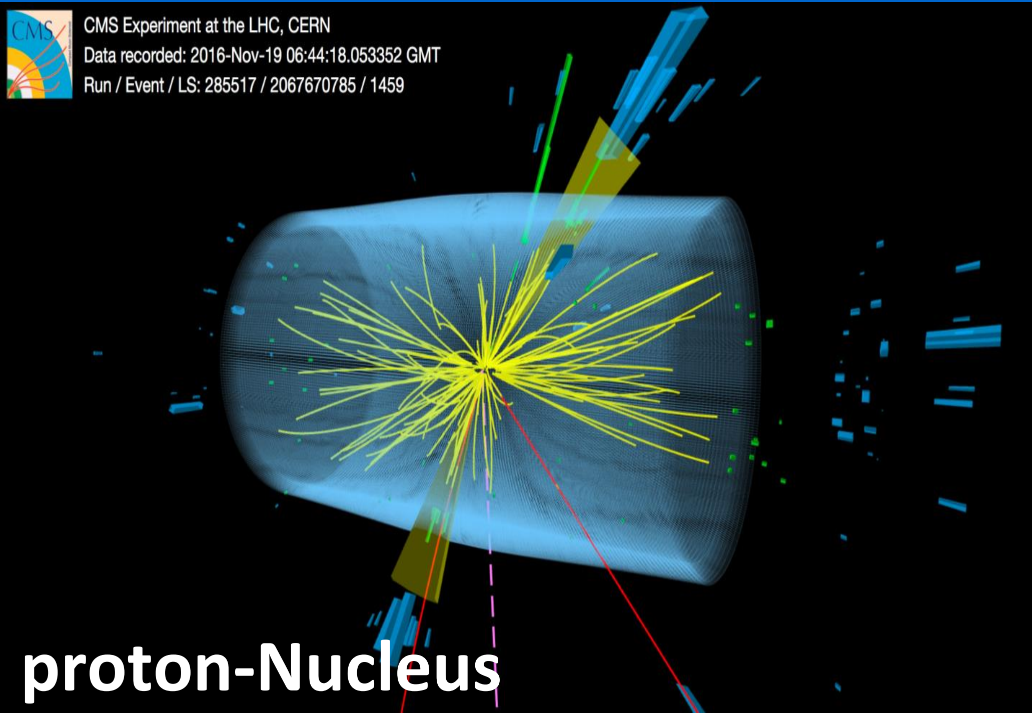
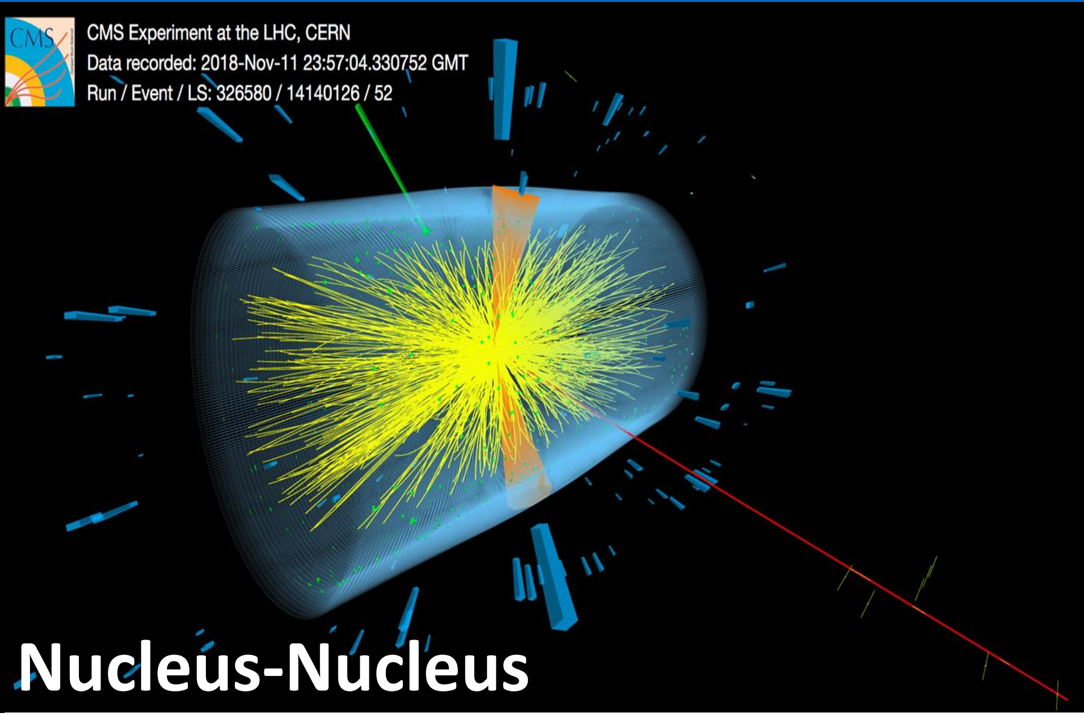
Top Quarks and the "Little Bang Standard Model"

arXiv: 1709.07411, 1711.03143, 2006.11110





G.K. Krintiras (cern.ch/gkrintir)
The University of Kansas

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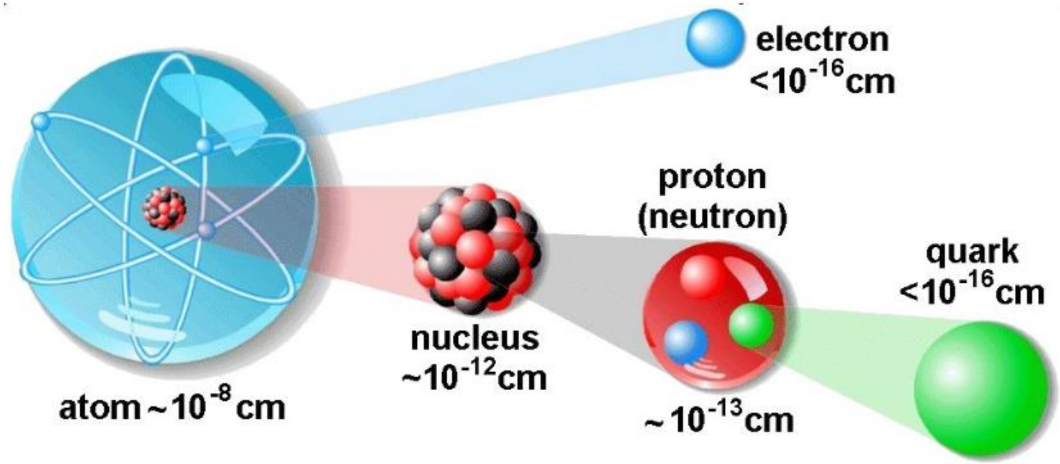
Structure of matter

- 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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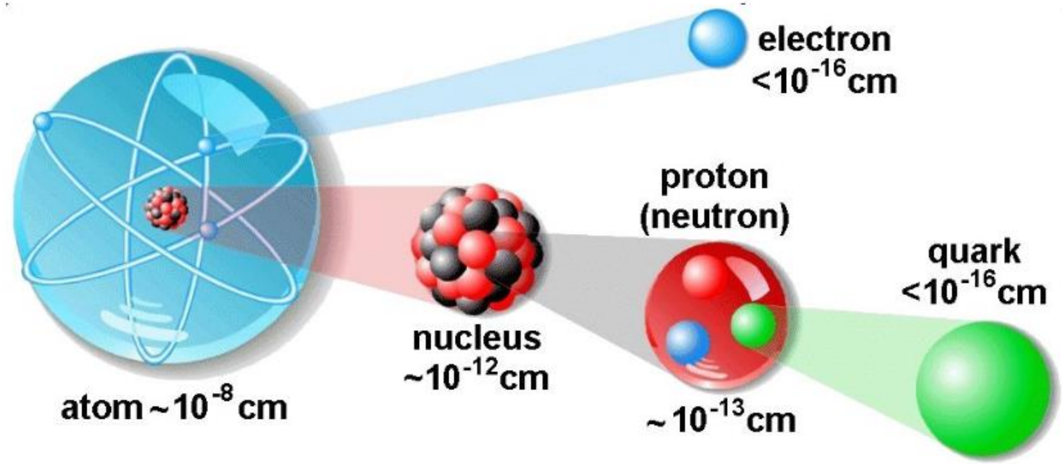
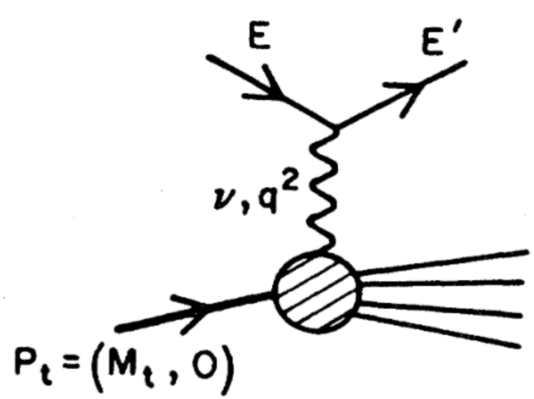
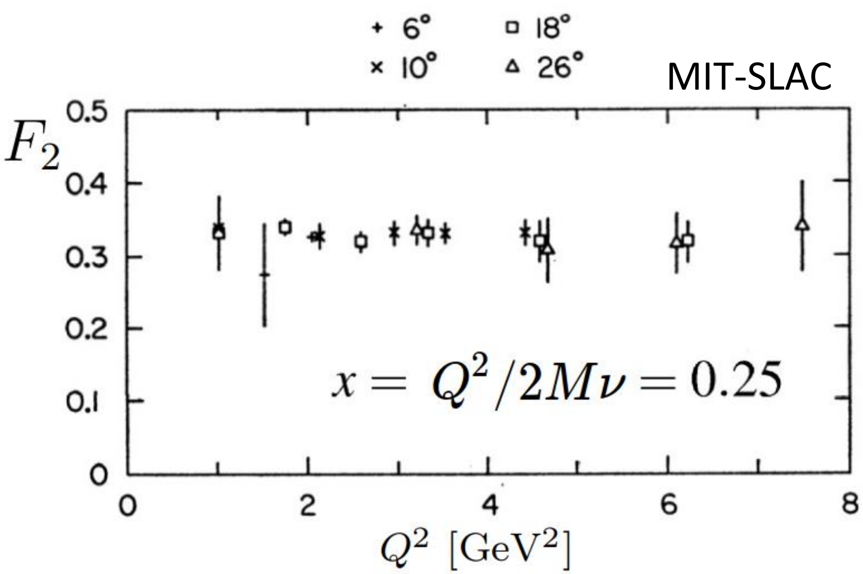


Unit for energy E (and mc^2): *electron-volt*, eV	
Chemical reactions, per atom	1 to few eV
Rest energy mc^2 of proton	billion eV GeV (Giga)

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

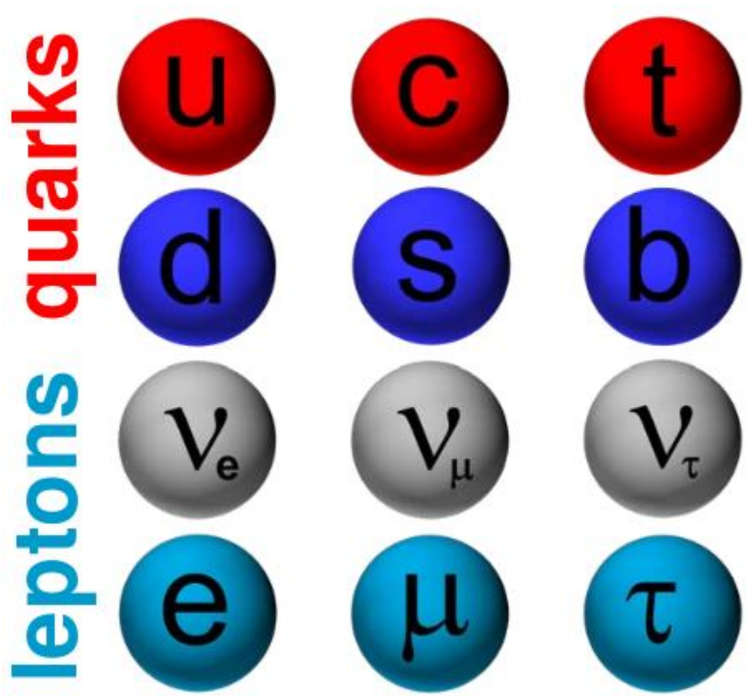


"Feynman" diagram of "deep inelastic scattering"



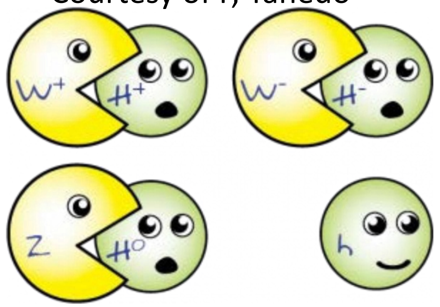
Elementary Particle Physics, aka High Energy Physics

