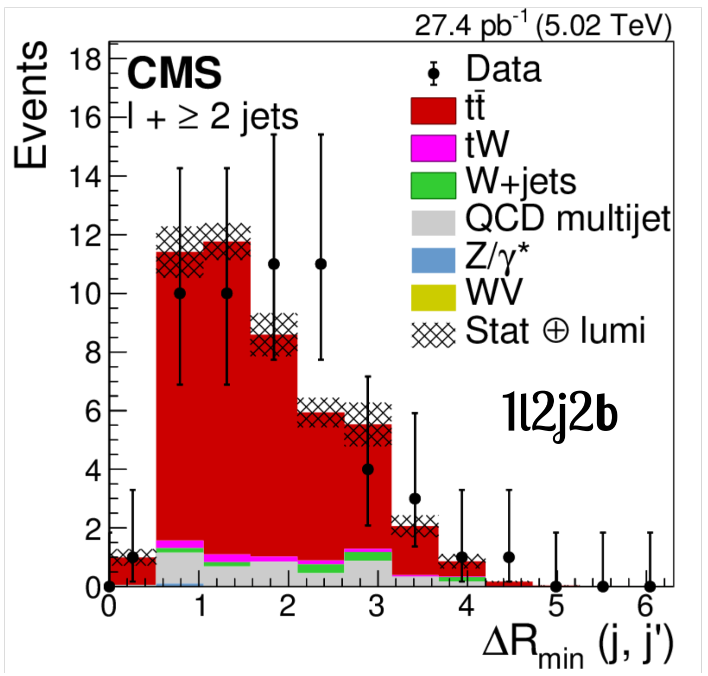
Further minimized the sensitivity to syst unc

- Good agreement between exp & obs μ
  - fit over distributions **drives sensitivity**
    - syst ≈ stat
  - mu+jets channel **better constrained**
    - looser selection









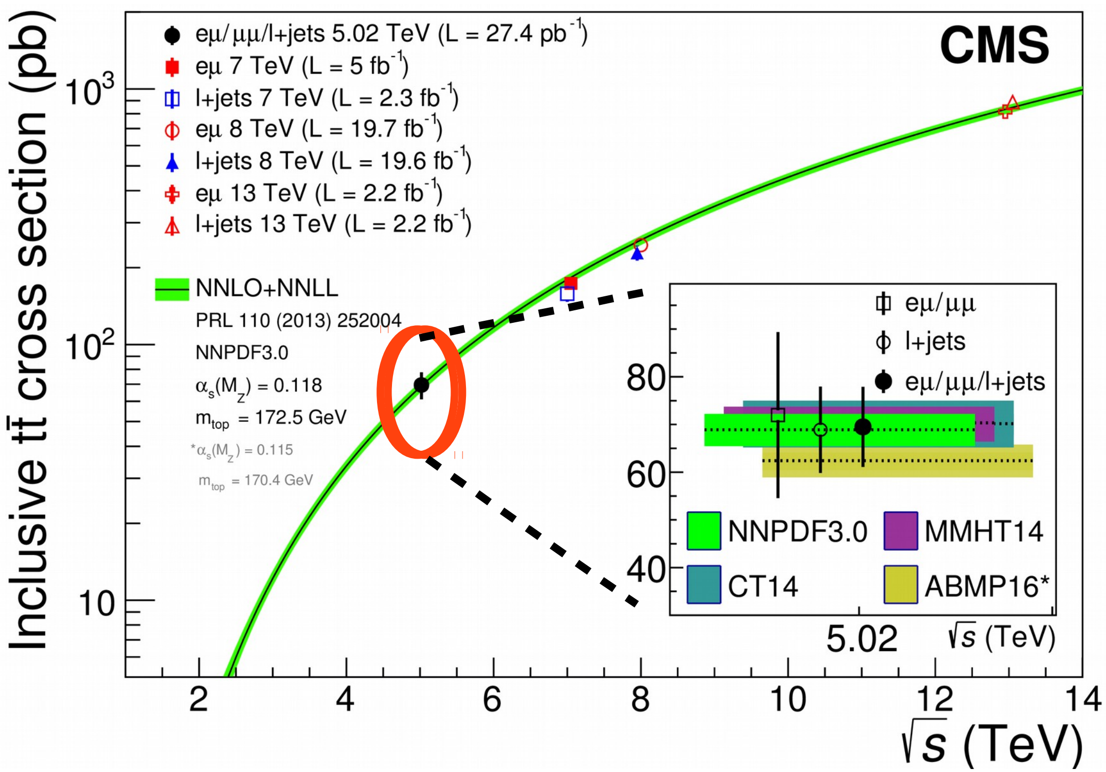
min**Δ**R(j,j') **≡** angular distance of the least separated jets

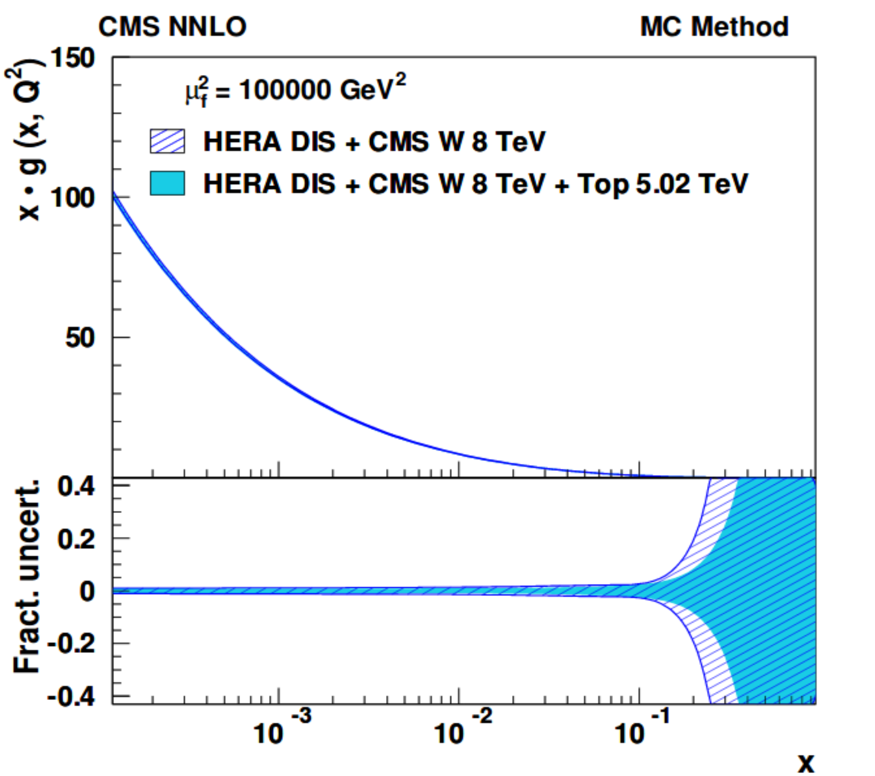
What is the attained precision in the combination?

- TOP-16-023 establishes CMS as **the only experiment** measuring *tt* inclusively in **4** energies
  - **independent** channels, i.e., eμ, $\mu\mu$, μ+jets & e+jets
    - combined based on the best linear unbiased estimator (BLUE) method
    - total unc. of **12%**
  - moderate **reduction of the uncertainty** in the gluon distribution at high *x*

JHEP **03** (2018) 115

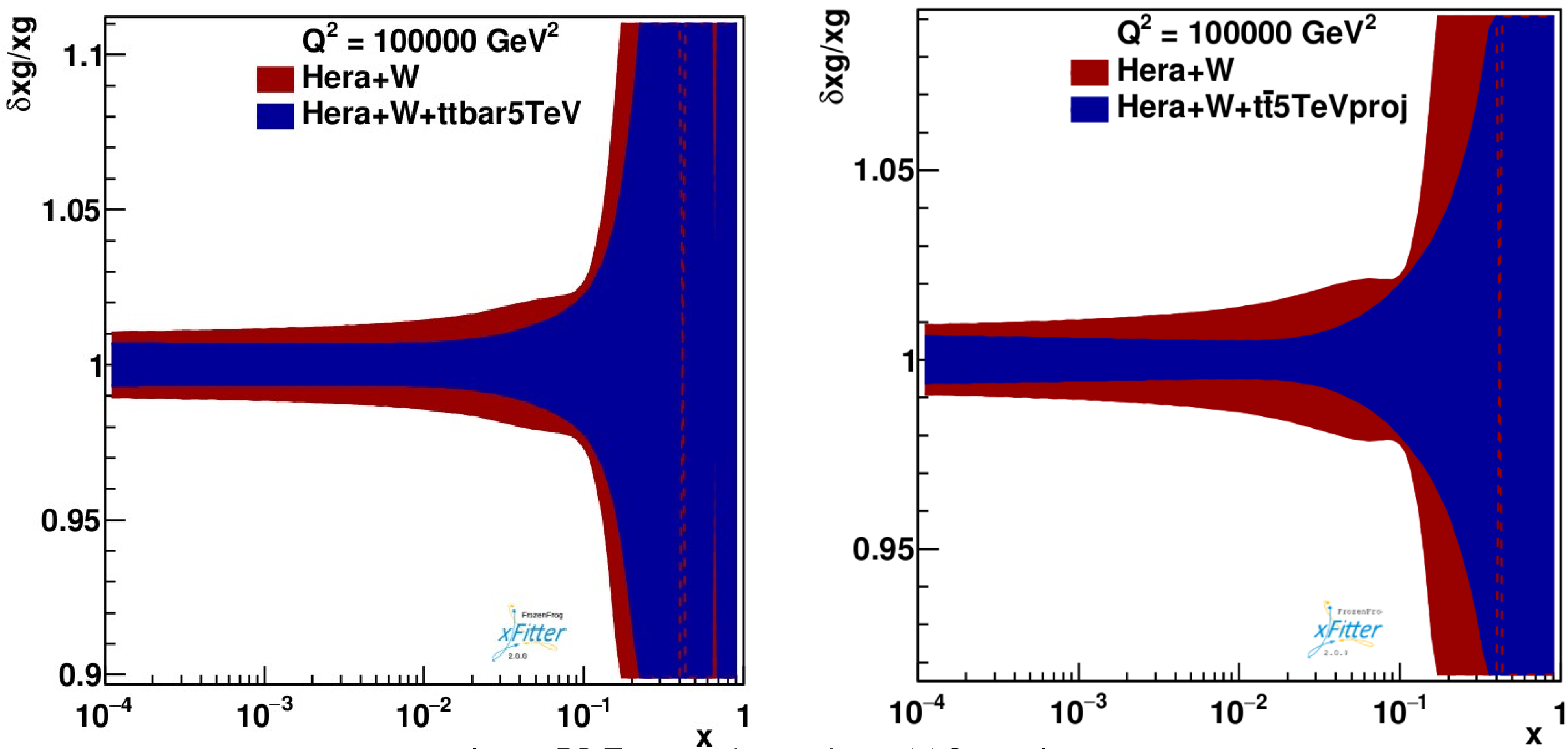
$$\sigma_{\text{tot}}(\text{pp} \to \text{t}\bar{\text{t}}) = 69.5 \pm 6.1\,(\text{stat}) \pm 5.6\,(\text{syst}) \pm 1.6\,(\text{lumi})\ \text{pb}$$





Reference pp data in 2017: update and extend measurements!

*As in JHEP **03** (2018) 115* | *As expected*



gluon PDF: unc. based on MC replicas

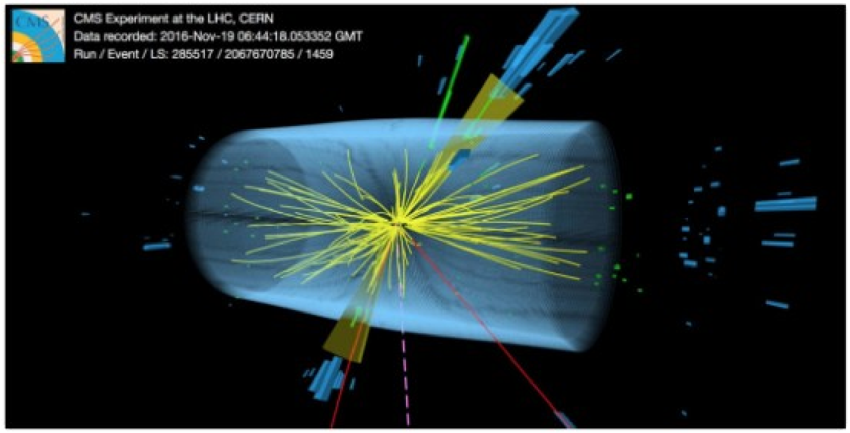
- Indeed, an increased sensitivity within $0.01 \lessapprox x \lessapprox 0.4$
  - an uncertainty reduction is expected for "valence" quark PDFs as well

The discovery of “top in nuclear collisions”

Marta Verweij @MartaVerweij

Follow

Look what we found in our pPb data!



6:30 AM - 29 Nov 2016

9 Retweets **17** Likes

2 9 17

John Jowett @JohnJowett · 29 Nov 2016

Replying to @MartaVerweij

Can't quite read off the invariant mass from that picture ?

1

Tristan du Pree @Tristan_duPree · 29 Nov 2016

You can leave that to @MartaVerweij ;)

1

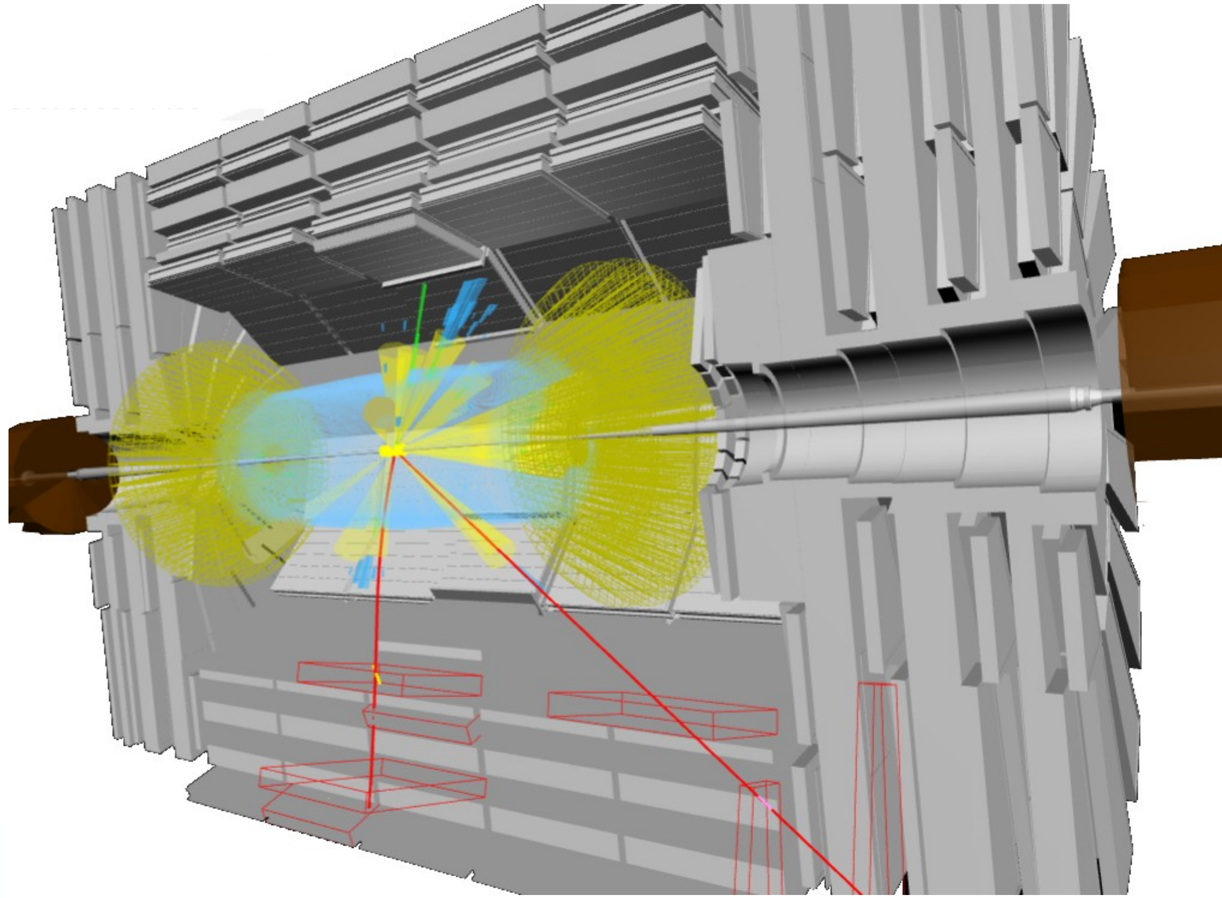
Marta Verweij @MartaVerweij · 29 Nov 2016

Need #MoarData from #pArunatLHC to give precise number!

Martijn Mulders @MuldersMartijn · 30 Nov 2016

Replying to @MartaVerweij

Hi @MartaVerweij ... is that what I think it is?

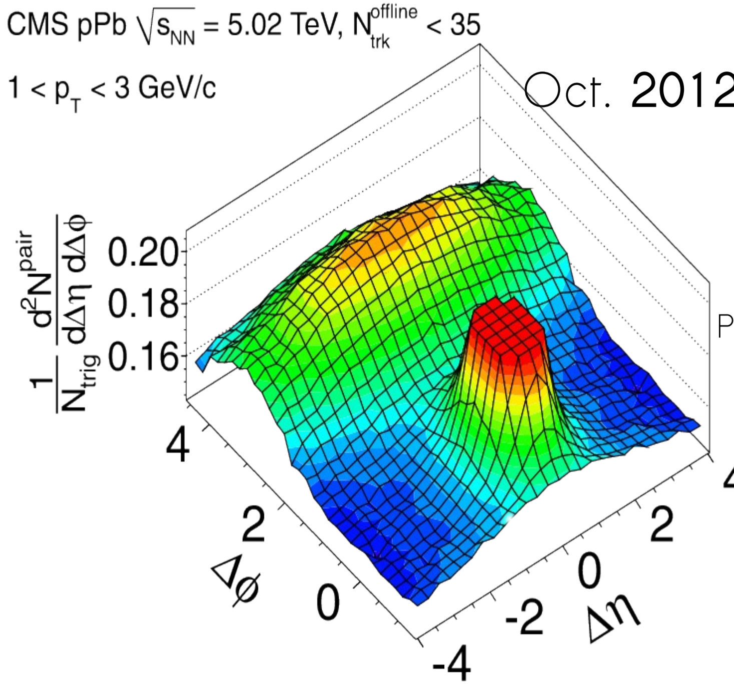


Phys Rev Lett **119** (2017) 242001

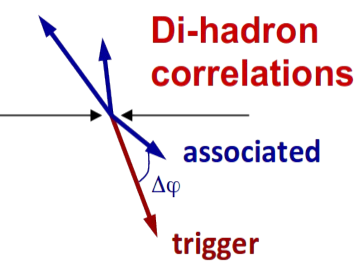
Throwing a bullet through an apple… Why?

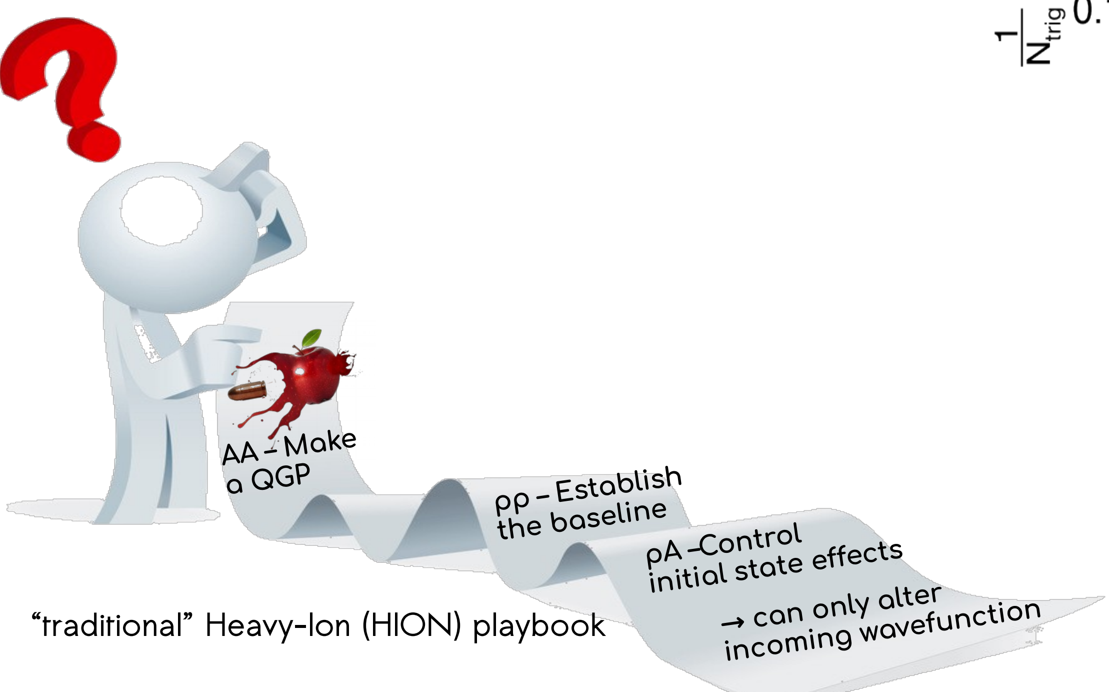
- Initially only thought to gain insight about **cold** QCD matter
  - The first collisions of unequal species @ LHC revealed **surprises**
    - signs **similar** to those of the quark-gluon plasma (QGP)
    - interest exploded (the 5th most cited CMS paper in PLB!)

Oct. 2012



Phys. Lett. B **718** (2013) 795

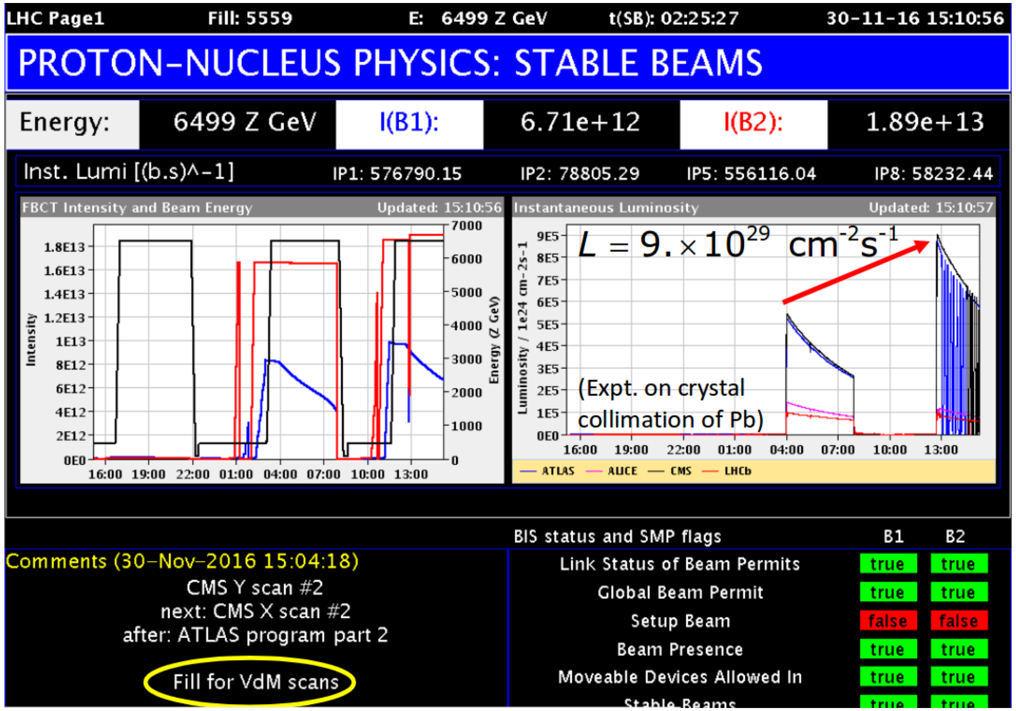




“traditional” Heavy-Ion (HION) playbook

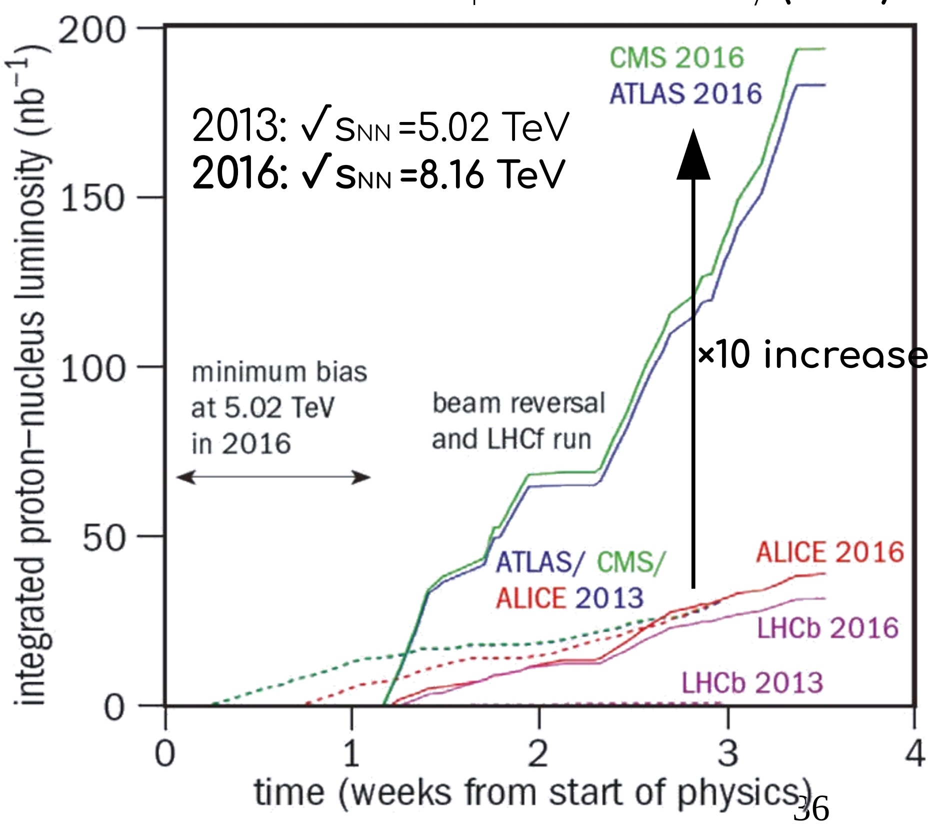
The first system fulfilled high-luminosity requirements!

- One of the primary goals of the **2016 pPb** run, i.e., **>** 100/nb, achieved
  - further data sets delivered parasitically, e.g, beam-gas interactions @ LHCb
- **Record** luminosity and Fill duration
  - instantaneous luminosity **surpassed** the “design” value by almost a factor 8
  - the longest-ever LHC Fill (5510) achieved: 38hr!



Pb **debris** prohibited from going even higher : (

pPb int. luminosity ($\mathfrak{L}$int)



Interest + ingenuity ⇒ $\mathfrak{L}$int =174±6/nb (!)

The first search analysis for tt in nuclear collisions!

- **l+jets** : $t\,t \rightarrow bW\,bW \rightarrow b\,l\;b\;jj'$

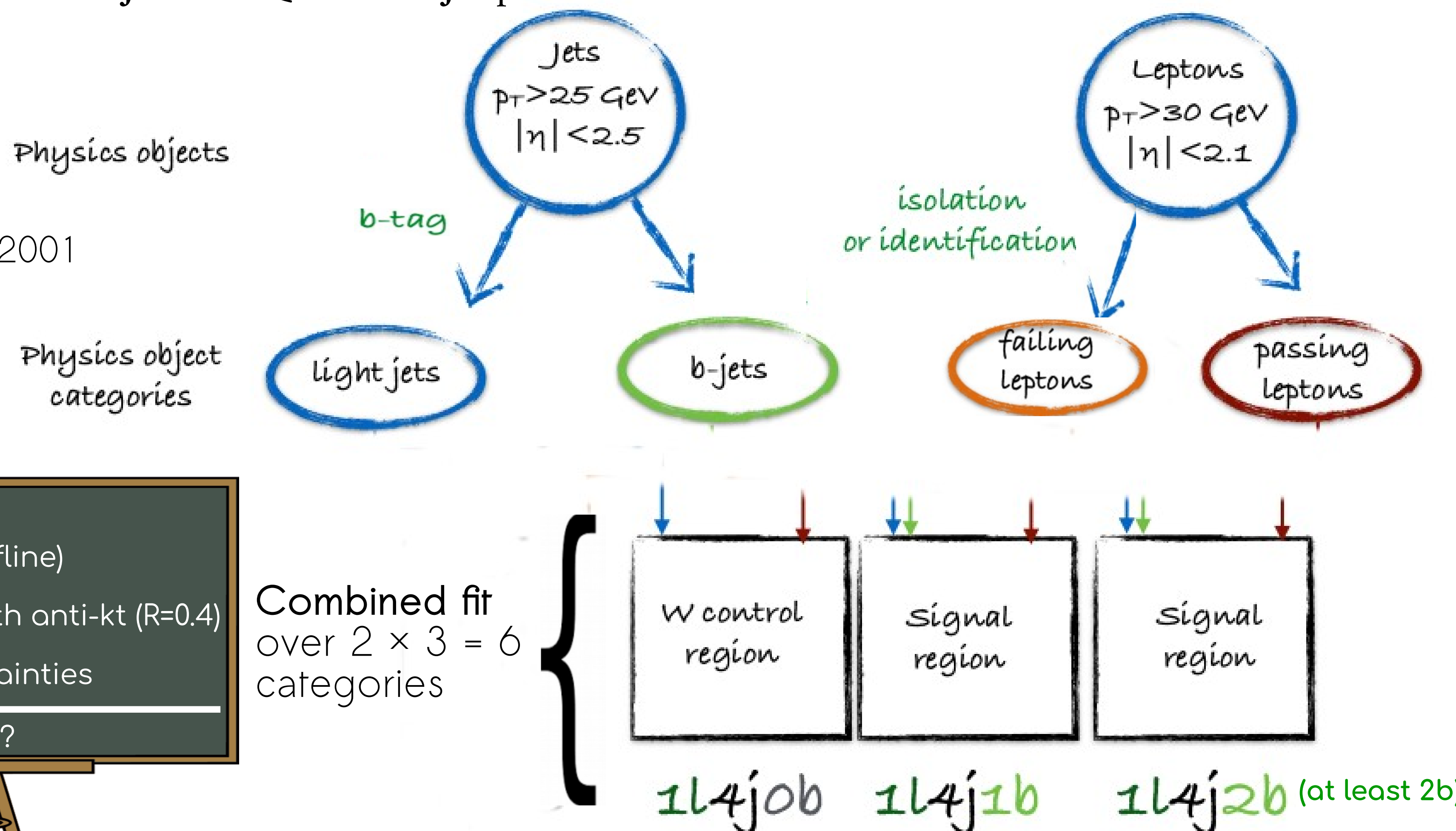
  we search for the lepton (l= e,μ) & the light jets j,j'

  - j,j' jets are paired based on their proximity in (η,φ) space (minΔR separation)

    → to construct the variable of interest; here the $\mathbf{m_{jj'}}$ inv. mass

  - main bkg from **W+jets** and **QCD multijet** production

PRL **119** (2017) 242001



1 triggered l (l=e,μ)

+ 0 extra leptons (offline)

+ 4 jets clustered with anti-kt (R=0.4)

+ systematic uncertainties

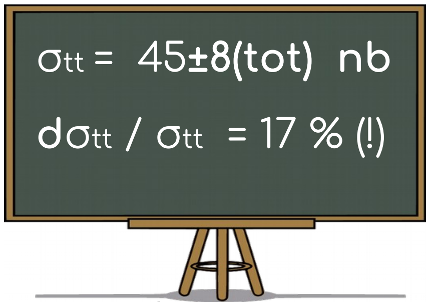
excludes *null* > 5σ ?