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



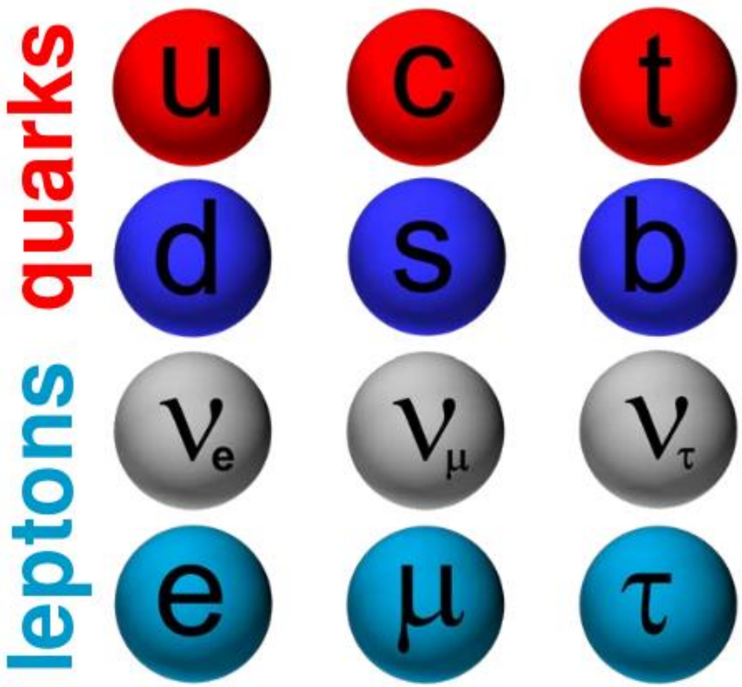
- What are the forces between them?
  - Four quanta for the combined “electroweak force”: a history of unification
  - Quantum chromodynamics: theory of quarks and gluons, and their “strong” interactions
    - built on the concept of “colour": only color-neutral states exist

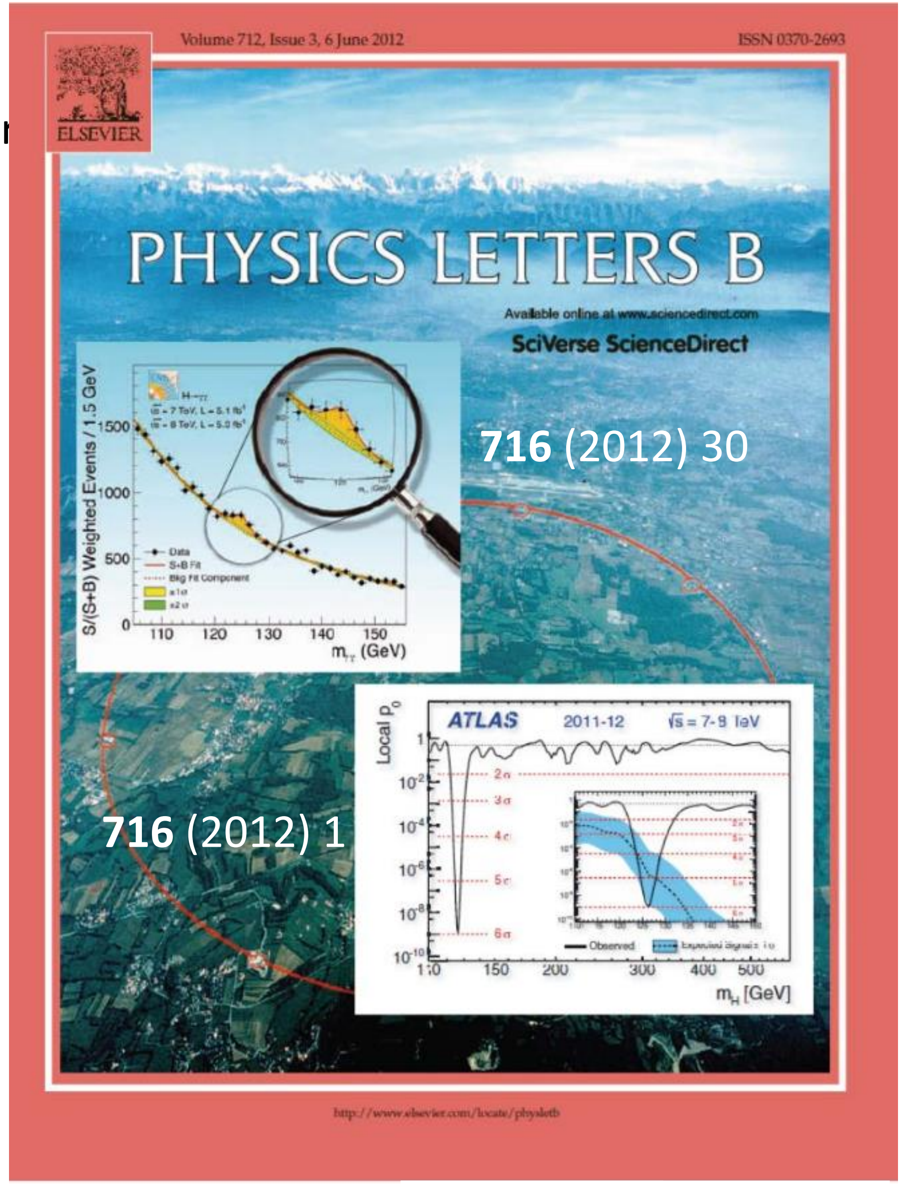
Courtesy of F, Tanedo

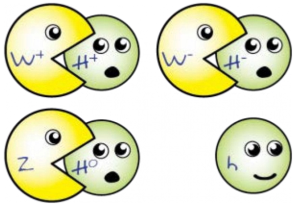


Elementary Particle Physics, aka High Energy Physics

- What are smallest building blocks of matter?
- Over time, two more massive "copies" identified but other







Elementary Particle Physics, aka High Energy Physics

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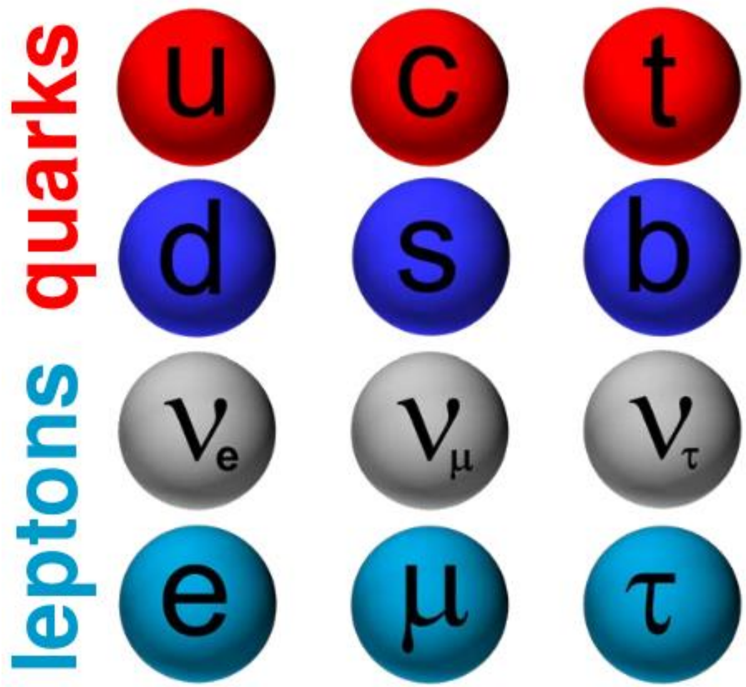

CERN 10 years HIGGS boson discovery

4 July 2022
CERN

nature

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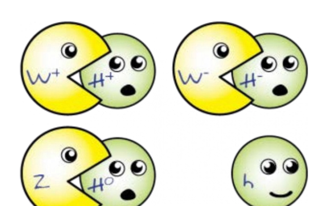
Article | Open Access | Published: 04 July 2022

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The CMS Collaboration



Top quark: The heaviest elementary particle known today

- What are smallest building blocks of matter?
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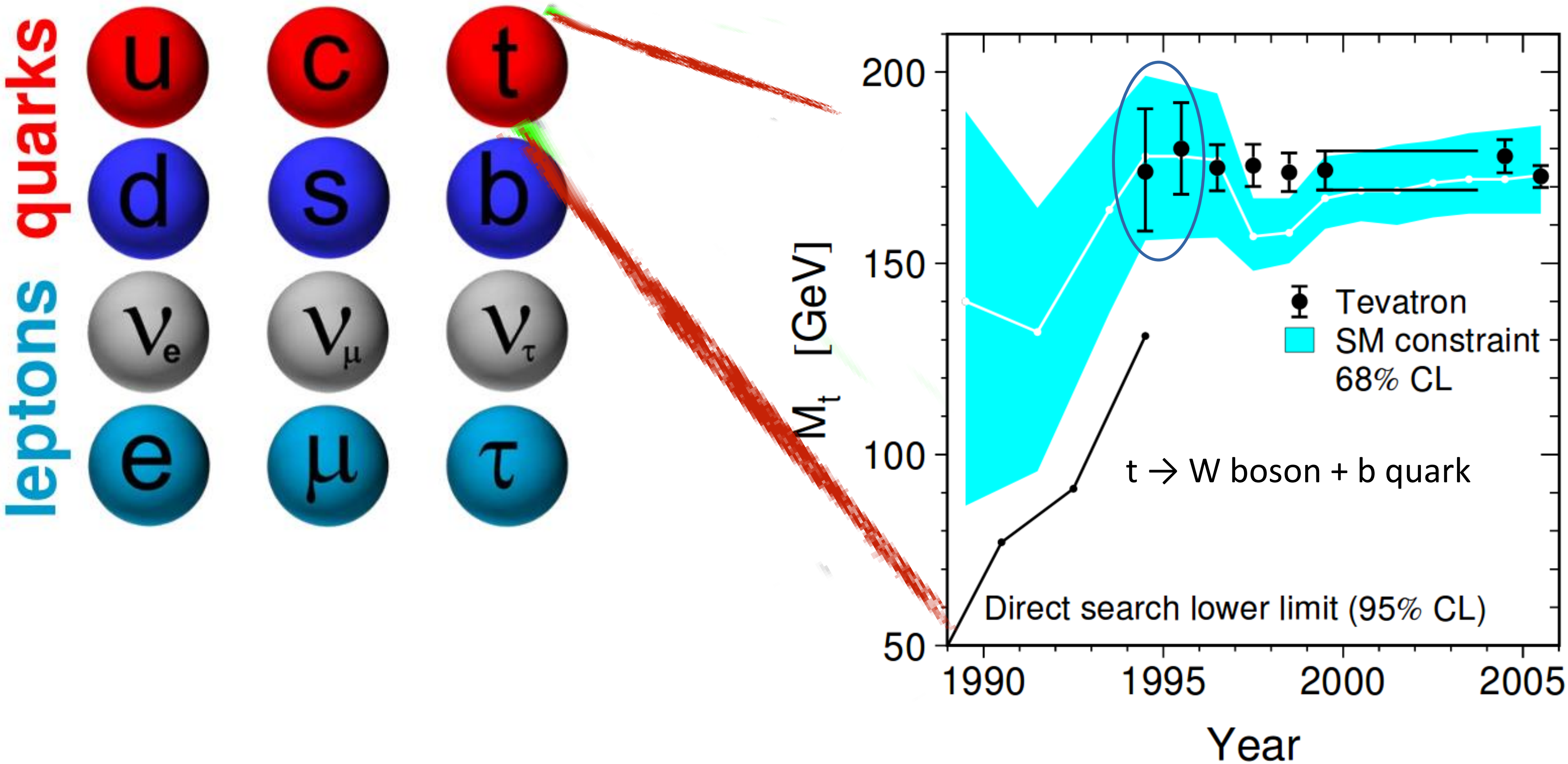
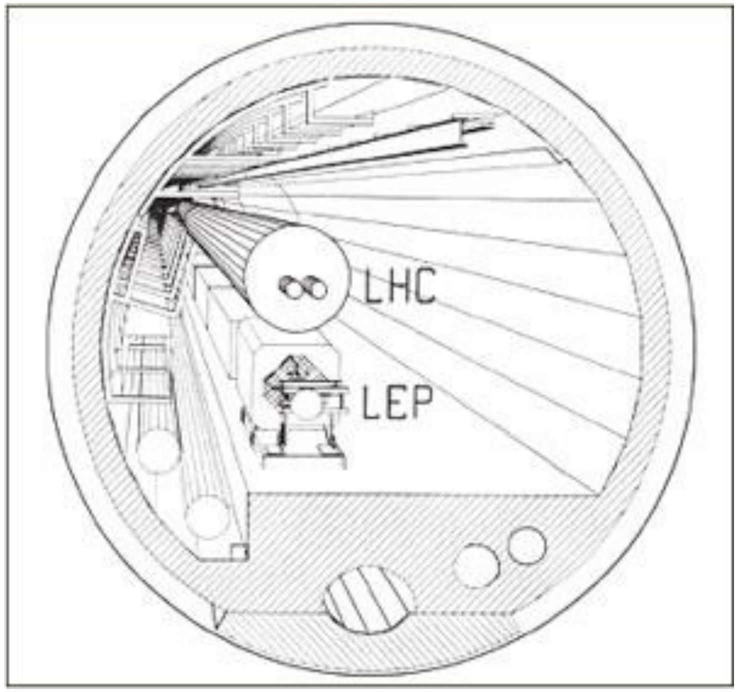