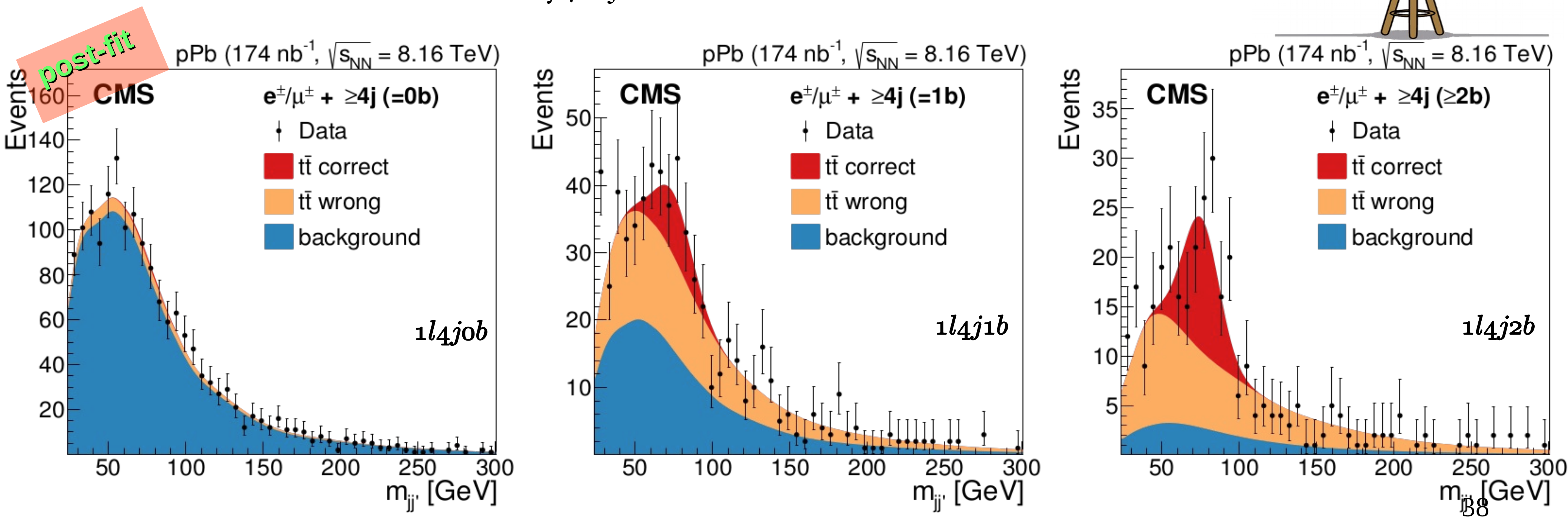
Measuring the *tt* production cross section (l+jets)

- Basic ingredients: **acceptance** (A) and **efficiency** (ε)
  - A = 0.060±0.002(tot) (0.056±0.002(tot)) in μ (e)+jets channel
    - determined @ NLO with **POWHEG** (v2) in the fiducial region
  - ε = 0.91±0.04(tot) (0.63±0.03(tot)) in μ (e)+jets channel
    - measured in data with "tag-and-probe" method (Z boson candle)
- Total number of signal (S) events in all 6 cats. : **S = 710 ± 130(tot)**
    - combination dominated by μ+jets channel

$$\sigma_{t\bar{t}} = \frac{N - N_{B}}{\varepsilon \, \mathcal{A} \, \mathcal{L}}$$

$\mathcal{L}_{int}$ =174 /nb

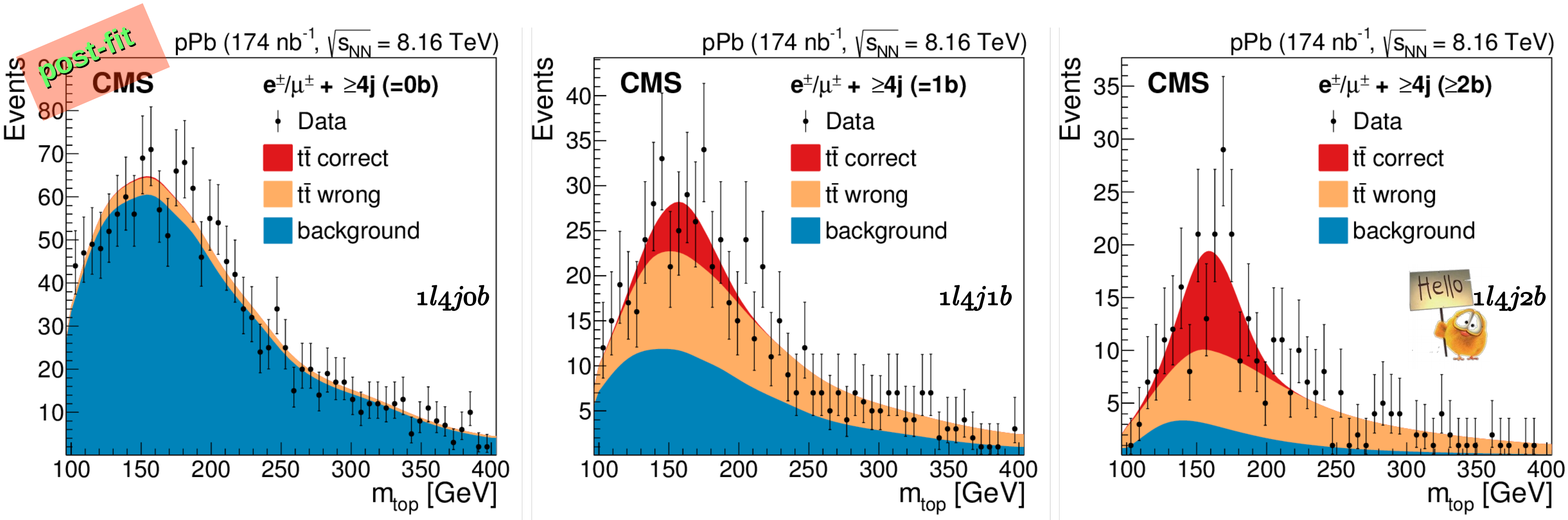




Background completely determined from data!

An "alternative" to the Bayesian posterior

- To further support the consistency with the production of top quarks
  - the inv mass of the **jj'b** triplet ("hadronic" top mass) is plotted
    - b jet candidate with the highest CSV value
  - signal and bkg contribution scaled to **post-fit** $m_{jj'}$ values

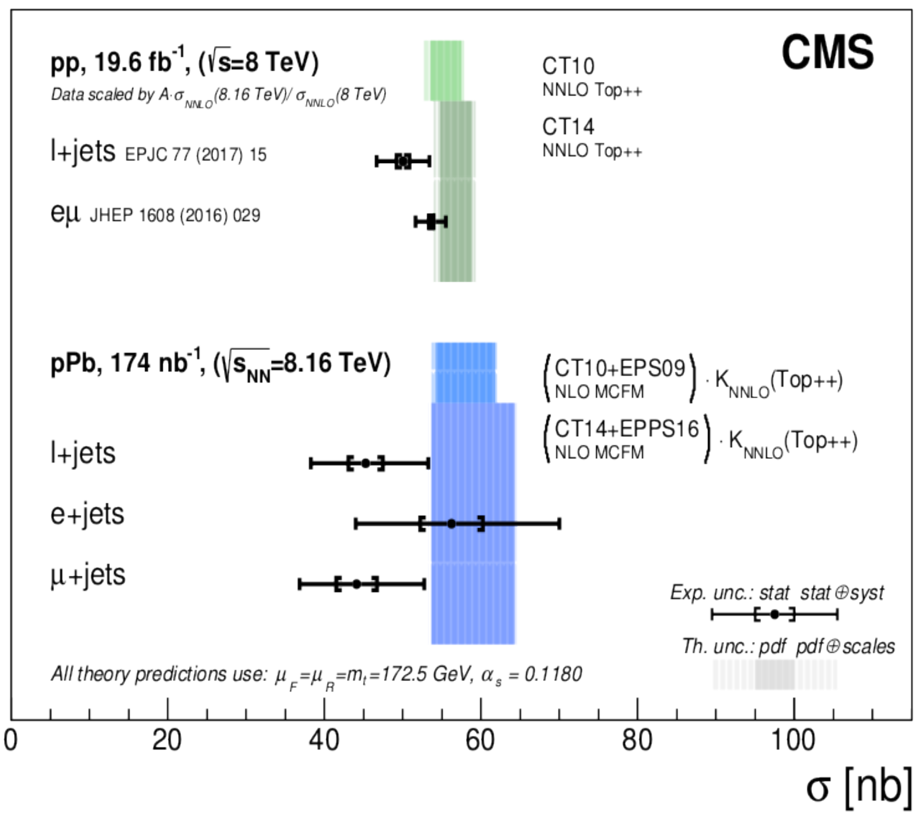


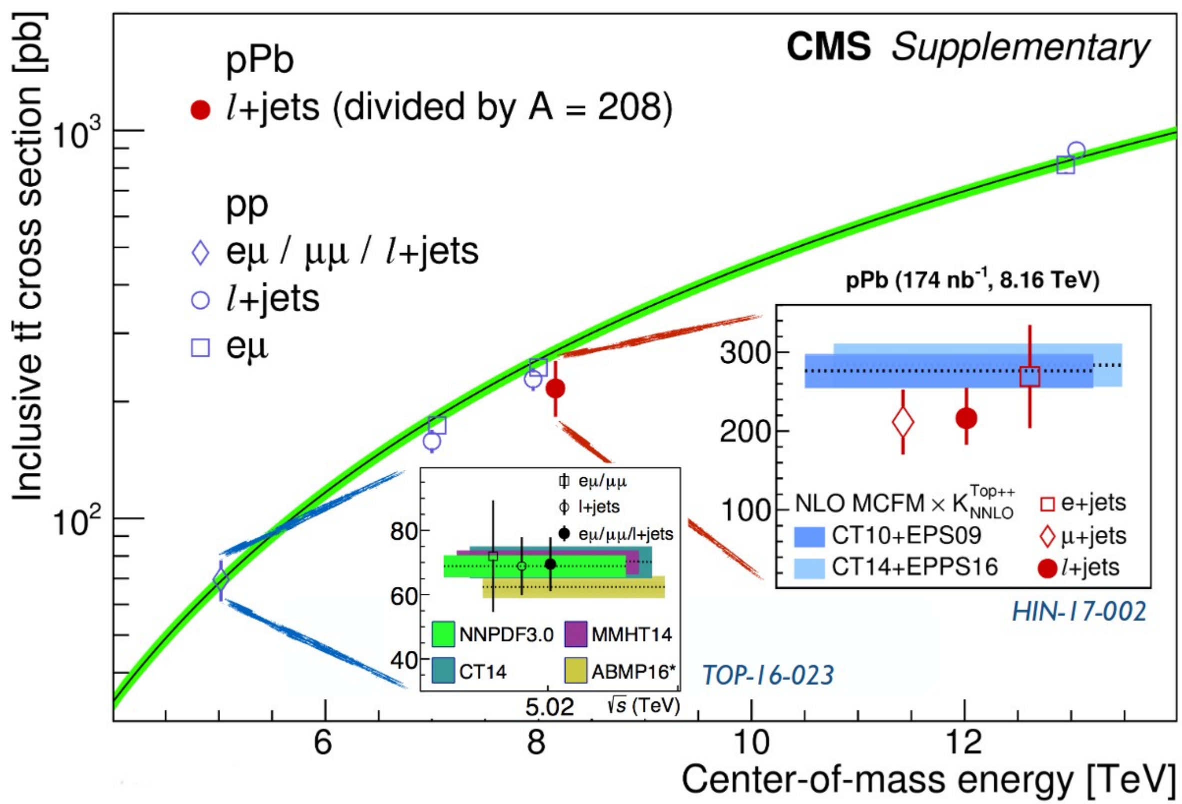
Even a peak is reconstructed close to m_t !

Up-to-date compilation: 4 $\sqrt{s_{NN}}$ & 2 systems @ LHC!

- First experimental **observation** of the top quark in nuclear collisions
  - σ_{tt} measured in **two** independent decay channels, i.e., μ,e+jets
    - **d**σ_{tt} / σ_{tt} = 17% in the l+jets combination
    - **consistent** with pQCD calculations and scaled pp data

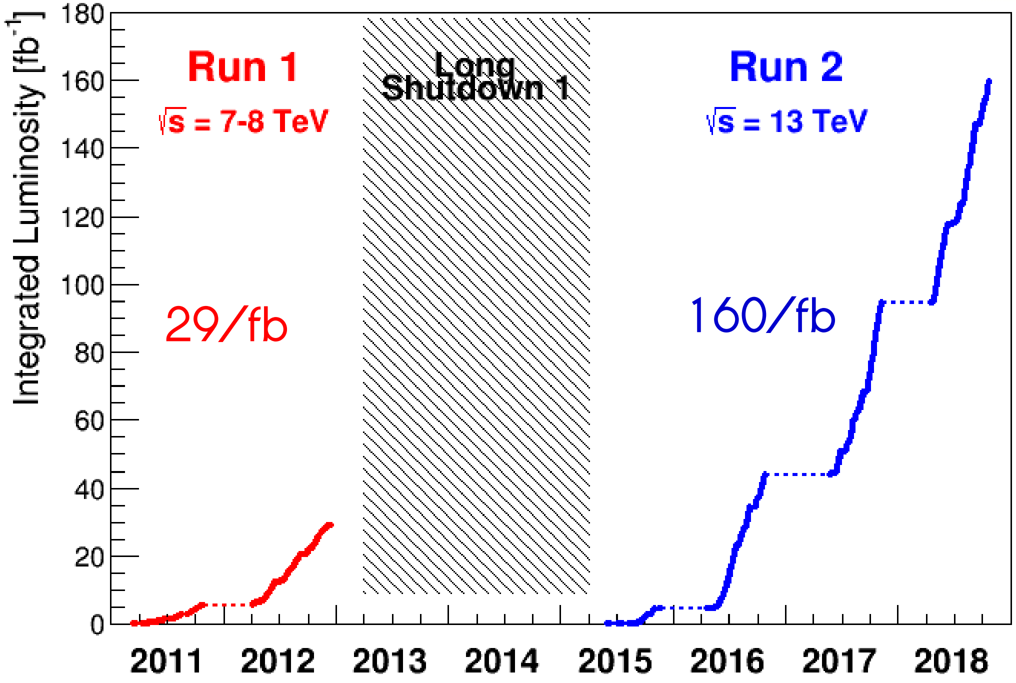
PRL **119** (2017) 242001



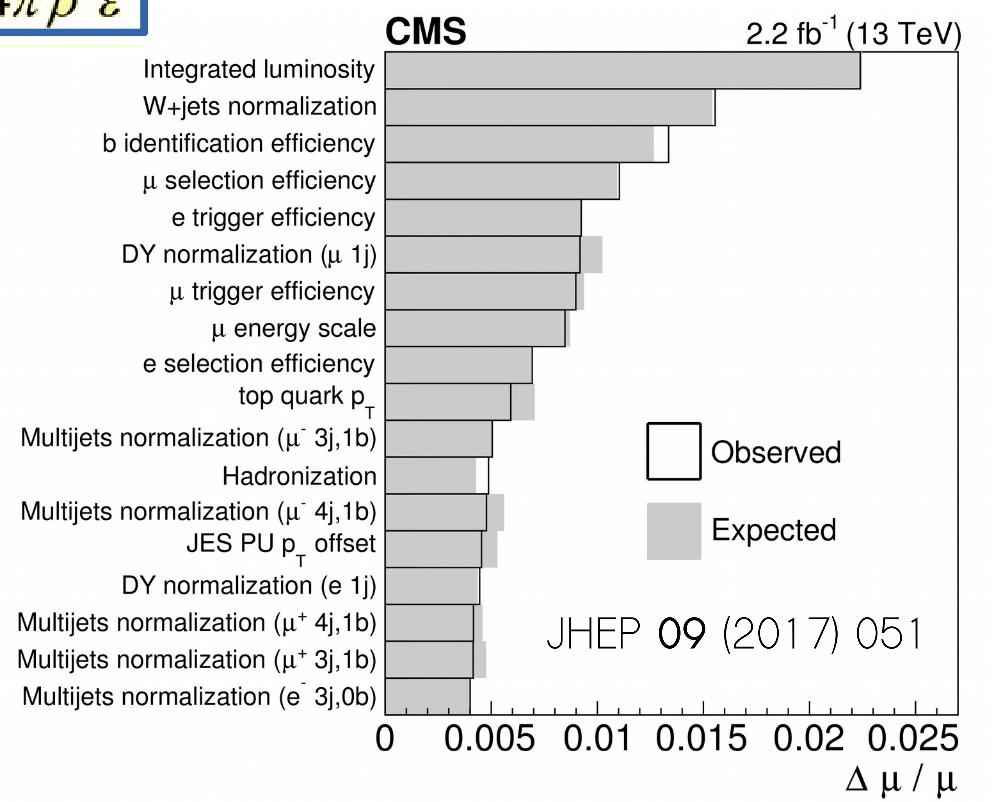


Luminosity: “a blessing and a curse”

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon}$$



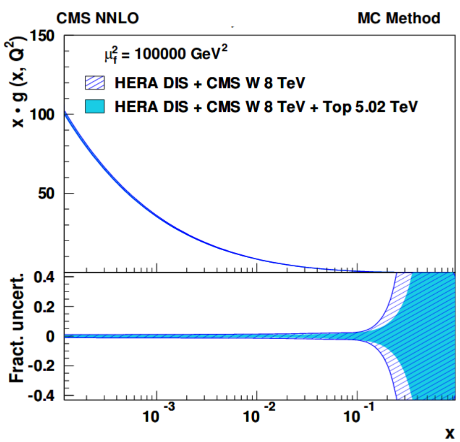
Impact of syst unc on *tt* cross section