Phys Rev Lett. **74** (1995) 2626
Phys Rev Lett. **74** (1995) 2632
hep-ex/0404010

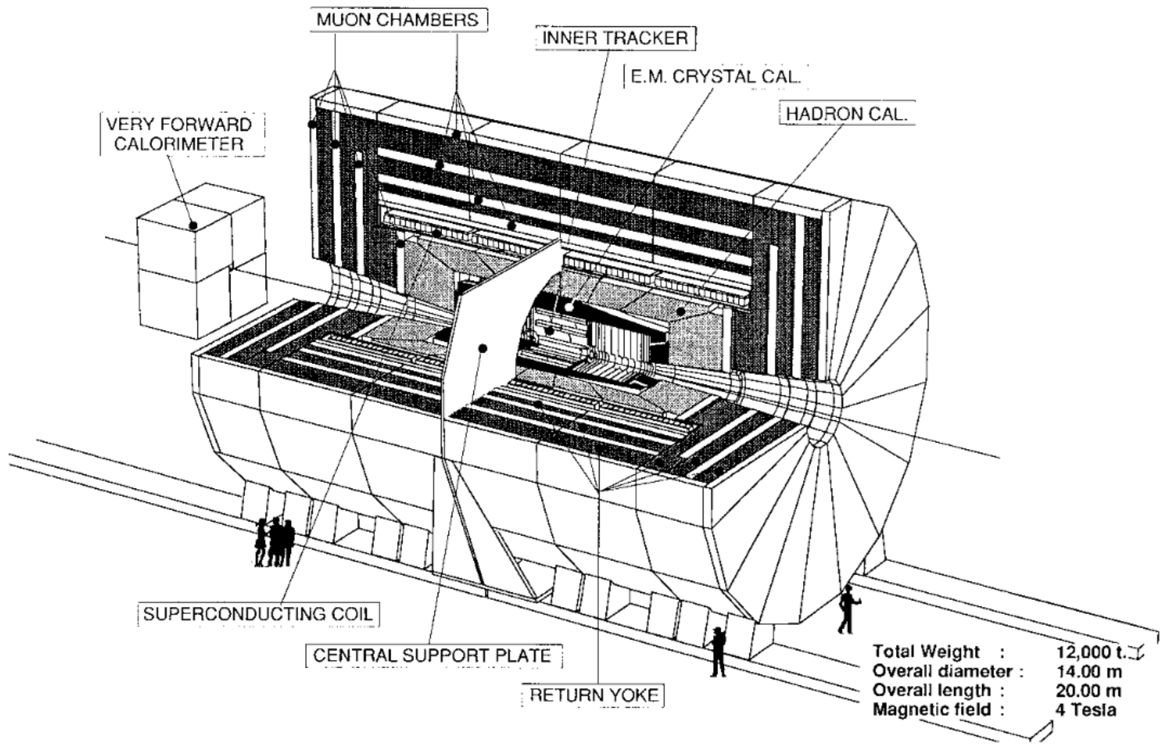
- Indirect, e.g., in LEP, and direct searches hinted to >> 50 GeV
- The first evidence and observation at Tevatron → top quark **established** with *a* mass of 178.0(4.3) GeV

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



Lausanne LHC workshop (**1984**)

Compact Muon Solenoid

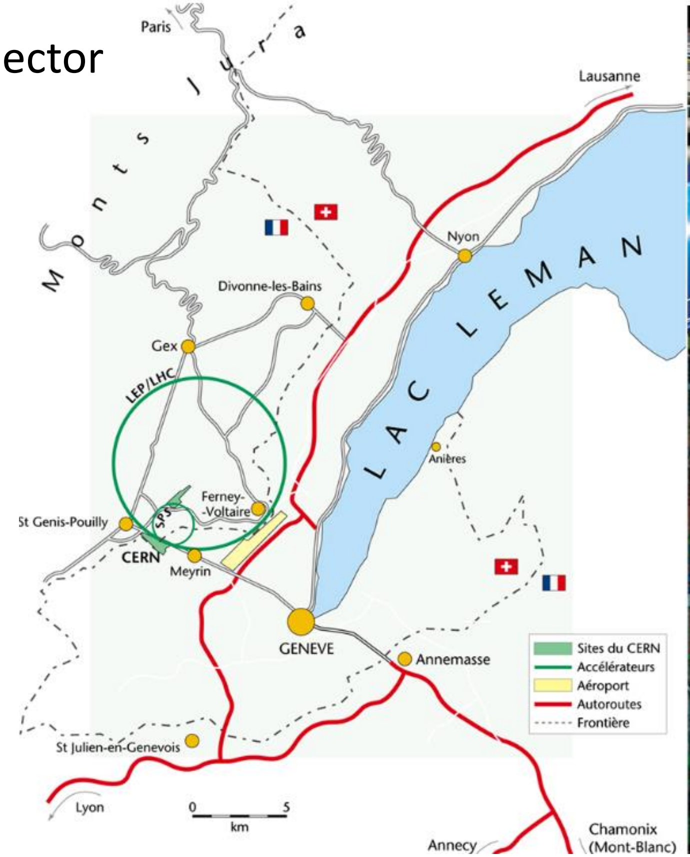


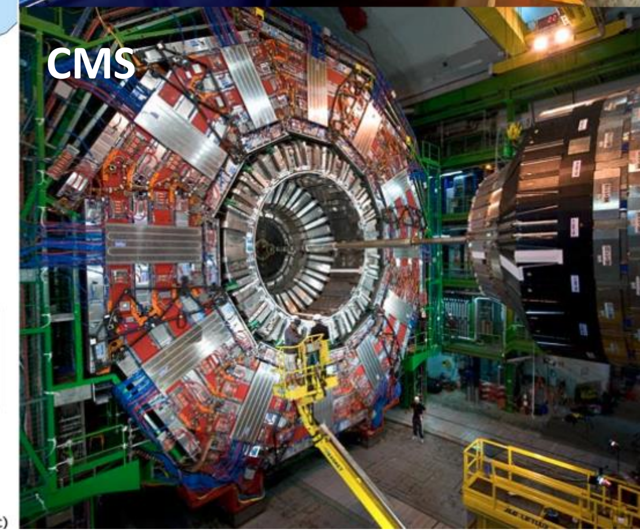
Evian "debut" (**1992**)

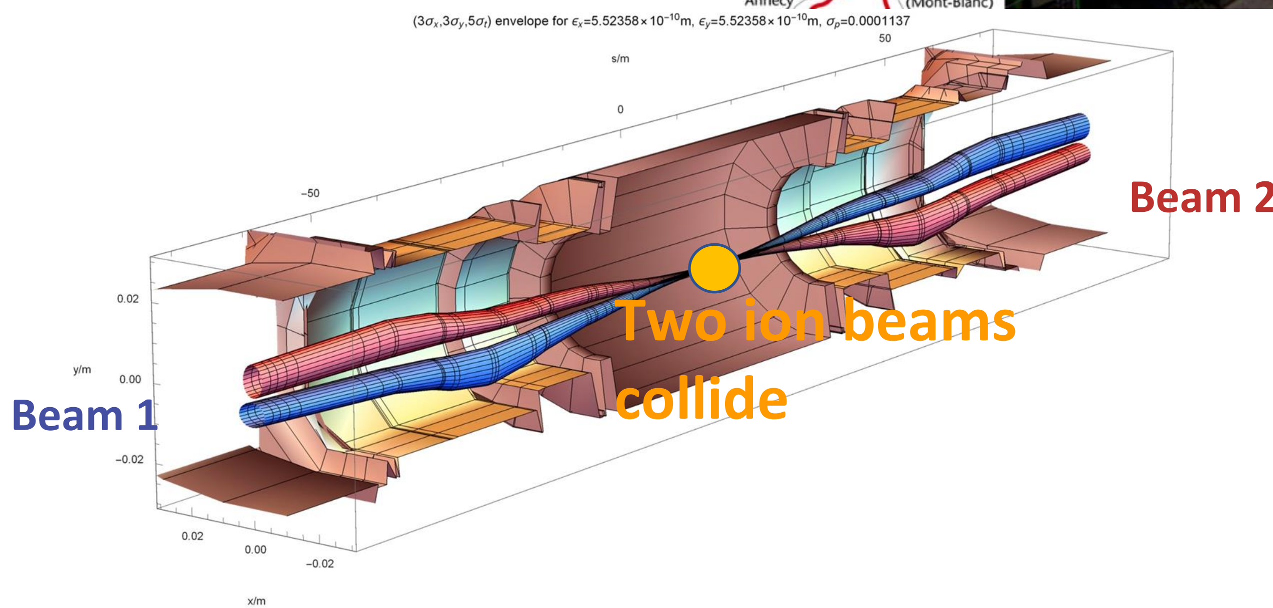
- The infrastructure for *a* **Large Hadron Collider** (LHC), if any, would be limited by
- the existed tunnel (radius and size) and its injectors: "Multipacket" collider + **10 T** magnets
- *Expressions of Interest* in 1992: LHC to handle proton and lead **ions**

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

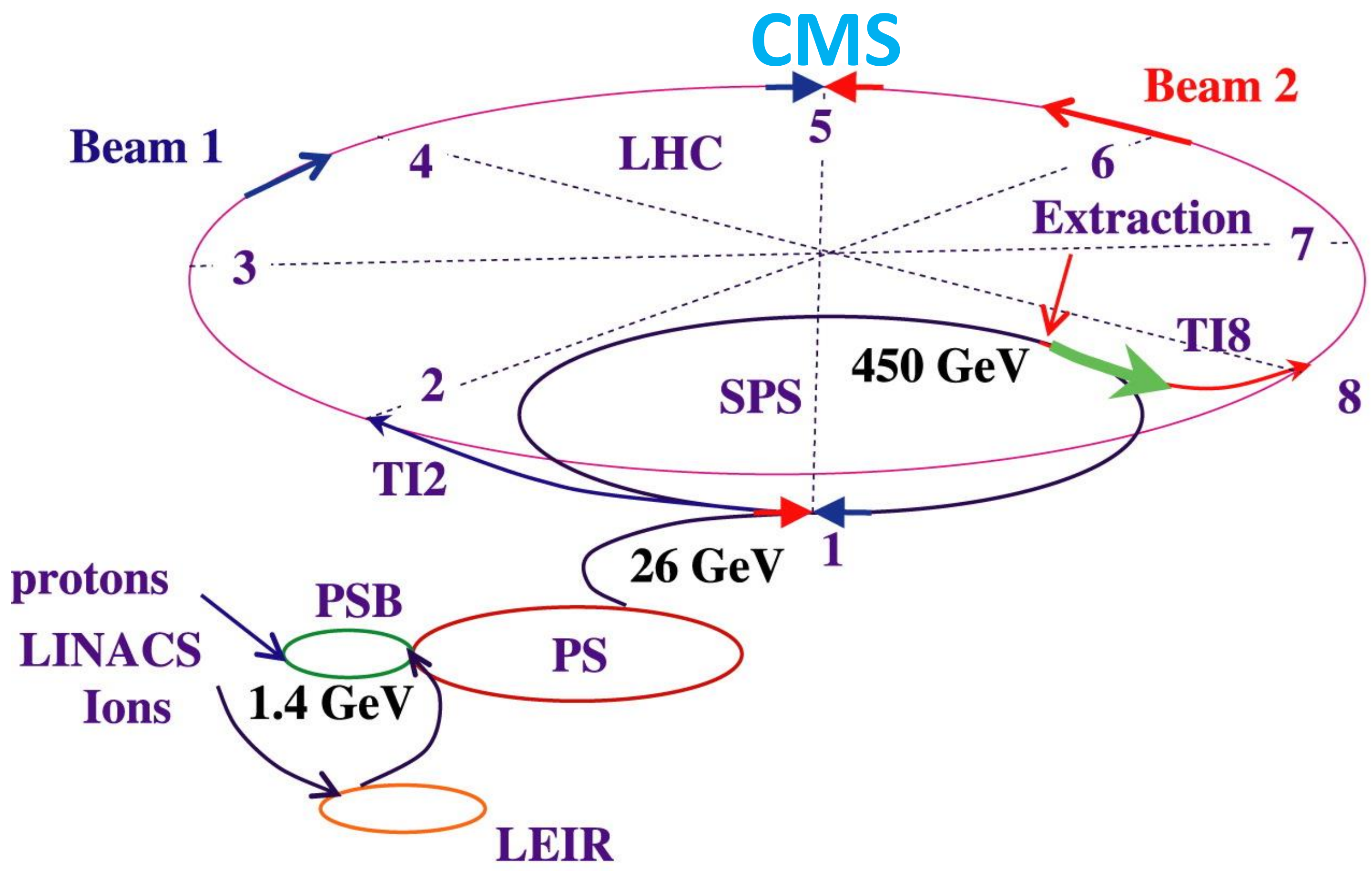
- CERN accelerator complex acts as injector
- A two ring-like accelerator
- Straight sections intercepted by the experimental caverns
- Two “high-”luminosity insertions
  - IR1 & **5**
- One “medium-” & “low-” insertion
  - IR2 & 8