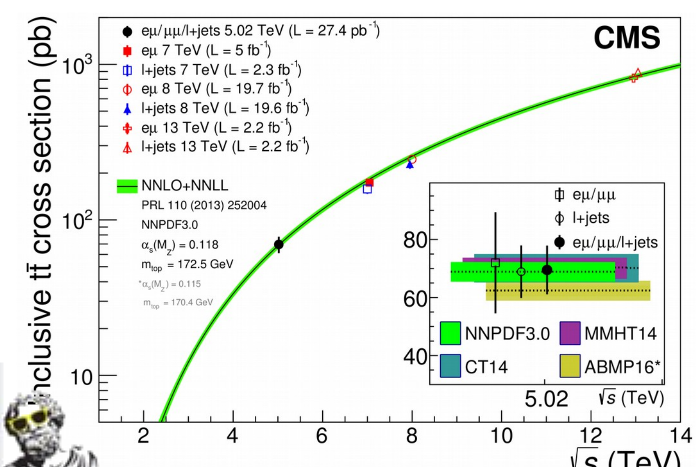


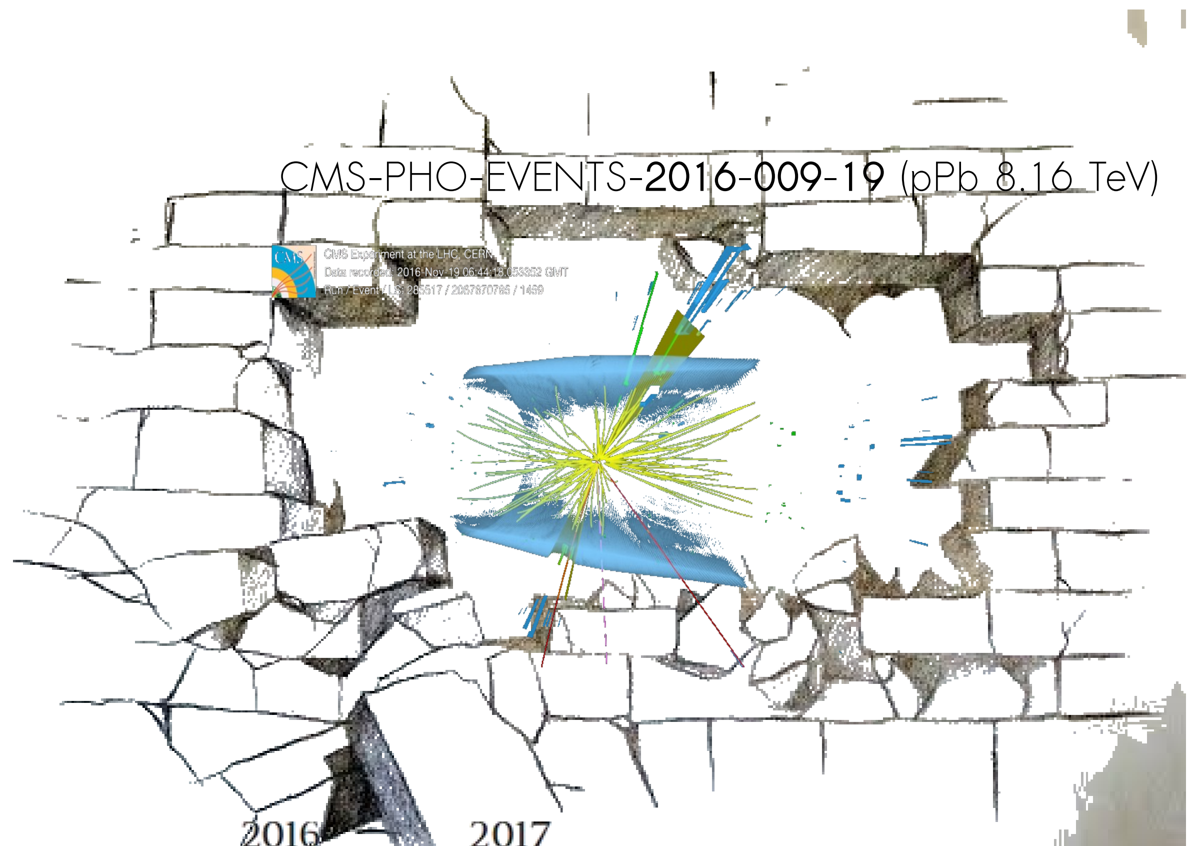
- LHC comfortably surpassed the target of 150 /fb with Run 2 pp data at 13 TeV
  - This is a **collider** FOM for delivering statistically significant data samples
- The precise knowledge of the absolute luminosity scale is of equal importance
  - This is a **synergy** among experiments; we can measure it at **O(2-4%)**, depending on the system

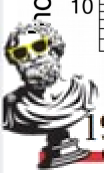
Preparing the way for the first study in nuclear matter

- **In CMS,** we suggest maximizing the contribution of **all** available datasets
  - Unfortunately, statistics is relatively low for "alternative" datasets such as pp @ 5.02 TeV
    - <u>However,</u> **tests** our knowledge in different energies & production modes
  - What left was the TOP study in nuclear matter, i.e.,
    - going from **pp** → **pPb** → **PbPb**





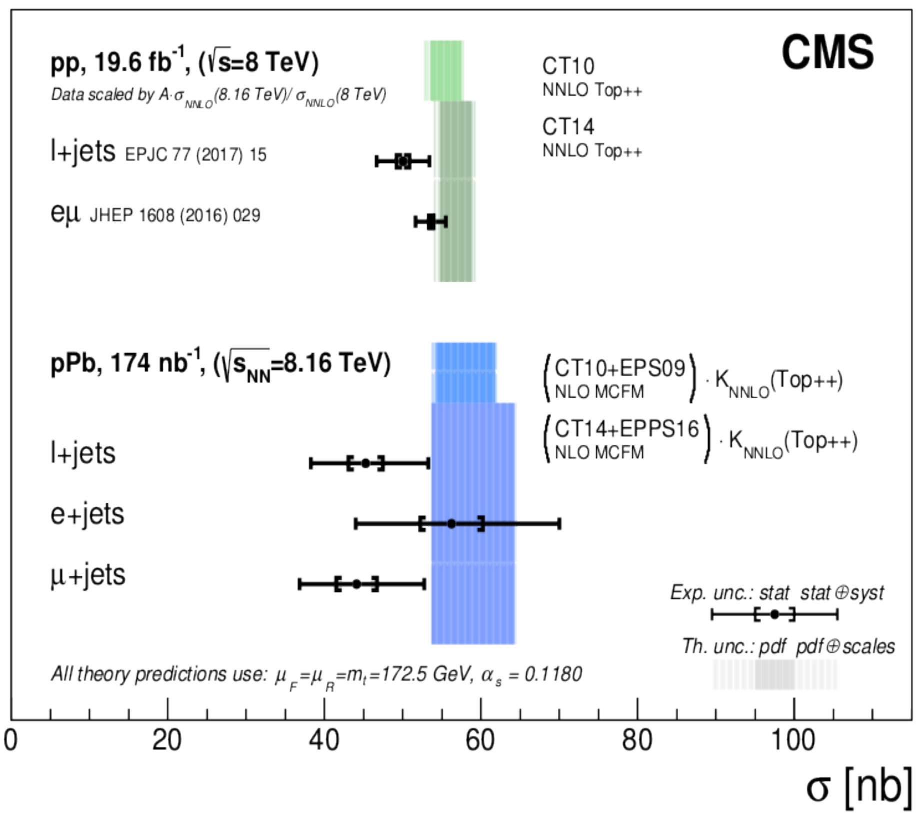


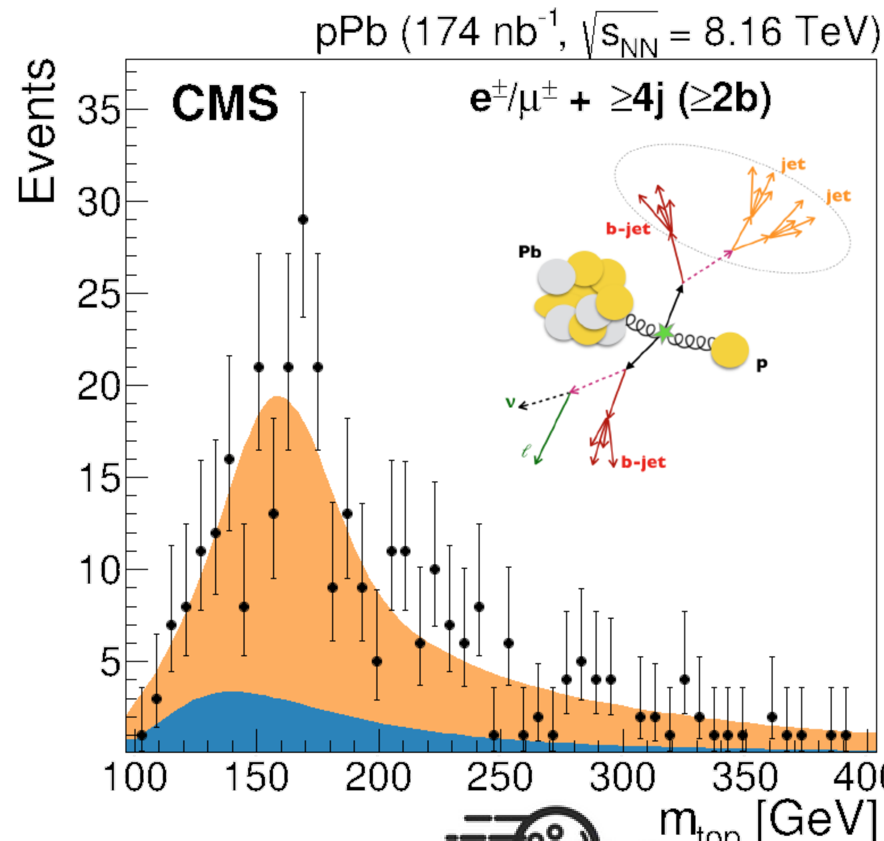


1995	2009	2015	2016	2017
Top at Tevatron	*Top at LHC (7 TeV)*	*Top at LHC (13 TeV)*	*Top at LHC (5.02 TeV)*	*Top at LHC (in nuclear matter)*

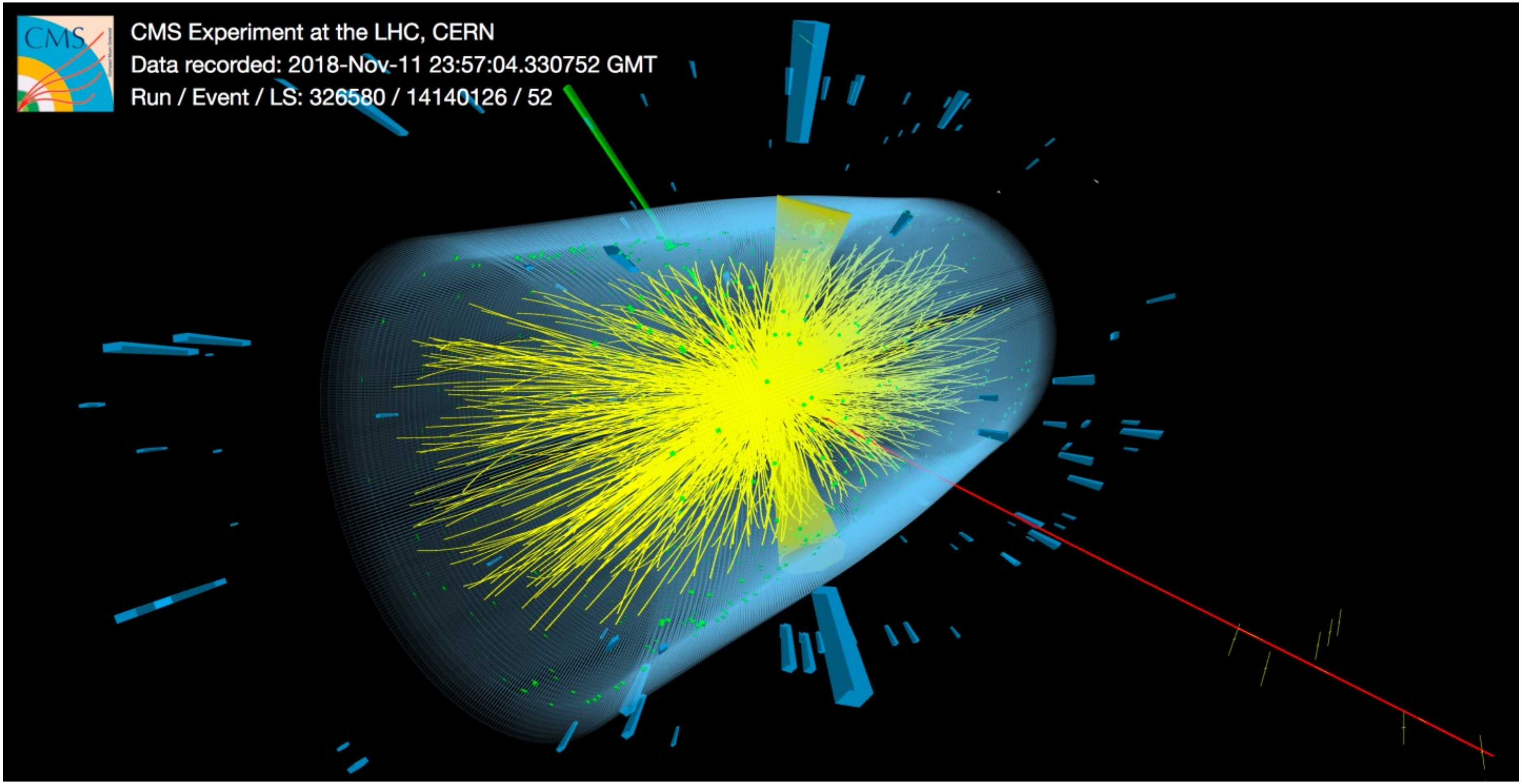
HIN & TOP & LUM synergy paid off

- Succeeded to give a nice deliverable to the community **once more** after 5.02 TeV
  - First study of top quark in nuclear collisions
    - using **two channels** that enhance credibility
    - the measurement paves the way for **dedicated** future studies, and
    - contributes to the **longevity** of nuclear collision program @ LHC and post-LHC





The road is finally open



CMS-PHO-EVENTS-**2018-010-5** (PbPb 5.02 TeV)

GIZMODO, Dec 2017

Biggest Quark Spotted in Whole New Way

Ryan F. Mandelbaum
12/15/17 6:00pm • Filed to: QUARKS

33.6K 17 8

Image: CMS/CERN

FNRS News , Mar 2018

News

ÉTUDE DES NOYAUX LOURDS

Le Large Hadron Collider (LHC) du CERN produit des collisions entre protons (collisions pp) afin d'étudier les particules élémentaires, telles que le boson de Brout-Englert-Higgs. Moins connue est sa capacité à produire également des collisions impliquant des noyaux atomiques lourds : plomb contre plomb (PbPb) et proton contre plomb (pPb). Le « quark top » est la plus lourde particule élémentaire connue, découverte en 1995 au Tevatron (États-Unis), et scrutée sous tous les angles par de nombreuses études au LHC, jusqu'ici toujours basées sur les données pp. Pour la première fois, la production de quark top a été observée dans les collisions pPb, avec une méthode innovante qui pourrait être appliquée aux prochaines données PbPb. Le but est de mieux comprendre la matière nucléaire en conditions extrêmes, semblables aux premiers instants après le Big Bang.

Physics Review Letters Phys. Rev. Lett. - Observation of top quark production in proton-nucleus collisions

Andrea Giammanco, PhD
Chercheur qualifié F.R.S.-FNRS
Georgios Krintiras, doctorant

Centre for Cosmology, Particle Physics and Phenomenology, UCL

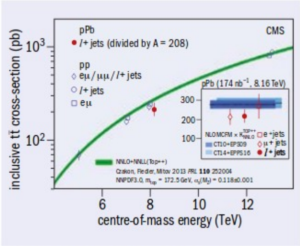
CERN Courier, Nov 2017

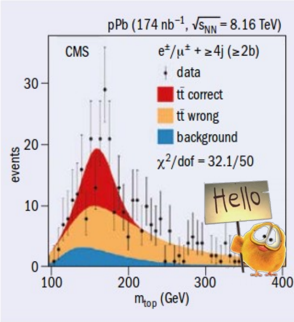
CMS observes top quarks in proton–nucleus collisions

The top quark, the heaviest elementary particle in the Standard Model, has been the subject of numerous detailed studies in proton–antiproton and proton–proton collisions at the Tevatron and LHC since its discovery at Fermilab in 1995. Until recently, however, studies of top-quark production in nuclear collisions remained out of reach due to the small integrated luminosities of the first heavy-ion runs at the LHC and the low nucleon–nucleon (NN) centre-of-mass energies ($\sqrt{s_{NN}}$) available at other colliders such as RHIC in the US.

Proton–lead runs at $\sqrt{s_{NN}} = 8.16$ TeV performed in 2016 at the LHC have allowed the CMS collaboration to perform the first-ever study of top-quark production in nuclear collisions.

Top-quark cross-sections at the LHC can be computed with great accuracy via perturbative quantum chromodynamics (pQCD) methods, thus making this quark a "standard candle" and a tool for further investigations. In proton–nucleus collisions, in particular, the top quark is a novel probe of the nuclear gluon density at high virtualities in the unexplored high Bjorken-x region. In addition, a good understanding of top-quark production in proton–nucleus collisions is crucial for studies of the space–time





(Above) Top-quark pair-production cross-section in pp and pPb collisions as a function of the centre-of-mass energy per nucleon pair. (Right) Invariant mass distribution of the hadronic top-quark candidates in selected events with two b-tagged jets.

science 2.0, Sep 2017

science 2.0 JOIN THE REVOLUTION

Top Quarks Observed In Proton-Nucleus Collisions For The First Time

By Tommaso Dorigo | September 22nd 2017 05:28 AM | Print | E-mail

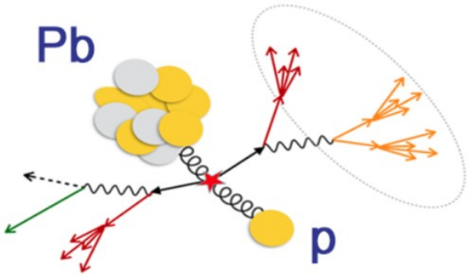
RSS Share / Save Tweet

PRL Synopsis, Dec 2017

Synopsis: Top Quark in Nuclear Collisions

December 14, 2017

The top quark—previously seen in proton collisions—has now been identified in collisions between protons and lead nuclei.



CMS Collaboration/CERN

S slides

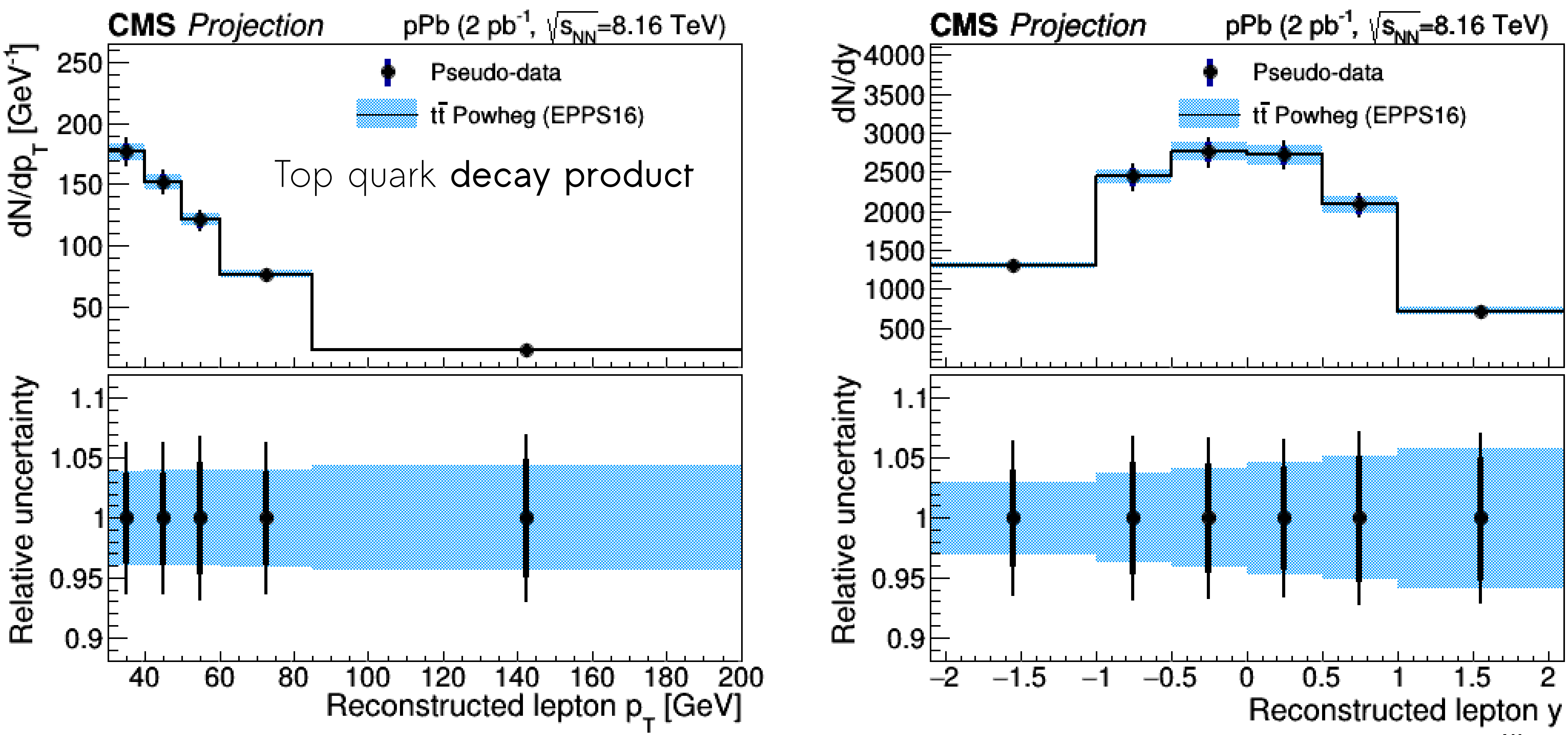
A non-exhaustive list of top quark-antiquark properties

	Property	Result (most precise or most recent)	Uncertainty	Journal Link (or Preprint)/ Conf. note
"Intrinsic"	Charge	0.64 e	0.02 (stat) ± 0.08 (syst) e	**JHEP 11 (2013) 031**
	Mass (kinematic extraction)	172.44 GeV	0.13 (stat) ± 0.47 (syst) GeV	**PRD 93 (2016) 072004**
	Mass difference	-0.15 GeV	0.19 (stat) ± 0.09 (syst) GeV	**PLB 770 (2017) 50**
	Width (direct method)	1.76 GeV	0.33 (stat) $^{+0.79}_{-0.68}$ (syst) GeV	**EPJ C 78 (2018) 129**
	Width (indirect method)	1.36 GeV	0.02 (stat) $^{+0.14}_{-0.11}$ (syst) GeV	**PLB 736 (2014) 33**
	Spin (polarization)	Not uniquely defined variables		**JHEP 03 (2017) 113** **PRD 93 (2016) 052007**
	Spin (correlation fraction)	1.20	0.05 (stat) ± 0.13 (syst)	**PRL 114 (2015) 142001**
"Production"	Rapidity cut-independent charge asymmetry	0.0055	0.0023 (stat) ± 0.0025 (syst)	**arXiv:1709.05327**
	Colour flow Underlying event	No "one-fits-all" prediction		**ATLAS-CONF-2017-069** **CMS-PAS-TOP-17-015**
	Gauge and Yukawa couplings	Wilson c compatible with 0 $\tilde{k}_t$ modifier: 1.43	+0.23-0.22 (tot)	**arXiv:1709.05327** **JHEP 08 (2016) 045**
"Decay"	W boson helicity fractions	F_0 = 0.709 F_L = 0.299 F_R = -0.008	0.012 (stat) +0.015-0.014 (syst) 0.008 (stat) +0.013-0.012 (syst) 0.006 (stat) ± 0.012 (syst)	**EPJ C 77 (2017) 264**

- We know some properties well, but several key properties **remain** poorly understood
  - modeling uncertainties typically dominant or important source

Future physics opportunities for high-density QCD

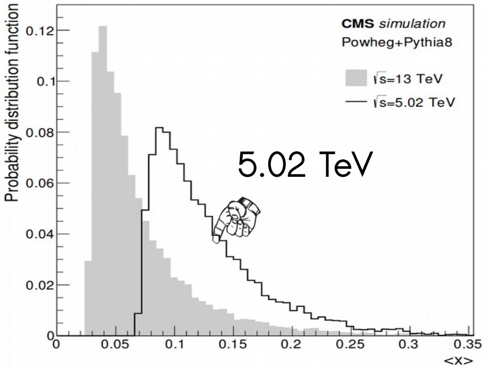
- We can get better constraints with more data
  - Runs 3+4 and High-Luminosity LHC era in the near future, i.e., >=2026
    - to substantially reduce the statistical uncertainty in the measurement



CMS-PAS-**FTR**-18-027
(High-Luminosity LHC Yellow Report)

But, do we really probe high-$\langle x \rangle$ gluons?

- QCD analysis @ **NNLO** with the latest release of xFitter **2.0.0**
  - baseline data: HERA inclusive DIS [EPJ C75 (2015)580], CMS $W^{\pm}$[EPJ C76 (2016) 469]
  - theory predictions obtained from Hathor (NNLO) with top mass of 172.5 GeV



14-parameter fit

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} \cdot (1+D_g x), && \text{gluons} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1+D_{u_v} x + E_{u_v} x^2), && \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, && \text{valence quarks} \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}} \cdot (1+E_{\overline{U}} x^2) && \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}. && \text{sea quarks}
\end{aligned}
$$

$Q_0^2 = 1.9\ \mathrm{GeV}^2$;

All datasets are consistent with the model
Good fit quality for the 5.02 TeV dataset

Data sets	Partial χ^2/n_{dp}
HERA1+2 neutral current, e^+p, $E_p = 920$ GeV	449/377
HERA1+2 neutral current, e^+p, $E_p = 820$ GeV	71/70
HERA1+2 neutral current, e^+p, $E_p = 575$ GeV	224/254
HERA1+2 neutral current, e^+p, $E_p = 460$ GeV	218/204
HERA1+2 neutral current, e^-p, $E_p = 920$ GeV	218/159
HERA1+2 charged current, e^+p, $E_p = 920$ GeV	43/39
HERA1+2 charged current, e^-p, $E_p = 920$ GeV	53/42
CMS $W^\pm$ muon charge asymmetry $\mathcal{A}(\eta_\mu)$, $\sqrt{s} = 8$ TeV	2.4/11
CMS inclusive $t\bar{t}$ 5.02 TeV, $e^\pm\mu^\mp$	1.03/1
CMS inclusive $t\bar{t}$ 5.02 TeV, $\mu^\pm\mu^\mp$	0.01/1
CMS inclusive $t\bar{t}$ 5.02 TeV, ℓ+jets	0.70/1
Correlated χ^2	100
Global χ^2/n_{dof}	1387/1145

JHEP **03** (2018) 115

Yes, we do really probe high-$\langle x \rangle$ gluons!

- QCD analysis @ NNLO with the latest release of xFitter 2.0.0
  - baseline data: HERA inclusive DIS [EPJ C75 (2015)580], CMS $W^{\pm}$[EPJ C76 (2016) 469]
  - theory predictions obtained from Hathor (NNLO) with top mass of 172.5 GeV
    - for 400 replicas the fit is performed and the error estimated from spread (**MC method**)
    - moderate **reduction of the uncertainty** in the gluon distribution at high $\langle x \rangle$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} \cdot (1 + D_g x), \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + D_{u_v} x + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}} \cdot (1 + E_{\overline{U}} x^2), \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}
$$

$Q_0^2 = 1.9\ \mathrm{GeV}^2$;

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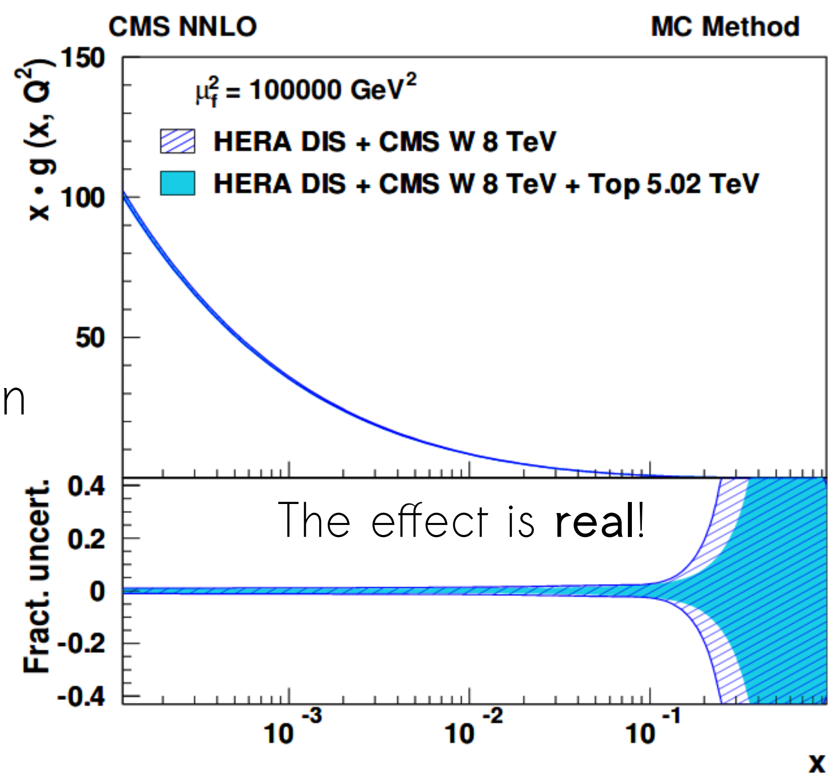


No bias from model input and PDF parametrization
No effect on light quarks

A naive expectation for improvements based on TOP-16-023

Part D (§ 7)

Table 1: Possible inputs to the combination and the PDF fits.

Channel	$e\mu$	$\mu\mu$	ℓ+jets		
Central value (pb)	68.9	68.9	68.9		
Uncertainties (%)				correlation	Note
Statistical	$25/\sqrt{10} \sim 8$	$48/\sqrt{10} \sim 16$	$9.5/\sqrt{10} \sim 3.0$	0	$\times$10 expected events
MC statistics	$1.4/\sqrt{2} \sim 1.0$	$2.4/\sqrt{2} \sim 1.7$	$0.1/\sqrt{2} < 0.1$	0	$\times$2 simulated events
b tagging	-	-	3.4 (*)	-	New algorithms; performance to be checked
electron ID	1.4 (*)	-	1.1 (*)	1	Some improvement from endcap electrons
muon ID	$3.0 \rightarrow 2.5$	$6.1 \rightarrow 5.0$	1.7	1	Less conservative approach
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	-	0.7	-	-	
Jet Energy Scale	1.3	1.3	3.0	1	
Jet Energy Resolution	<0.1	<0.1	0.6	1	
QCD background	-	-	2.4 (*)	-	Some improvement from endcap electrons
W+jets background	$2.5/\sqrt{10} \sim 0.8$	$0.7/\sqrt{5} \sim 0.3$	$3.5/\sqrt{5} \sim 1.6$	1	$\times$10(5) from stats. (simulation)
tW background	1.4	1.6	1.3	1	
WV background	0.7	0.9	-	1	
Drell-Yan background	$2.7 \rightarrow \sim 2.0$	$15.4/\sqrt{10} \sim 5.0$	-	1	$\times$10 from stats.; in $e\mu$ partly due to stats.
Parton Shower scales	1.2	1.7	4.4	1	
Matrix Element scales	<0.1	1.1	<0.1	1	
Hadronization model	1.2 (**)	5.2 (**)	2.8 (**)	1	
PDF $\oplus\, \alpha_S$	0.5	0.4	<0.1	1	
Luminosity	$2.3 \rightarrow 1.7$	$2.3 \rightarrow 1.7$	$2.3 \rightarrow 1.7$	1	From the updated LUM16001(link)

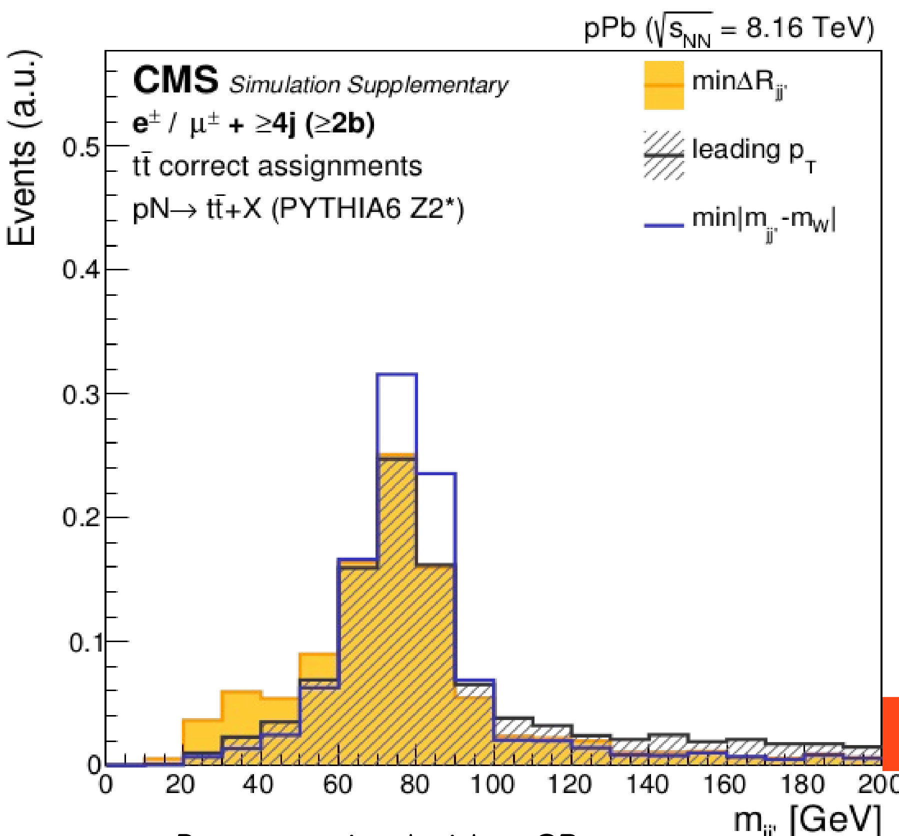
(*) Expected but difficult to quantify improvement
(**)Revised theory prescription