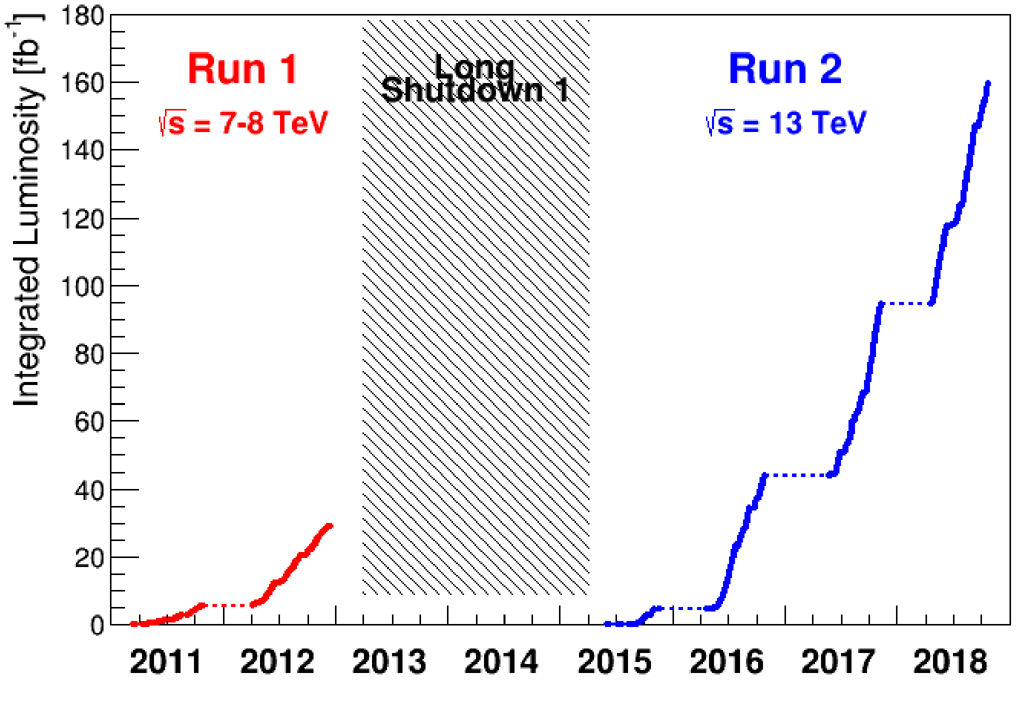
NB: LHC success is also based on its injectors



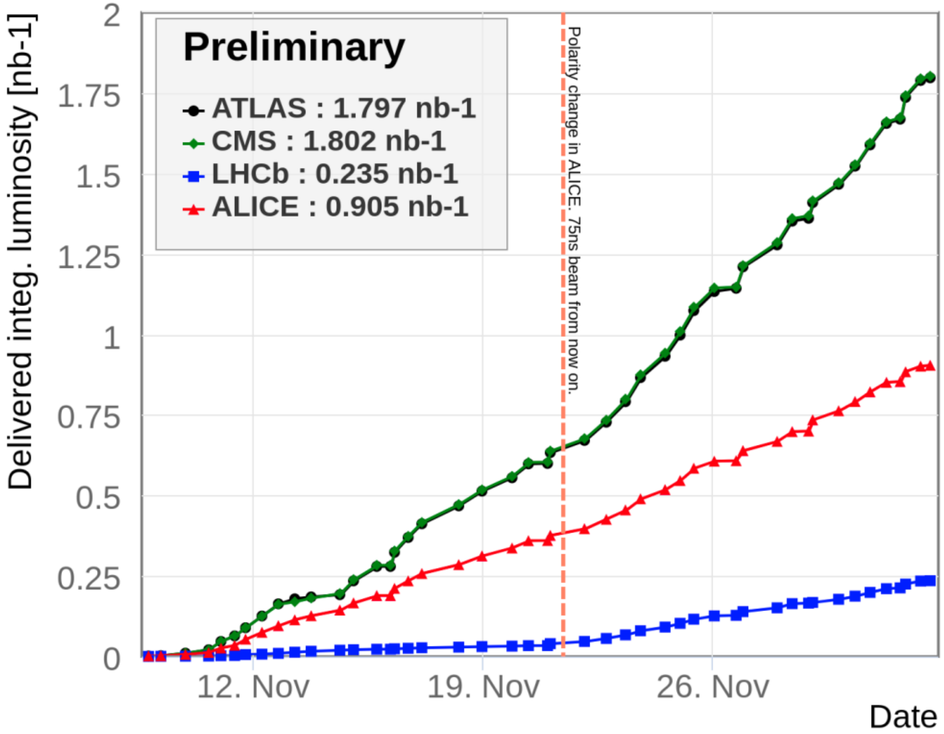
- While speaking about ions: The original LHC design foreseen **only** pp and PbPb (A=208) collisions
- Slight different path for Pb ions up to SPS; their source had to be reconditioned in 2018!
- Novel modes **established**: pPb (2011), XeXe (2017), and partly stripped Pb ions (2018)
- **No** other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

A lot of progress in the accelerator forefront

Number of **proton-proton** collisions

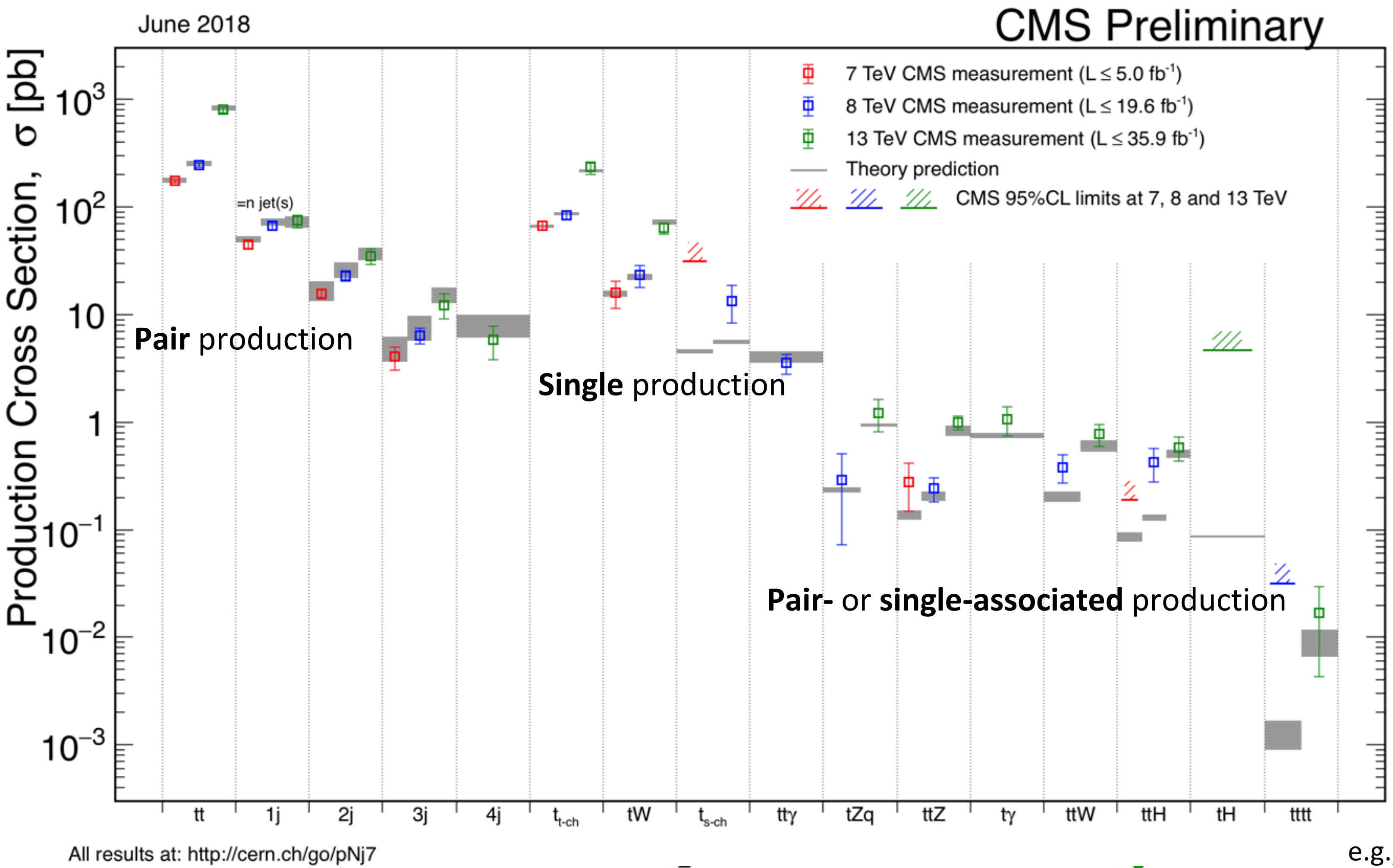


Number of **lead-lead** collisions (in 2018)



- Luminosity is the collider "footprint" for delivering statistically 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!
- **But** we know the level of luminosity **with the same level of precision** as in pp! CMS-PAS-LUM-18-001

It works spectacularly good: the top quark paradigm



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

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

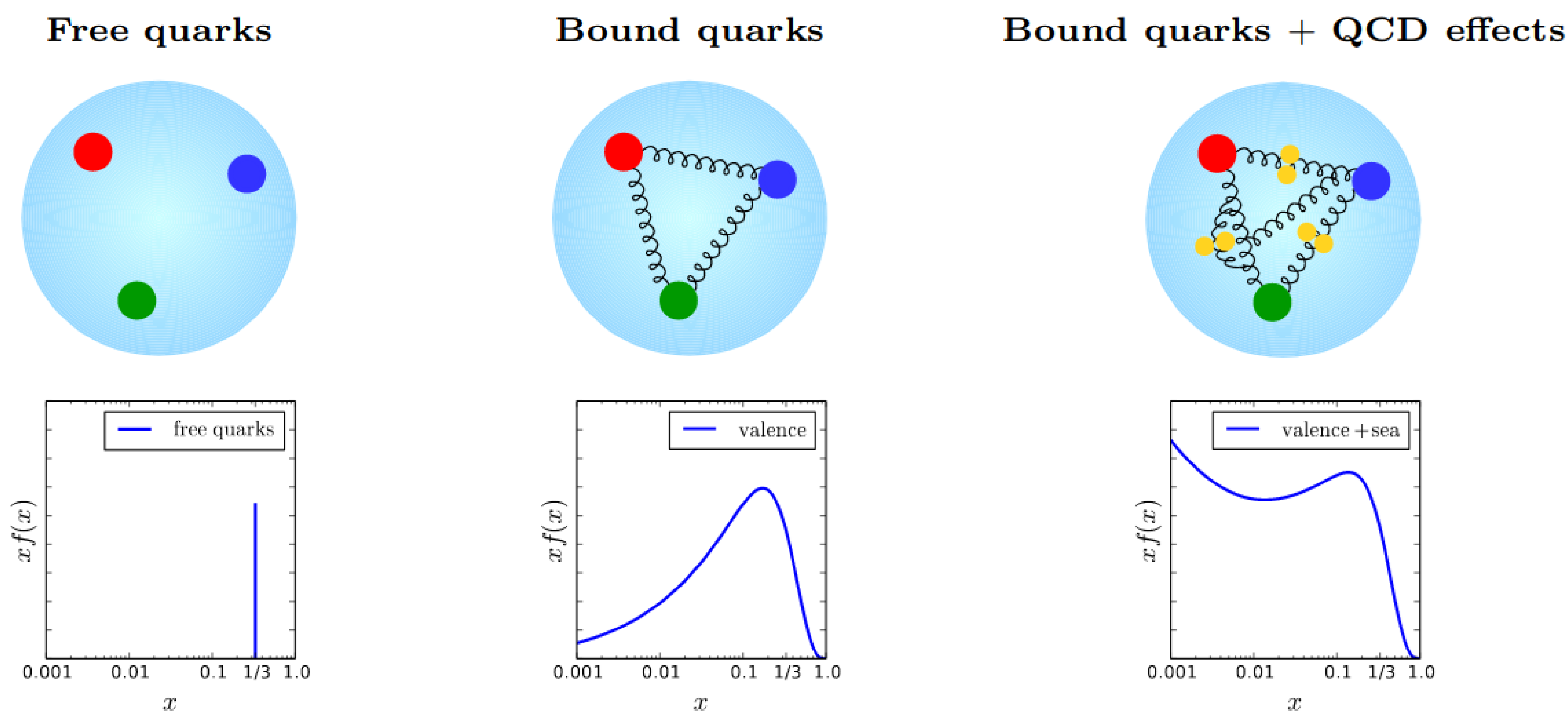
PDFs — partonic cross section — power corrections