- Main improvement due to increased event count in data (MC)
  - direct impact on estimation for the main bkg. based on data (MC)
- Decreased luminosity unc. relative to high PU conditions

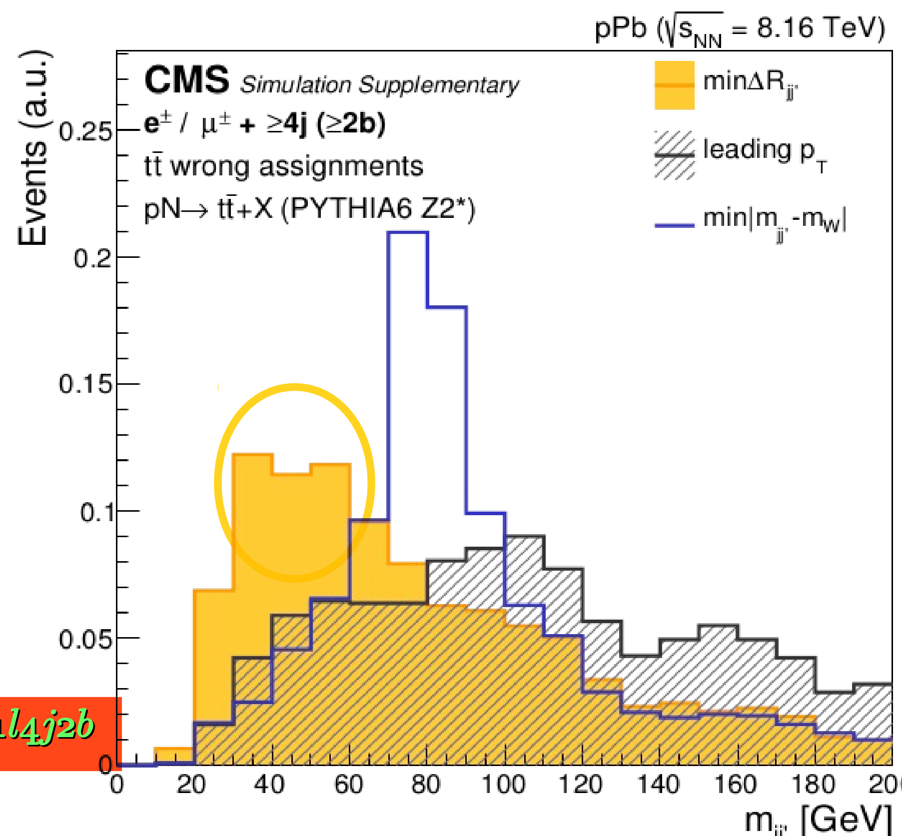
The signal and data-driven bkg modeling

- *tt* process modeled with **PYTHIA** (v.6.424, tune Z2*)
  - pN → *tt* + X (**N=p,n**), i.e., a mixture of pp and pn interactions – not crucial
    - effects from nuclear modifications studied with **POWHEG** (v2) interfaced with CT14+EPPS16
  - split the total contribution in a **resonant** (left Fig.) and a **non resonant** (right Fig.) part
    - resonant: both j,j' (reco) matched with a light flavor parton (truth)
    - proximity of j,j' in (η,φ) reproduces a crucial **feature**

tested j,j' pairing criteria



Parameterized with a **CB+gamma**



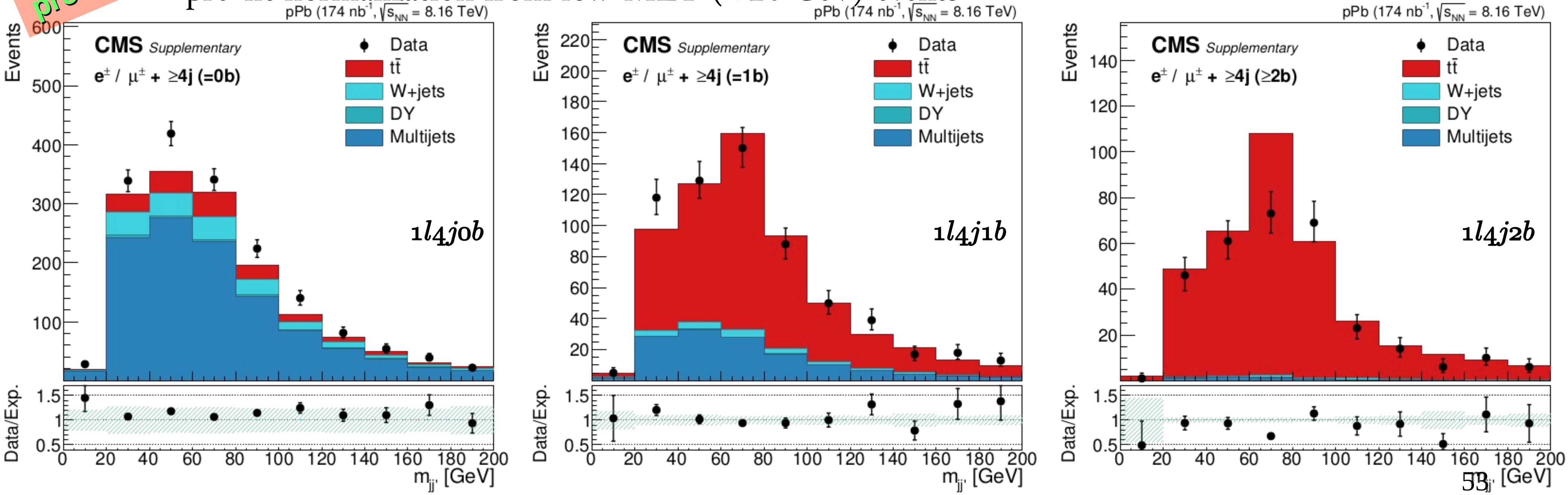
1l4j2b

Parameterized with a **asym. Gaussian+Landau**

The signal and data-driven bkg modeling

- EW processes (W+jets, also DY) modeled with **PYTHIA** (v.6.424, tune Z2*)
  - pN → W + X (**N=p,n**) i.e., a mixture of pp and pn interactions – this is **crucial**
    - **Landau** parameterization found as a proper description (hint: combinatorics)
    - also supported from **POWHEG** (v2) interfaced with CT14+EPPS16
    - effects from nuclear modifications inferred *in situ*
- QCD multijet process extracted from failed iso (ID) control region in μ (e)+jets channel
    - **kernel** parameterization (hint: non trivial behavior for fake/non prompt l)
    - pre-fit normalization from low-MET (< 20 GeV) events

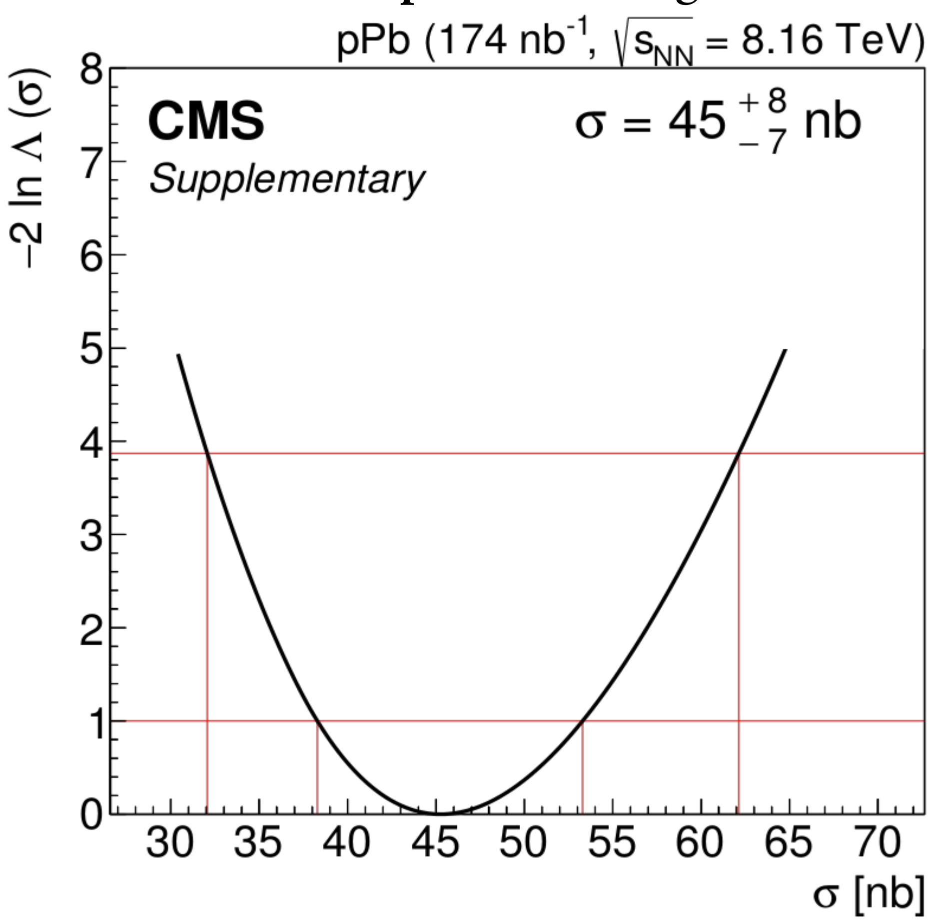
pre-fit

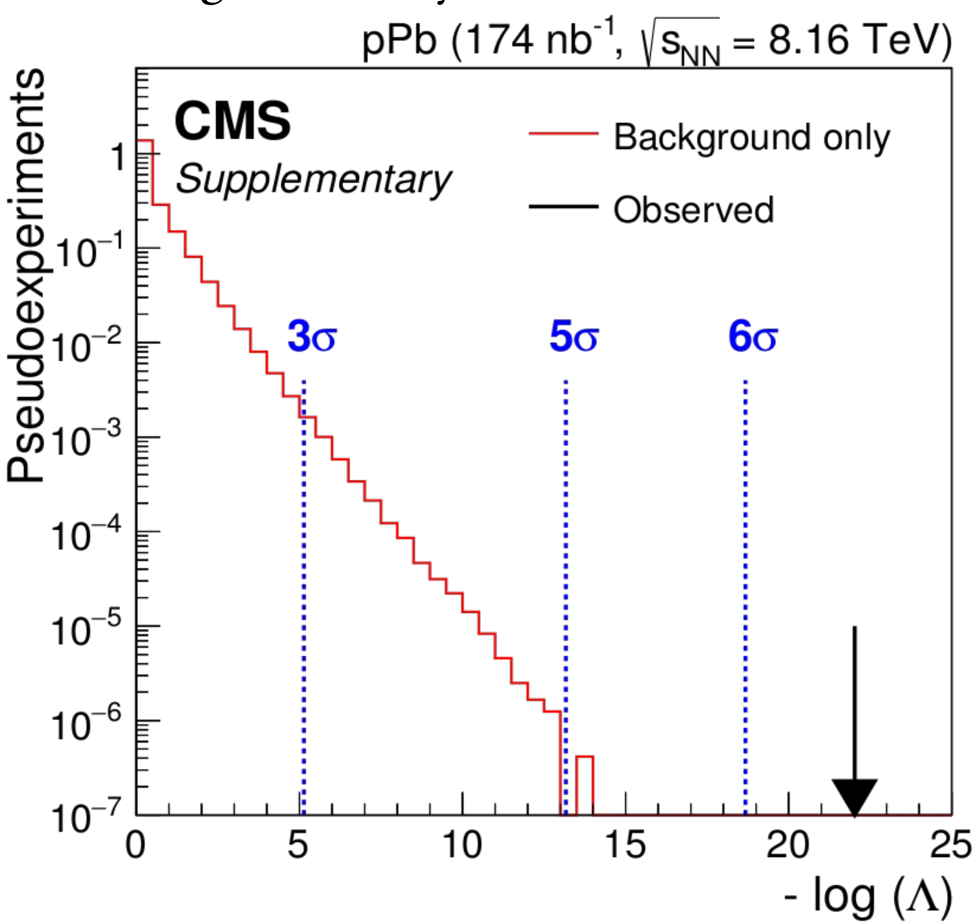


All samples are tuned to reproduce the global pPb event properties

The statistical significance of the measurement

- The *null* hypothesis is excluded at a level of
  - **>5σ** taking into account syst unc by
    - the observed variation of the **likelihood** as a function of the POI
    - PLR from **pseudo-data** generated from the background-only model

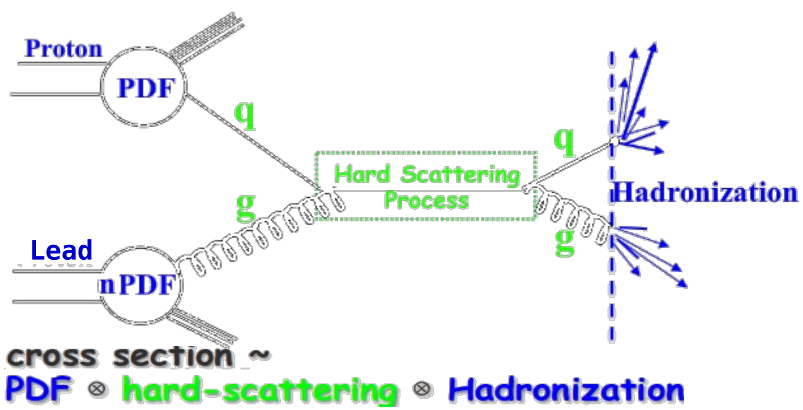




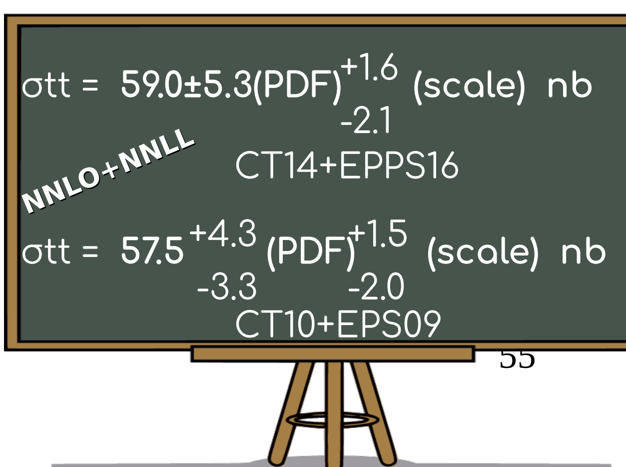
Indeed, the first observation of top quarks in pPb!

Theoretical setup for cross section calculation

- Rely on the two fundamental concepts of QCD
  - **factorization** (calculable) and **universality** (input from PDFs)
    - $\sigma_{pA} = A \times \sigma_{pp}$ (A=208 for Pb isotope @ LHC)
- **MCFM** (v8.0, nproc = 141) NLO event 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 +4% modification (R_{pPb}) of $\sigma_{t\bar{t}}$
  - nPDF⊗ PDF uncertainty from the provided 56+40 eigenvalues → **9%**
  - full calculation repeated with **CT10+EPS09** combination
    - considering the 52+32 error sets → 7%
  - QCD scales choice: $\mu_R = \mu_F =$ **172.5** GeV
    - scale variations by halving/doubling the μ_R, μ_F → **3%**
- **k**-factor (NLO → NNLO) obtained with **TOP++**

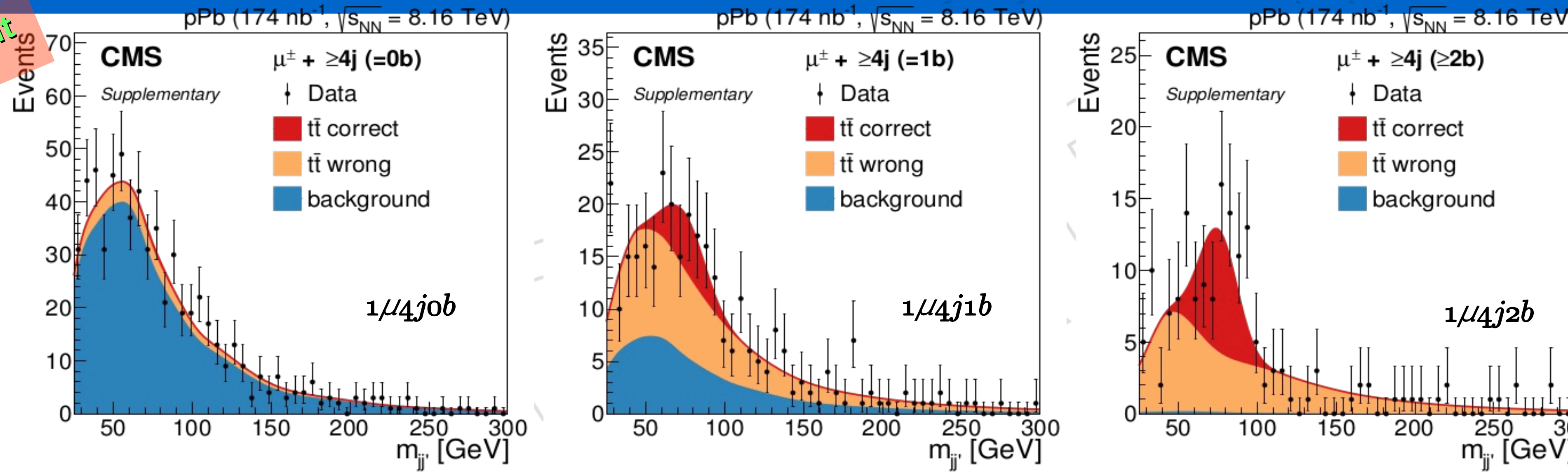


@ $\sqrt{s_{NN}}$ =8.16 TeV



Measuring the tt production cross section (μ,e+jets)

post-fit



- e+jets hampered more by bkg. contamination
  - less precise than μ+jets i.e., $d\sigma_{tt}$ / σ_{tt} = **23 % vs 18 %**
    - **crucial** consistency check

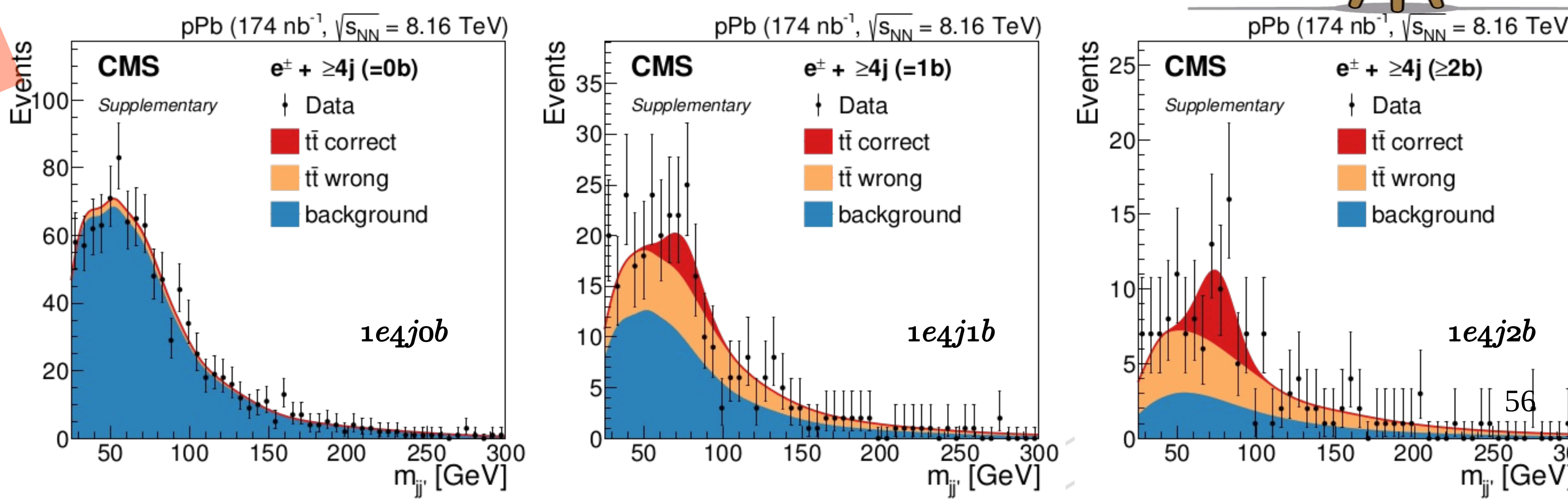
μ+jets:

σ_{tt} = 44±3(stat)±8(syst) nb

e+jets:

σ_{tt} = 56±4(stat)±13(syst) nb

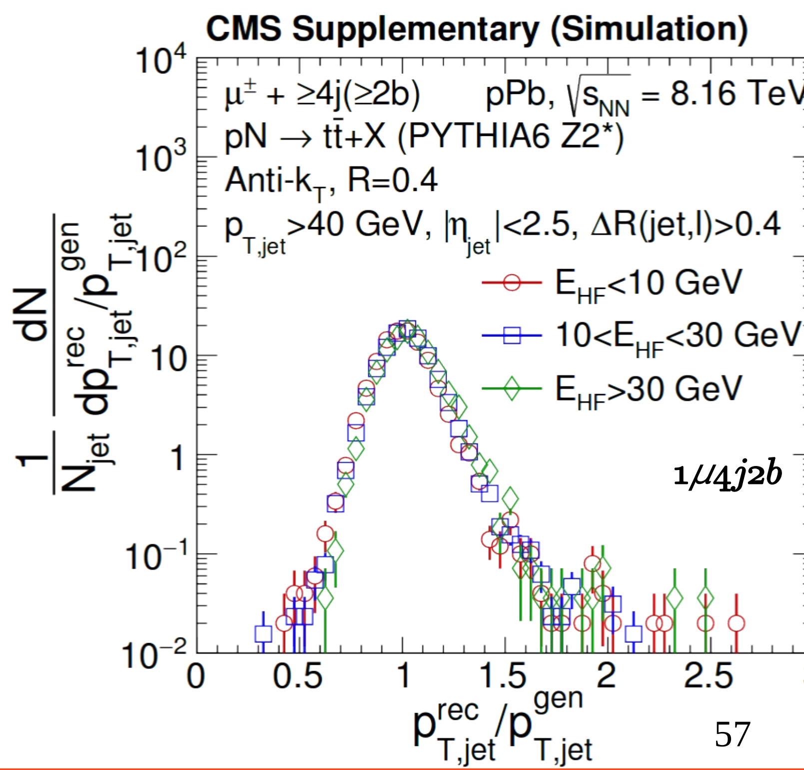
post-fit



Splitting uncertainty in a stat & syst component

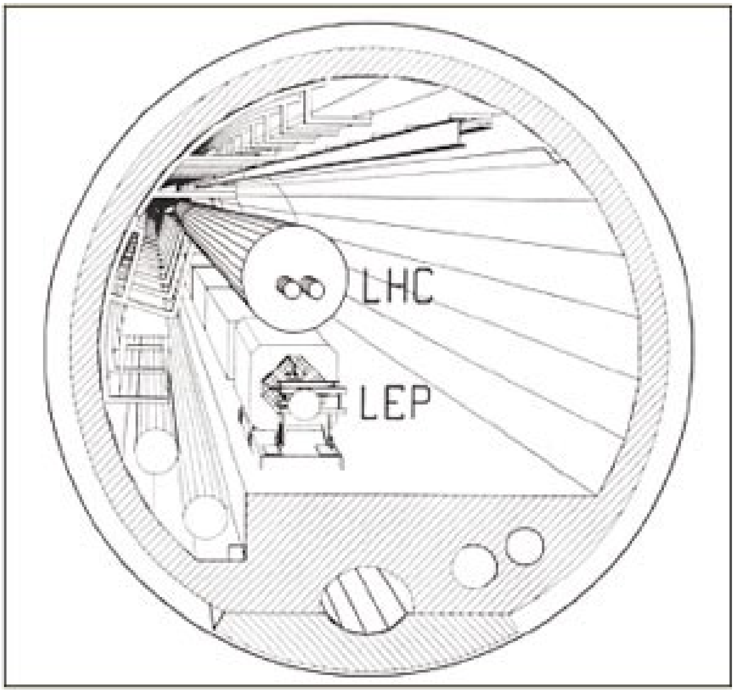
- Neither trivial nor unique task
  - **stat:** fix nuisances to post-fit values and refit with floating σtt
  - **syst:** √ (tot^2– stat^2)
- effect of identified sources for systematic variations
  - fix all other nuisances to post-fit values and refit within ±1σ

UNCERTAINTY DESCRIPTION	EFFECT (%)
EVENT COUNT σtt floats in the fit and all other parameters fixed to their post-fit values	5
b FINDING EFFICIENCY the probability that a b jet passes both the kinematic and the b tagging selections	13
BACKGROUND Shape and normalization uncertainties	7
LUMINOSITY Preliminary offline calibration for pPb data taking 2016 period	5
JET ENERGY SCALE 3%-level non-closure of the jet energy corrections in MC events and a 3% residual calibration uncertainty from data	4
LEPTON EFFICIENCY Dominated by the underlying event dependence	4
ACCEPTANCE QCD, strong coulping and PDF⊗nPDF (POWHEG)	4

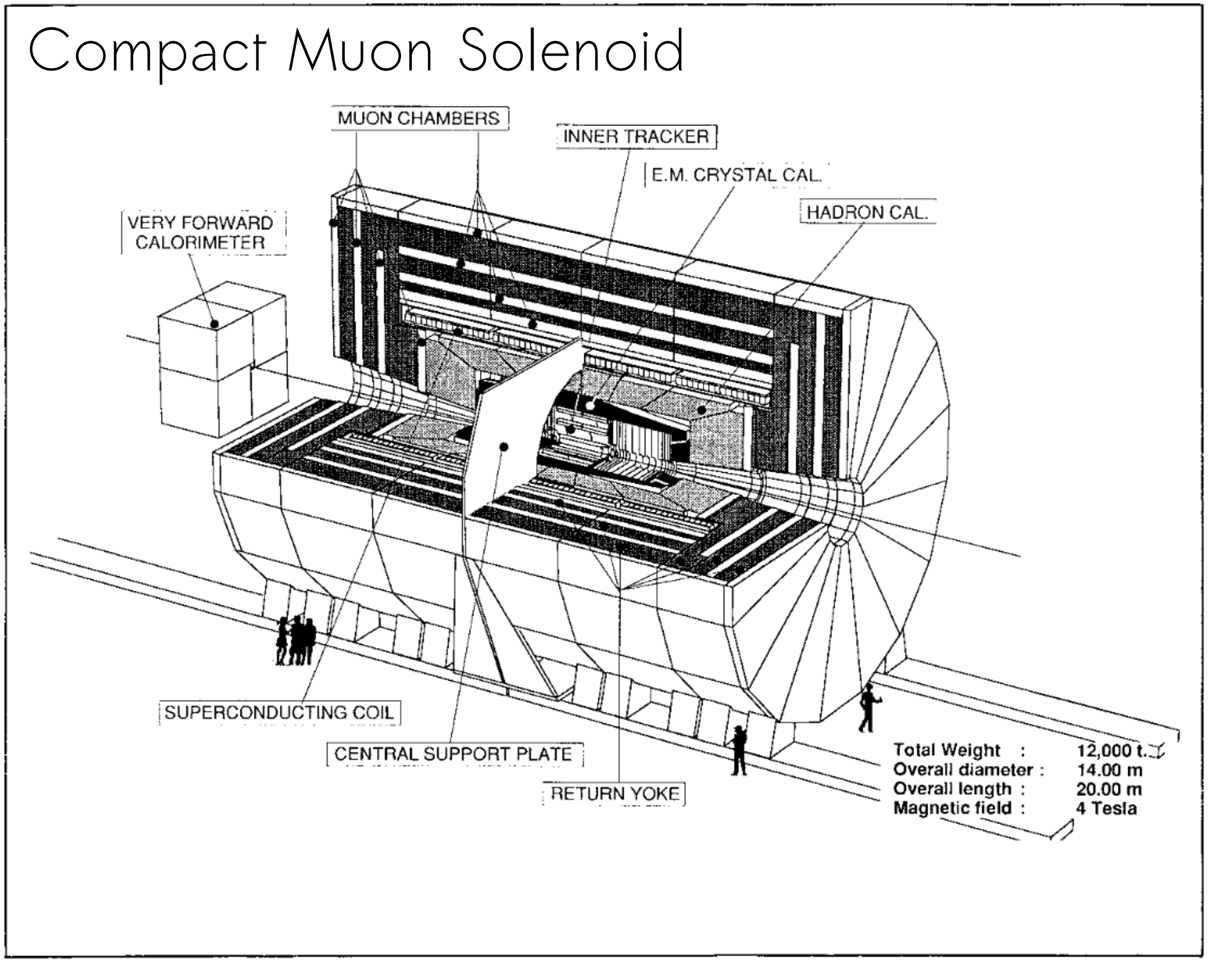


Careful treatment of UE dependence

So, what's after the Large Electron–Positron Collider (1989-2000)?



Lausanne LHC workshop (1984)

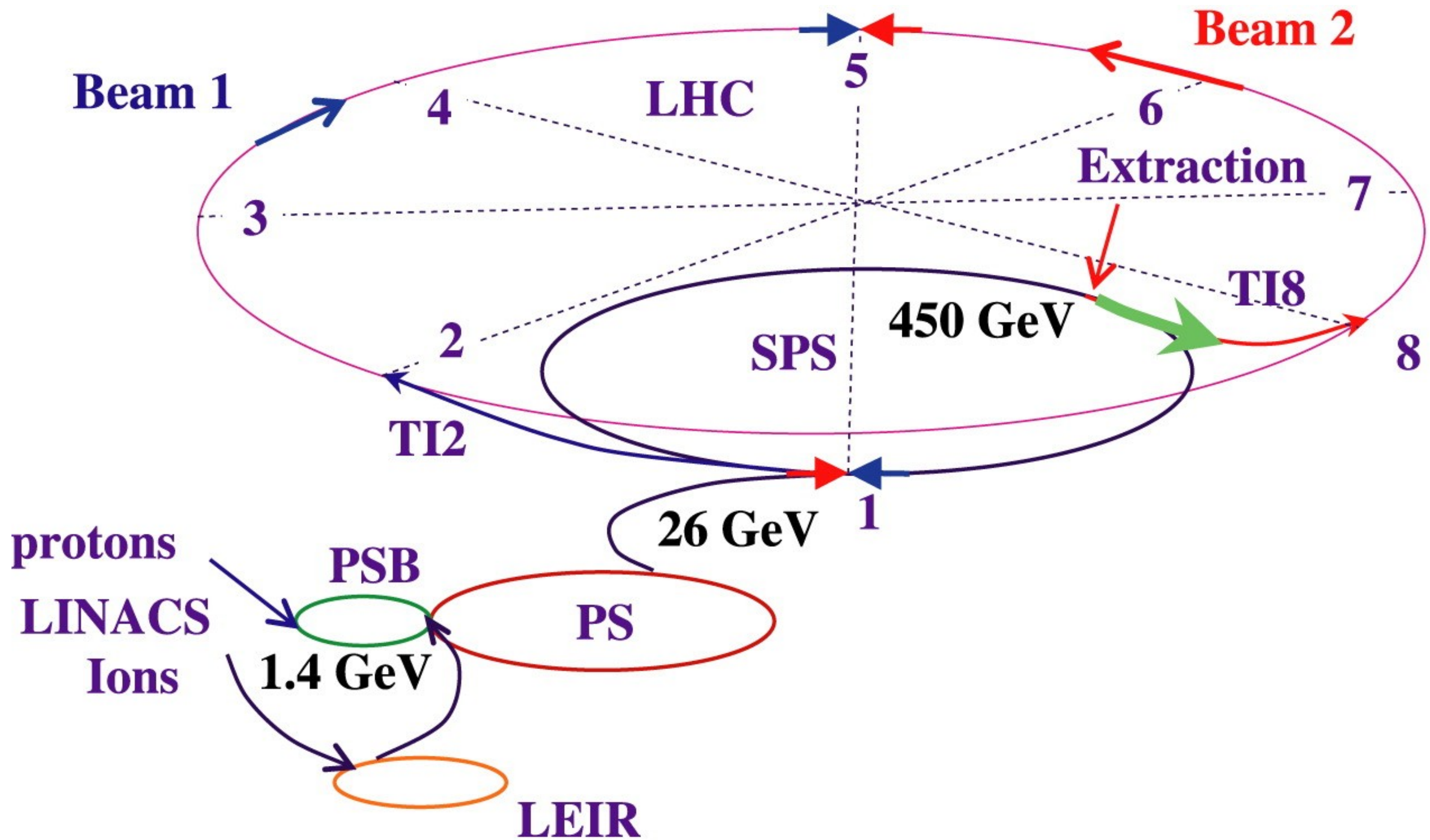


Evian "debut" (1992)

- The infrastructure for *a* **Large Hadron Collider** (LHC), if any, would be limited by
  - the existed tunnel (radius and size) and its injectors: "Multipacket" collider + **10 T** magnets
  - *Expressions of Interest* in 1992: LHC to handle proton and lead **ions**