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

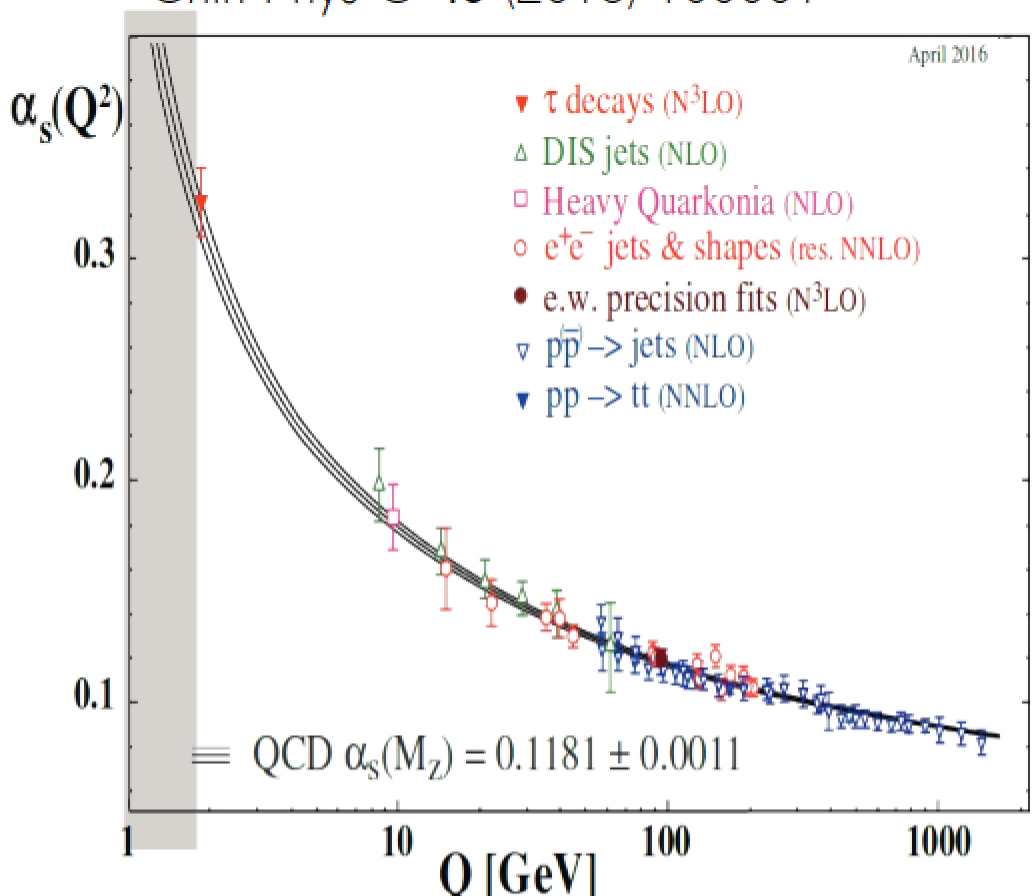
PDF $[f_{a/p}(x,\mu)]$: "probability" that a parton a carries fraction x of proton's momentum (valid at leading-order of QCD).



- 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

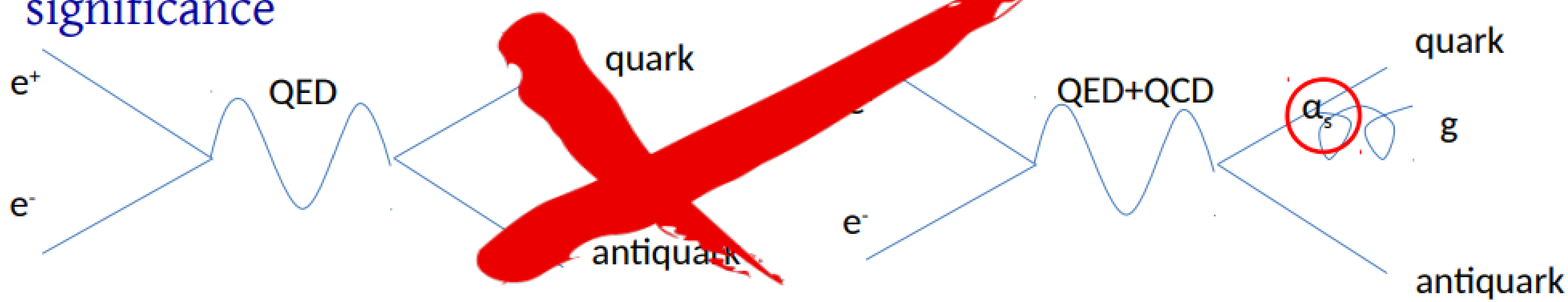
But why QCD is called the strong interaction?

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

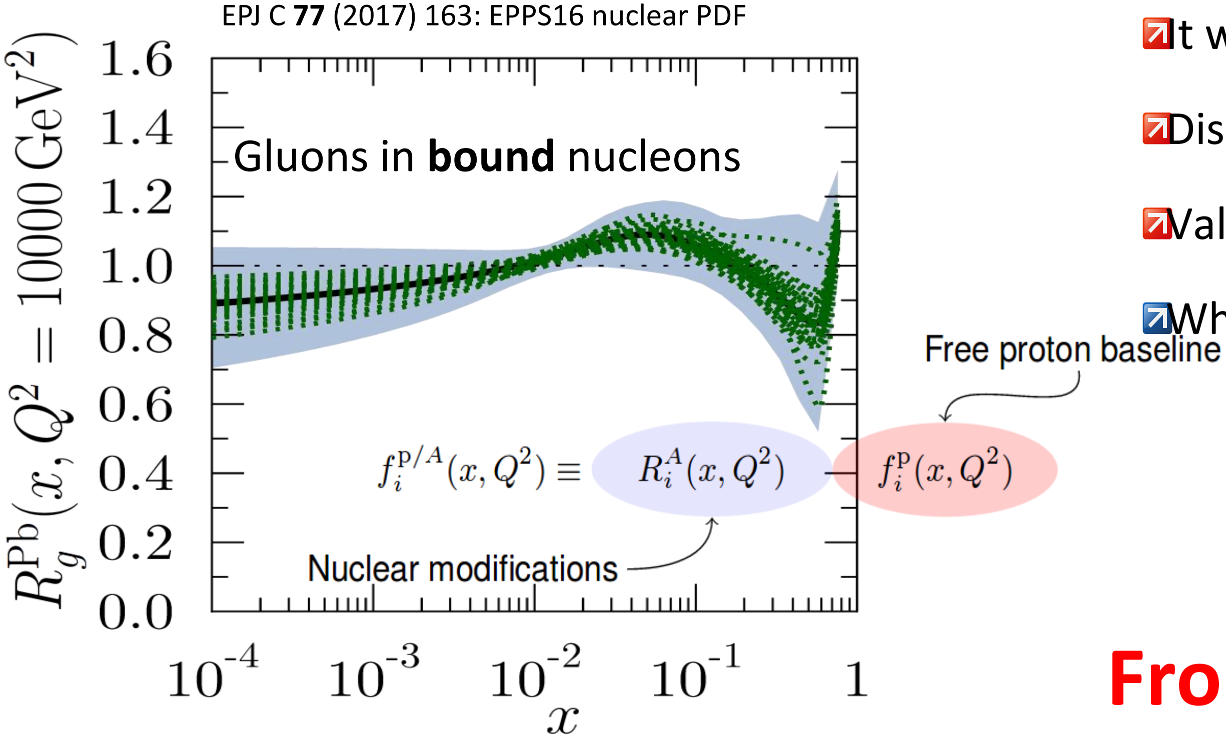


- Hard scattering cross sections calculable
  - **provided** the scale μ is chosen large
- Does the large-distance behavior of QCD implies
  - a transition region where "color" degrees of freedom dominate?
  - I.e., a **deconfinement** phase exists?

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



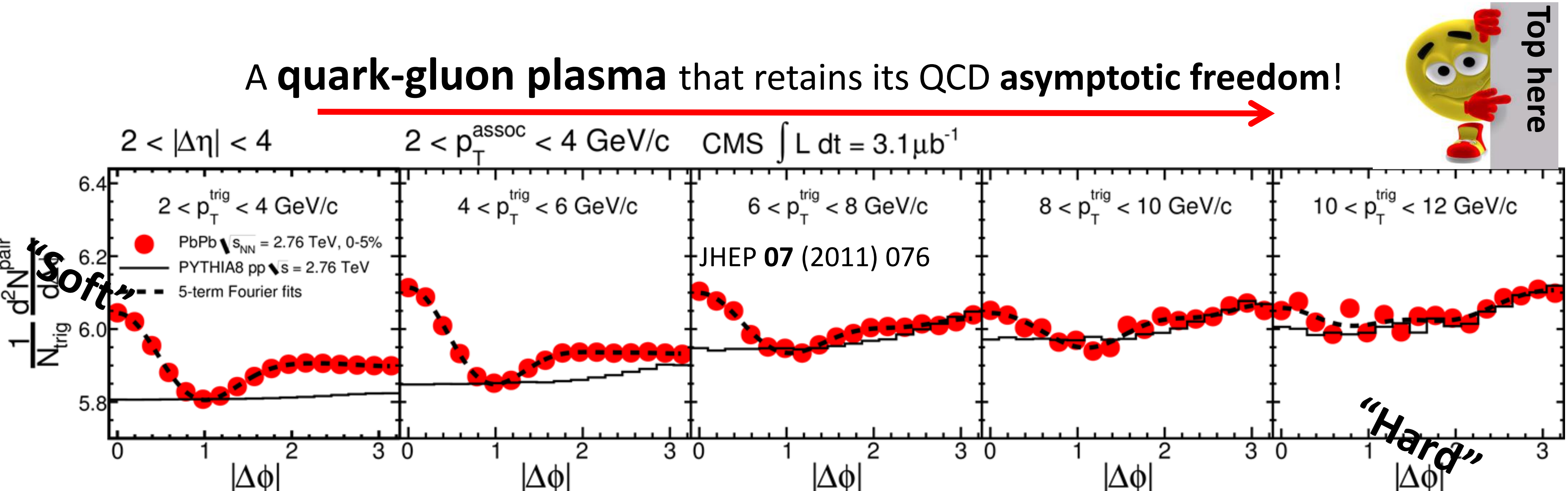
What is the primordial form that early Universe existed in?



- 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?

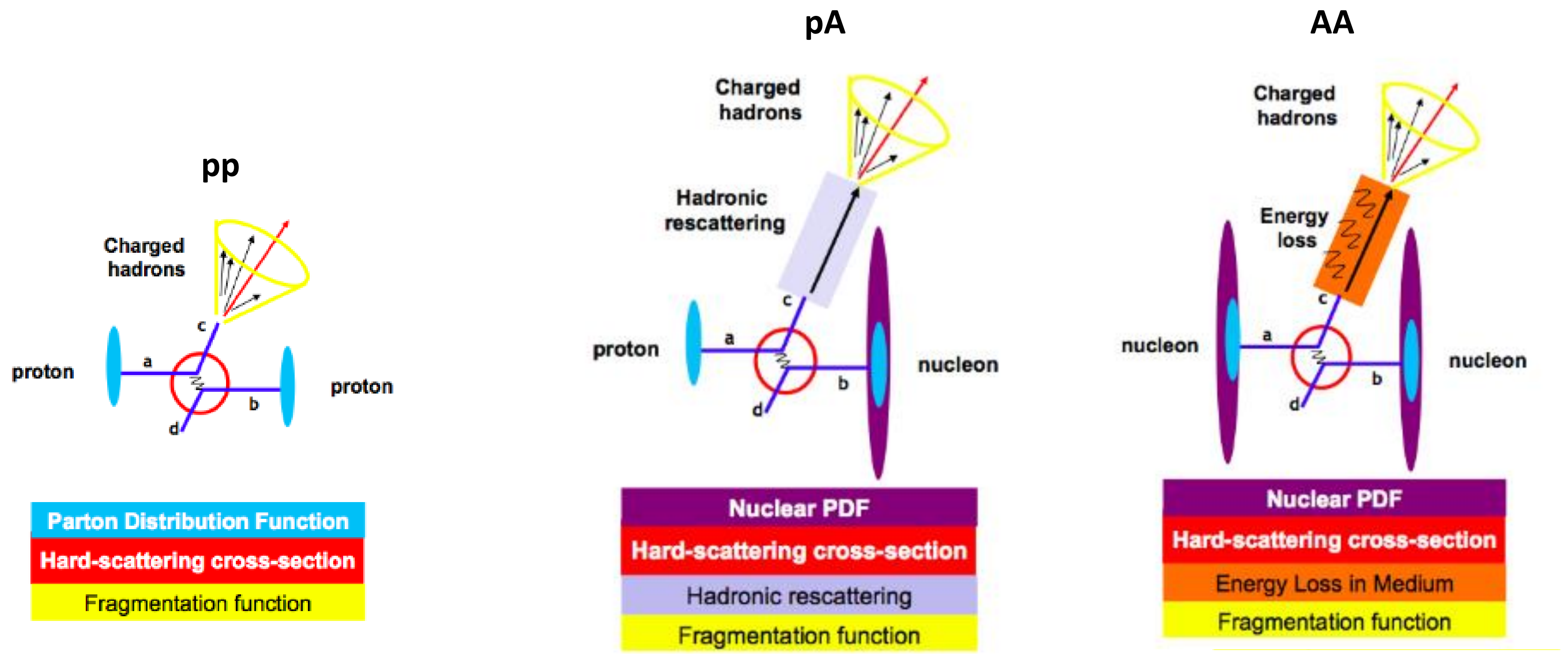
From big to little bangs

A **quark-gluon plasma** that retains its QCD **asymptotic freedom**!