NB I: LHC success is also based on its injectors

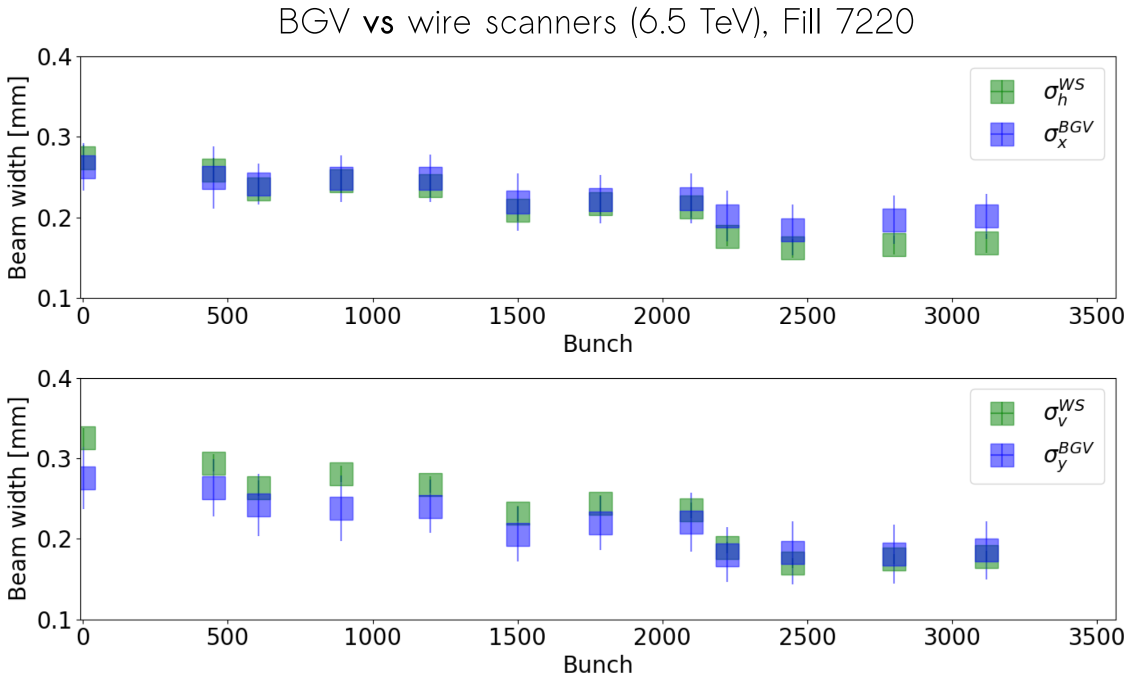
Part A (§ 2)

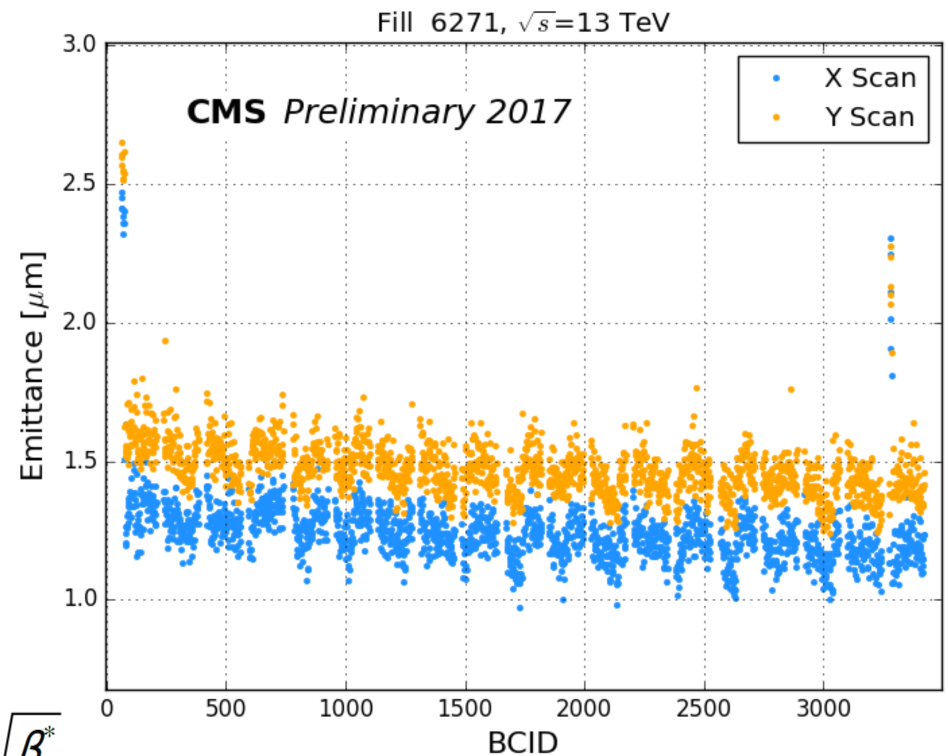


- While speaking about ions: The original LHC design foreseen **only** pp and PbPb (A=208) collisions
  - Slight different path for Pb ions up to SPS; their source had to be reconditioned in 2018!
  - Novel modes **established**: pPb (2011), XeXe (2017), and partly stripped Pb ions (2018)
  - **No** other combination of asymmetric collisions, e.g, pXe, pO, etc. has been feasible so far

NB II: LHC performance is assessed with prompt feedback

Part A (§ 2)





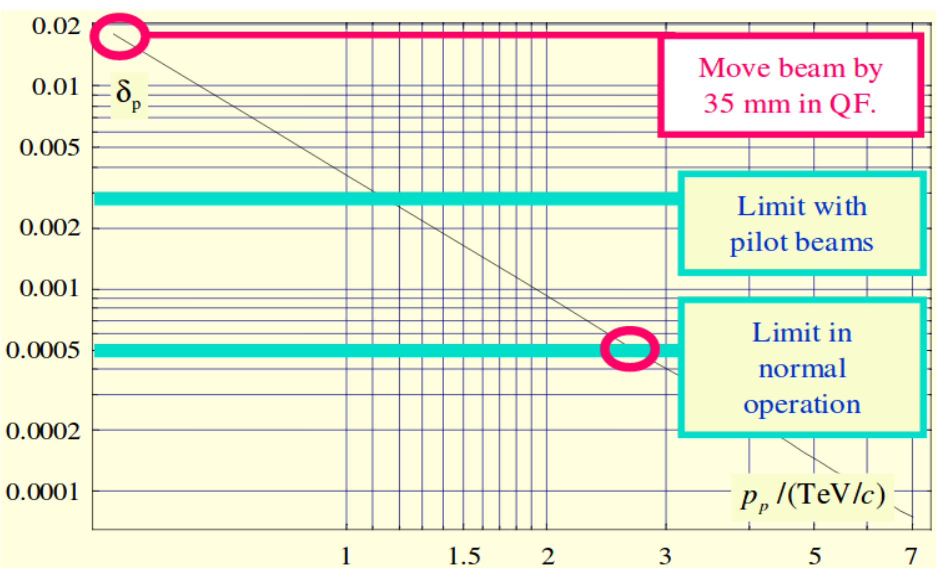
$$\sigma^* \propto \sqrt{\beta^*}$$

- LHC diagnostic equipment (transfer line and main rings) crucial for **safe operation** and **adjustments**
  - E.g., beams' position, current and intensity, transverse motion, emittance, losses, longitudinal profiles …
  - Novel approaches for **noninvasive** measurements to minimize impact on the beam quality
    - Expertise from beam-gas (LHCb) & beam-imaging (CMS) analyses applied to beam-profile measurements (BGV)
- Synergy is a key parameter, e.g, CMS publishes "emittance" measurements in **real-time**

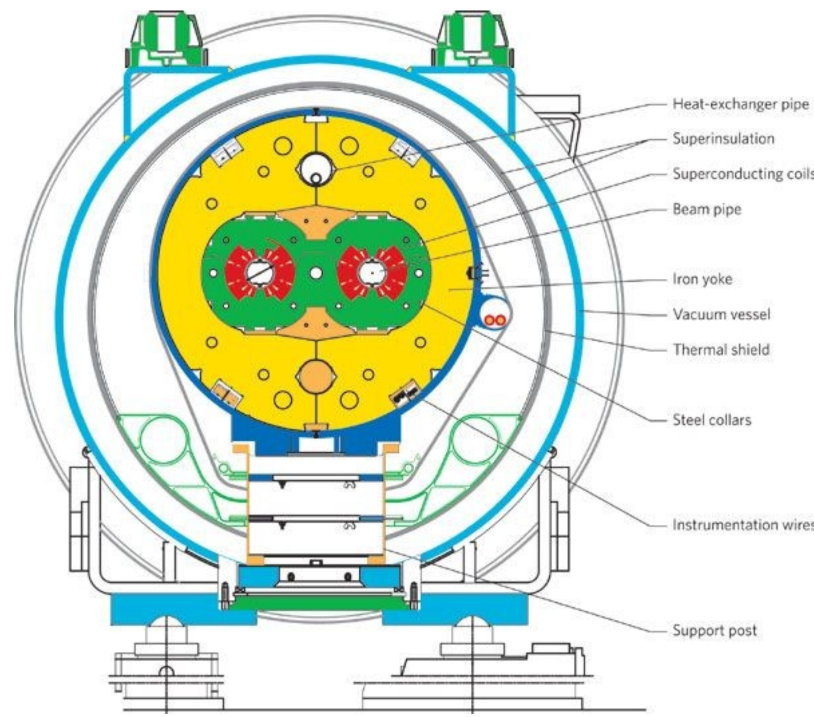
Throwing a bullet through an apple... How?

- Ideally LHC is **meant** for equal colliding species
  - Its "two-in-one" magnet design gave birth to "cogging" (O.o ?)
    - **no** preceding design (!= BNL RHIC)
  - Other constraints should be **monitored**, e.g., collimation, or **surpassed**, e.g, from position monitors
    - synchronous orbit mode → increased proton intensity

proton beam displacement

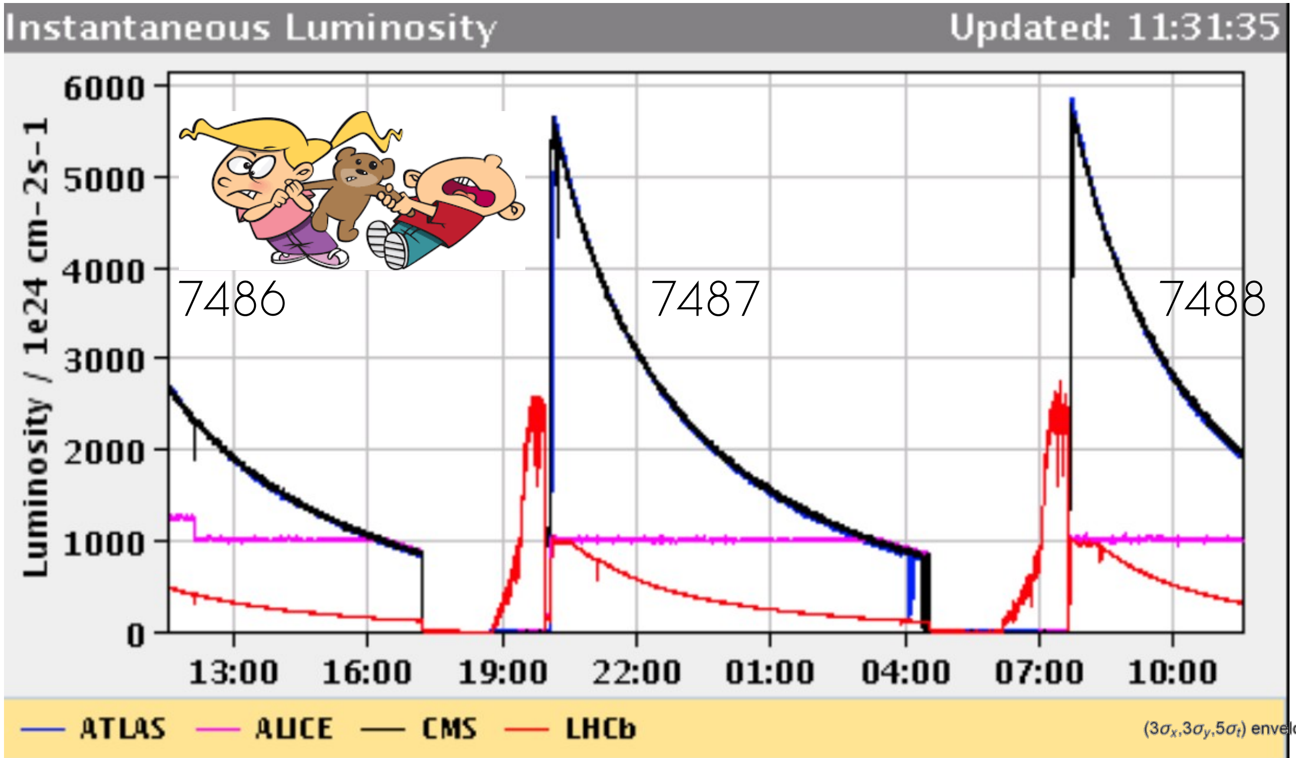


A **lower (!)** limit on the achieved energy ($\sqrt{s_{NN}}$)



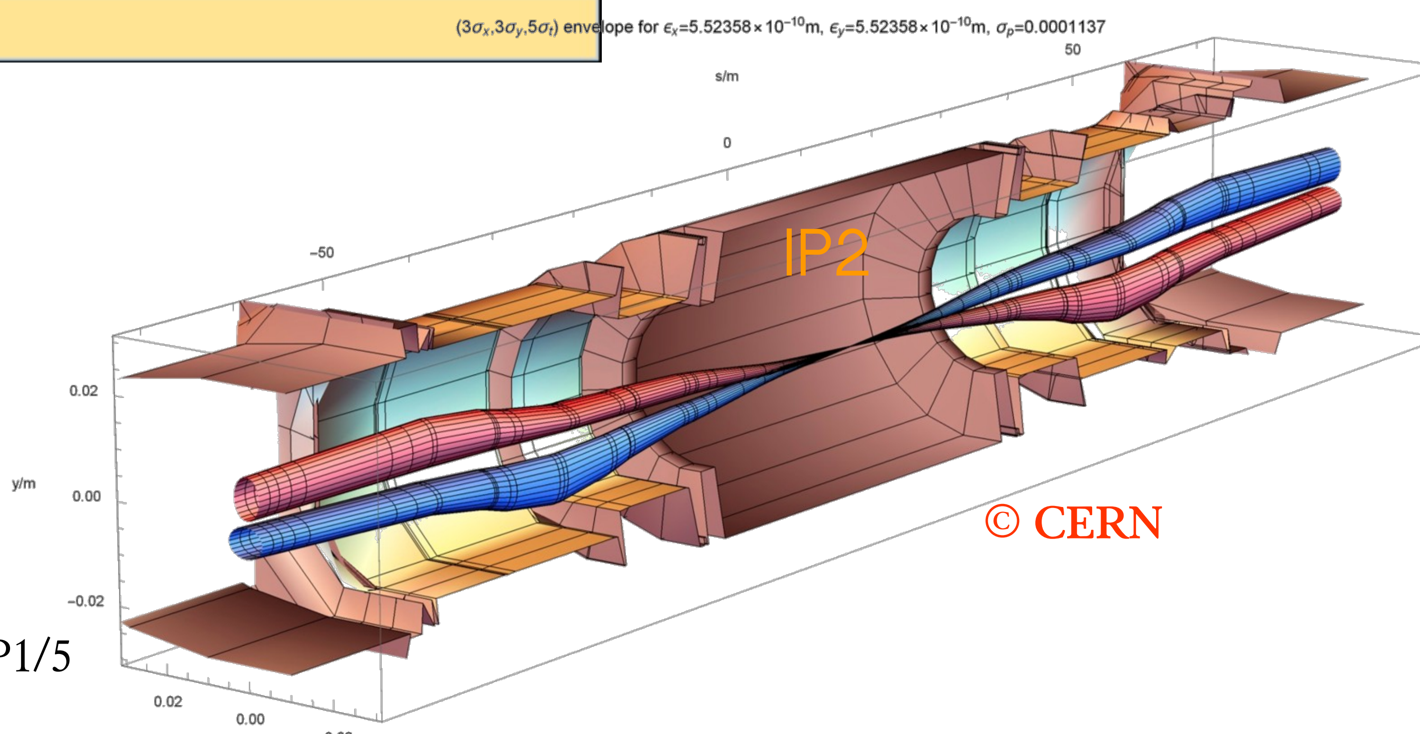
LHC **dipole** magnet cryostat

Luminosity sharing is puzzling



- Short time frame to fulfill all goals
  - ATLAS/CMS ≫ 10^27Hz/cm2
  - ALICE = 10^27Hz/cm2
  - LHCb ≥ 10^27Hz/cm2

    → ×10 than 2015



- Completely new optics cycle
  - β^*=(0.5, 0.5, 0.5,1.5)
- Beam size at IP2 ×2
  - reduce peak luminosity at IP1/5

RUN OVERVIEW OF THE RELATIVISTIC HEAVY ION COLLIDER