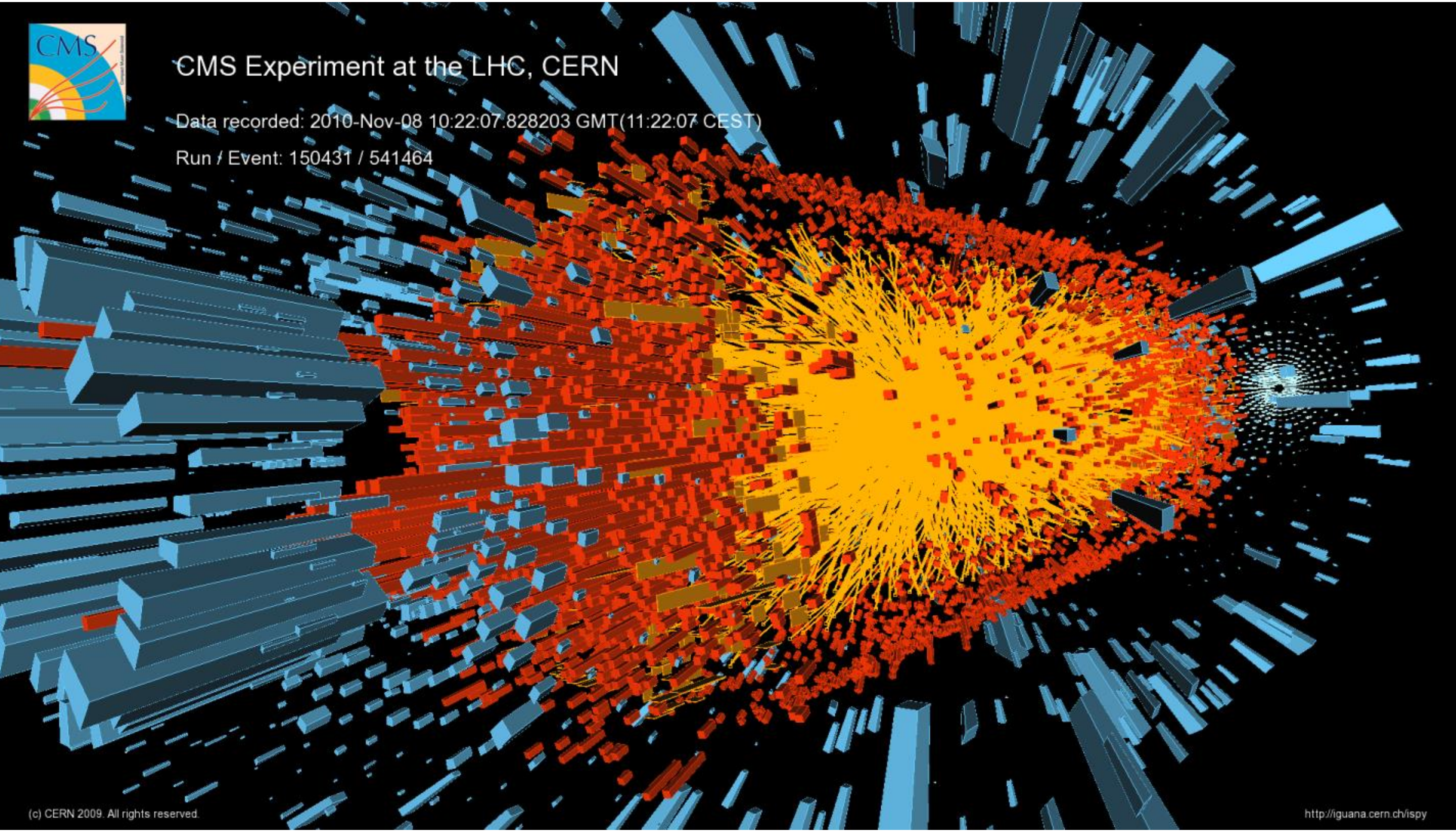
Experimental search for "interesting" phenomena

- Look at elementary pp and pA collisions
- Measure a physical procress, e.g., top quark production
- Look at heavy ion (AA) collisions
- Measure **the very same process** as in pp, pA collisions
- Compare them: Is there something new, e.g., **incompatible to** the A scaling?



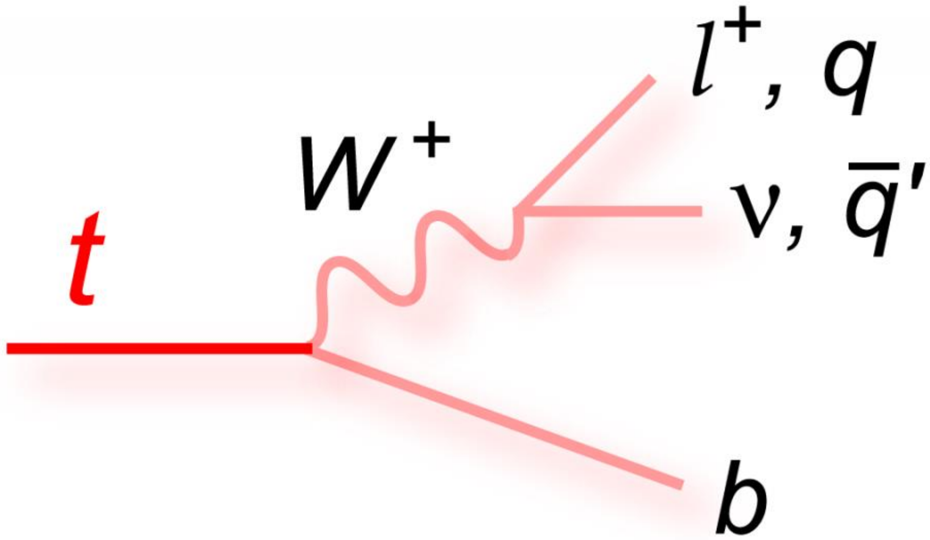
That's a mess ツ

CMS-PHO-EVENTS-**2010**-**002**-**51**



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

A multifaceted quark!

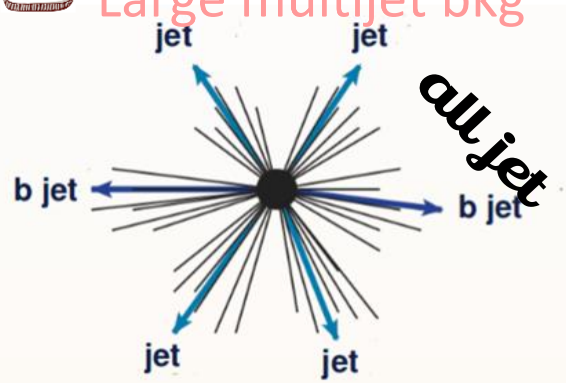


W boson dictates top quark ;D

"Ideal" top-decay channels

The highest BR

Large multijet bkg

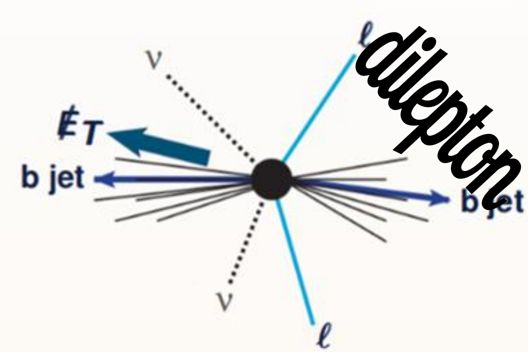


High BR, good S/B

W+jets bkg

Excellent S/B

The lowest BR



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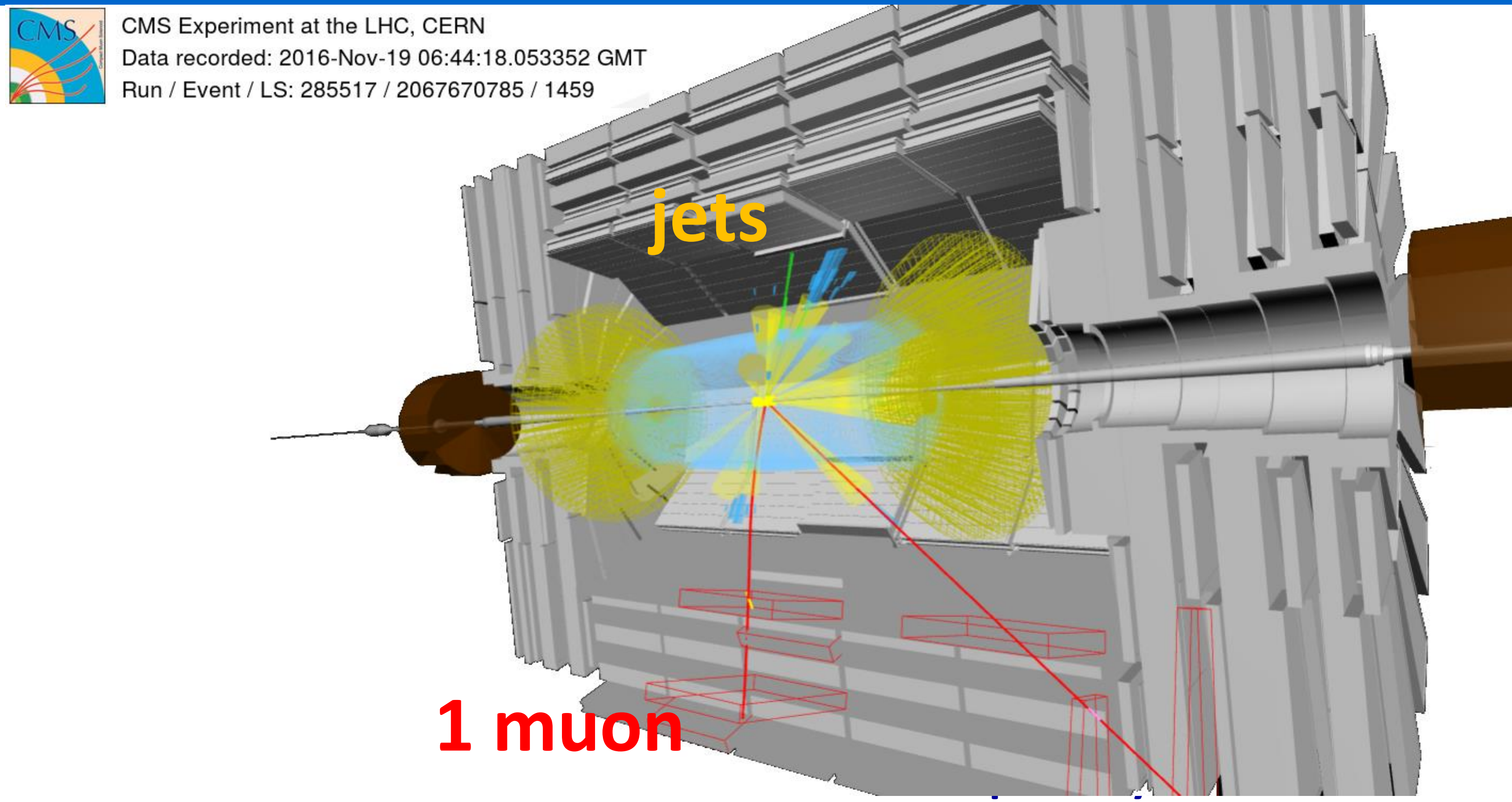

The highest BR

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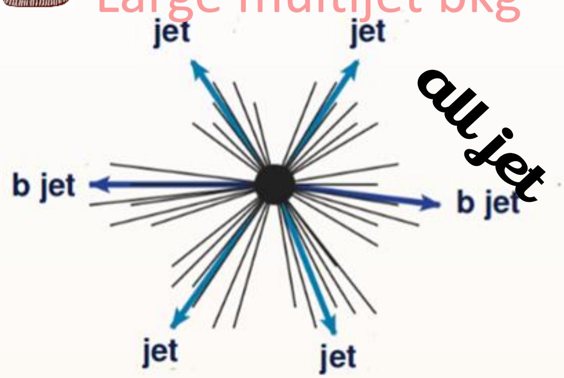

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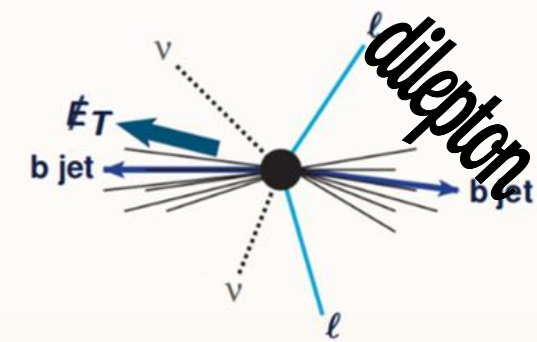

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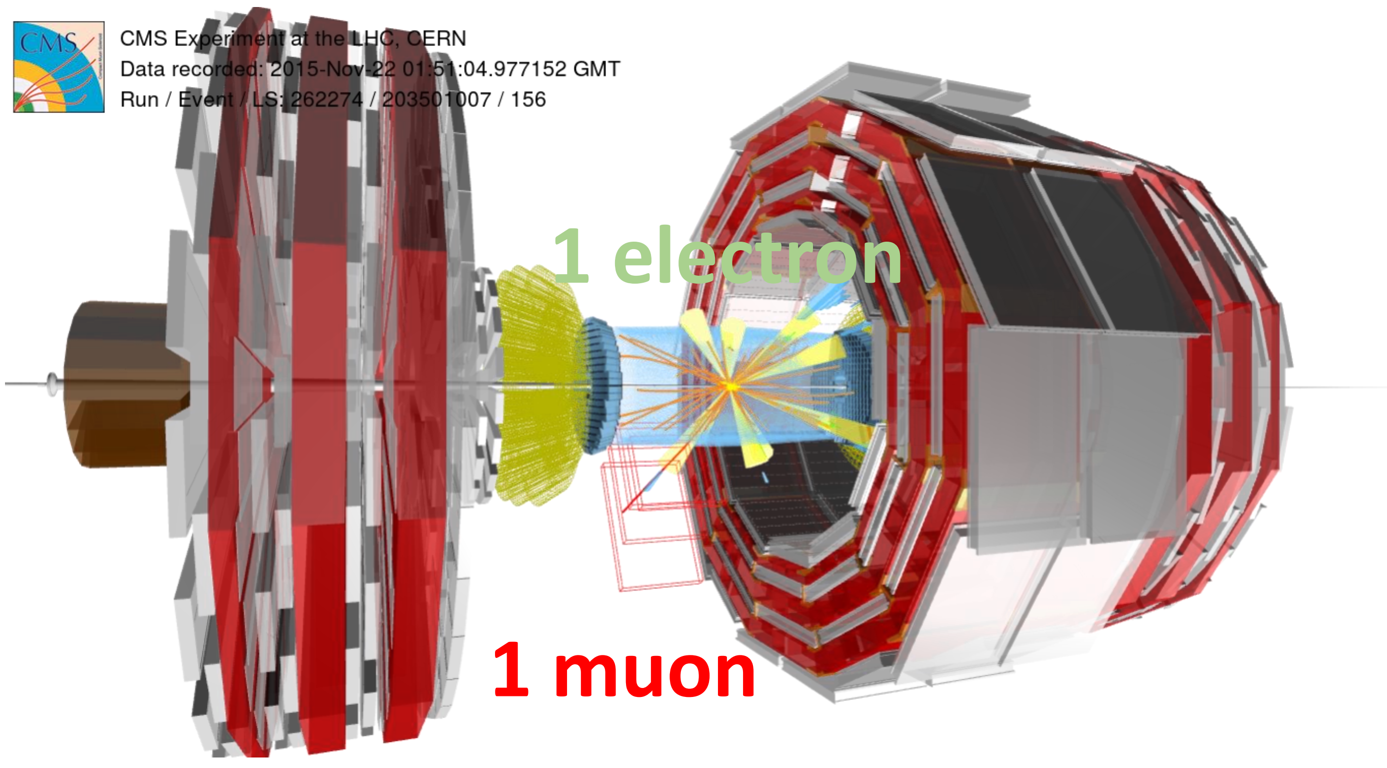

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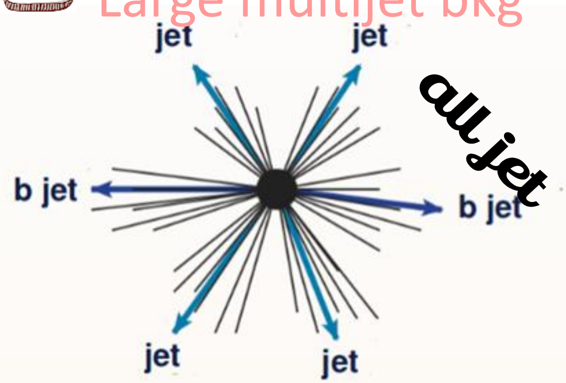

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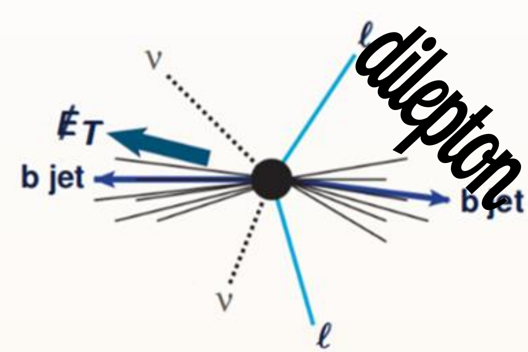
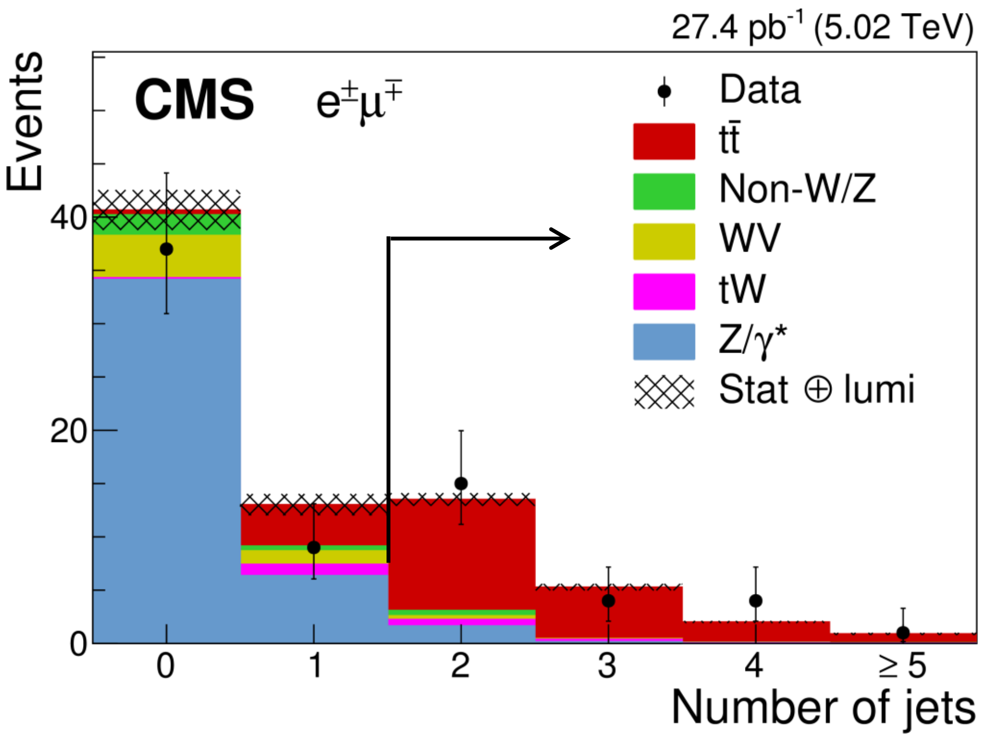
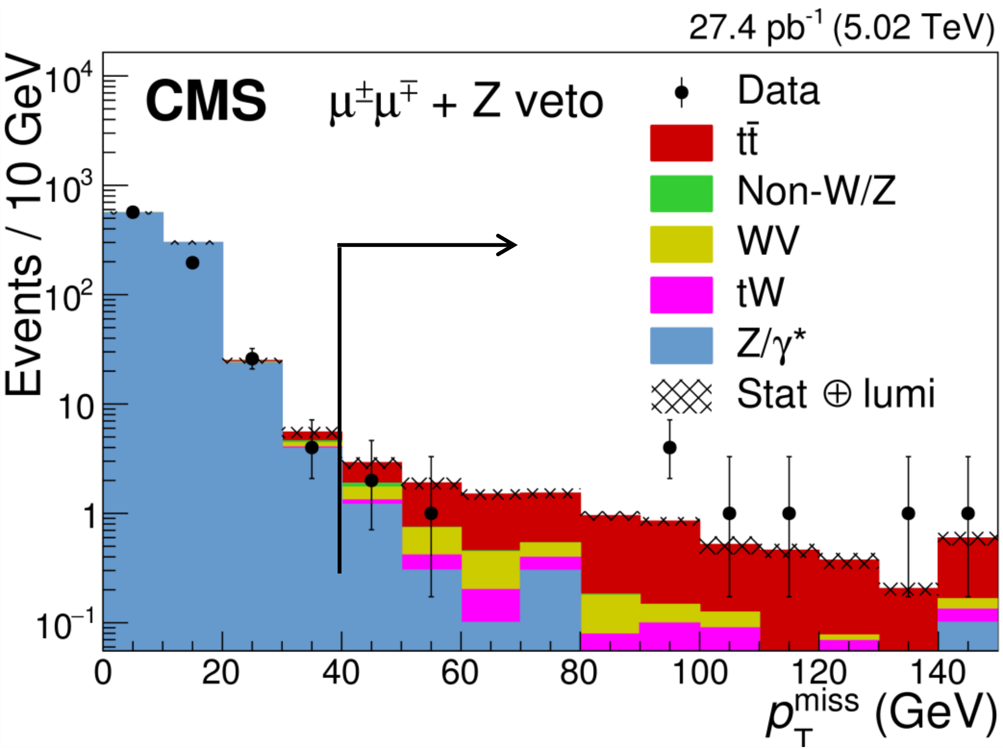


How to extract with confidence top quarks from data

- Choose the **cleanest** final states
  - (di)leptons +jets
- Define the "visible" phase space based on kinematic requirements on physics objects
- Optimize analysis techniques
  - **MVA** for b jet identification and signal extraction
- Perform likelihood fits to physically motivated distributions → cross section ($\sigma_{t\bar{t}}$) is **extracted**

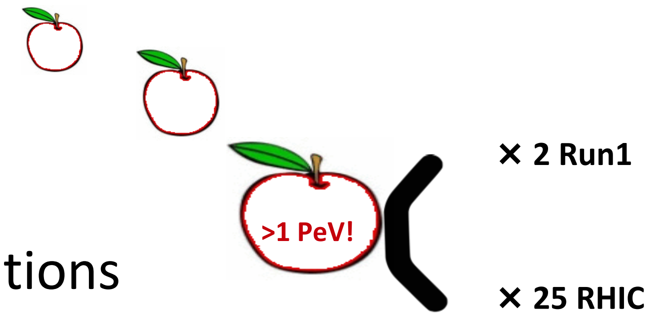
arXiv: 1711.03143

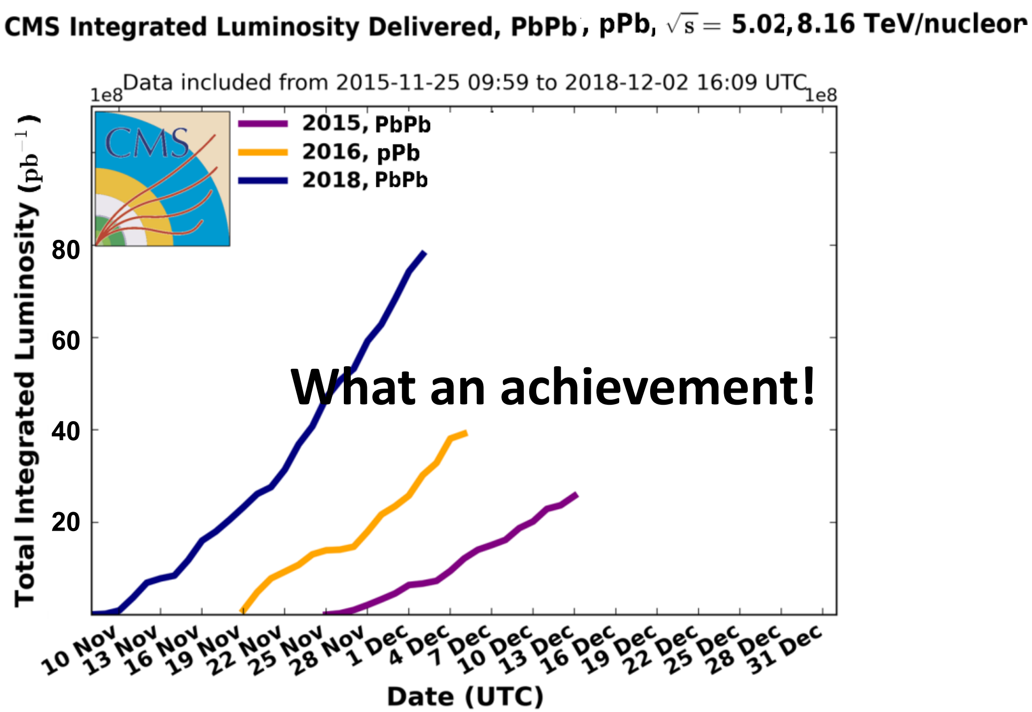


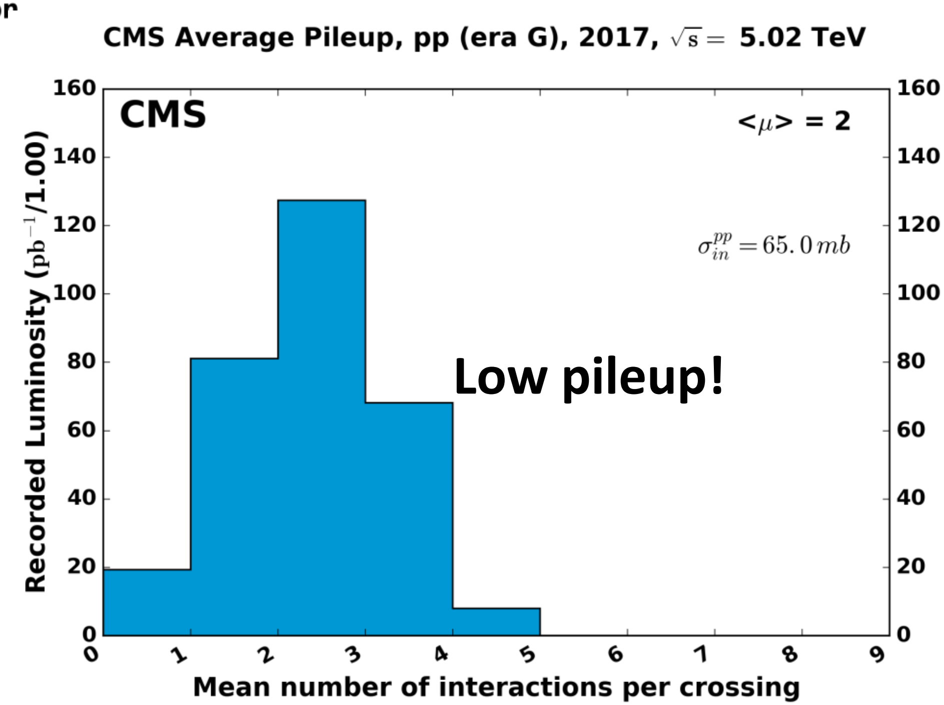


Why recording collision data @ 5.02 TeV?

- 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 4*Z* TeV; Jan-Feb 2013
  - **PbPb** (beam) energy of 6.37*Z* TeV; Nov 2015 (+2018)
- Price to pay: rapid commissioning between LHC configurations
  - PbPb delivered to **all experiments** for the first time though





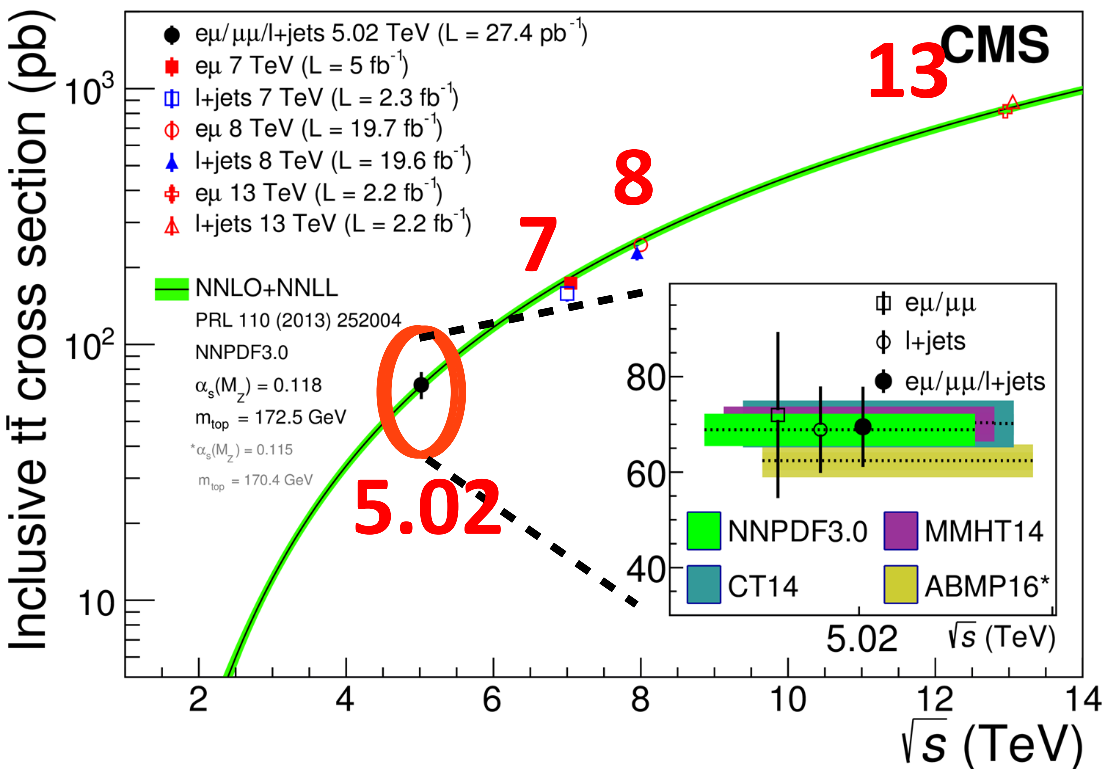


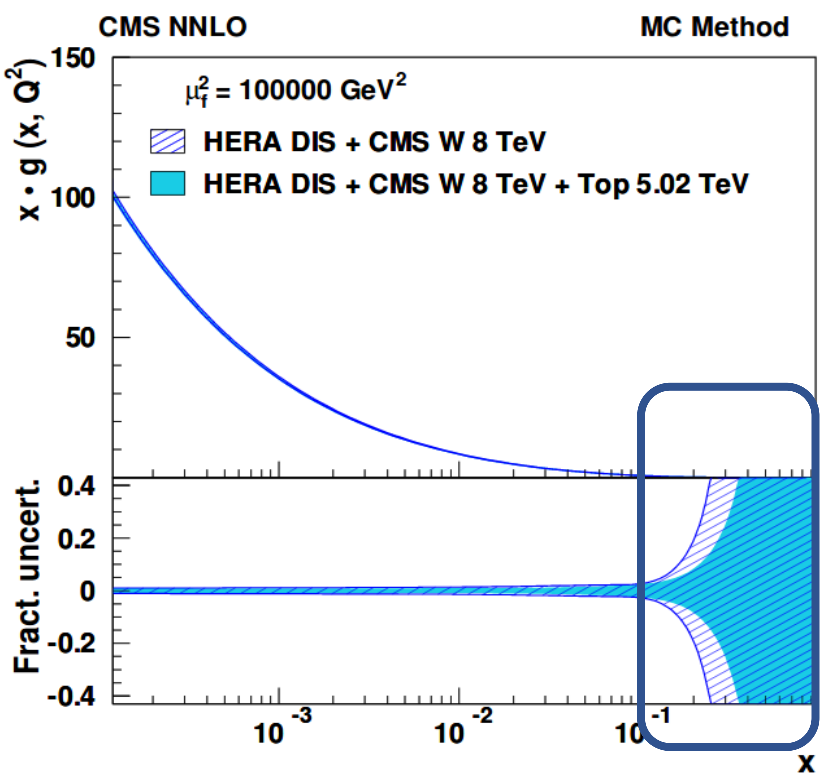
Starting from the basics: SM works very well at 5.02 TeV too

- CMS was **the first experiment** to measure *tt* inclusively in **4** energies
- **Reduction of the uncertainty** in the gluon distribution at large *x*

arXiv: 1711.03143

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

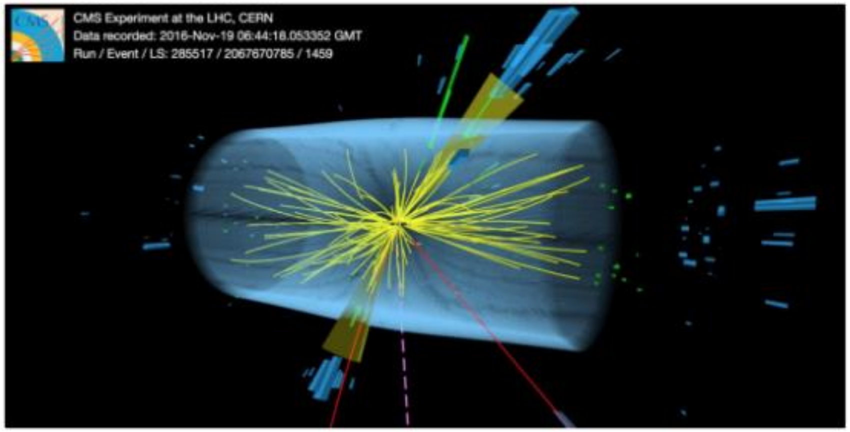




The discovery of "top in nuclear collisions"

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 ?

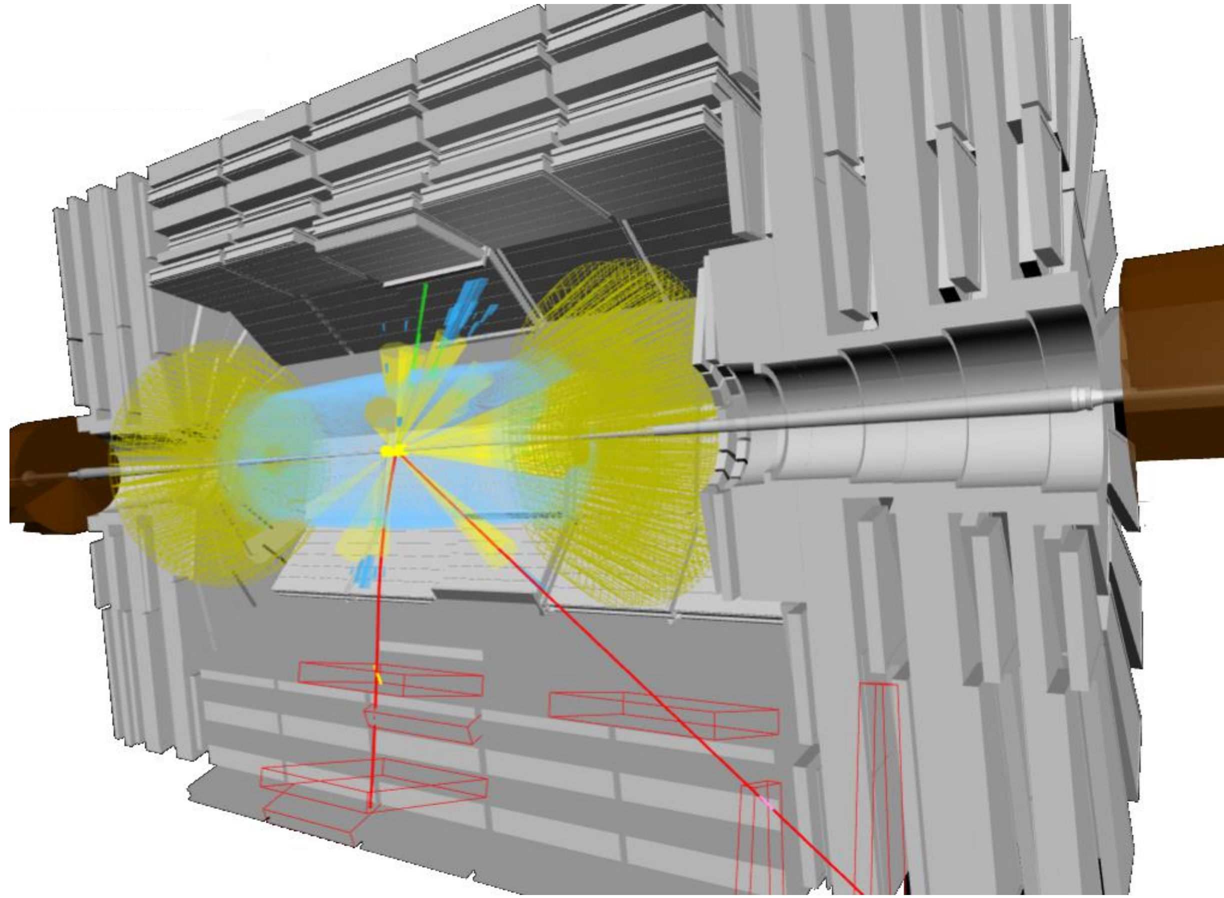
1

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?

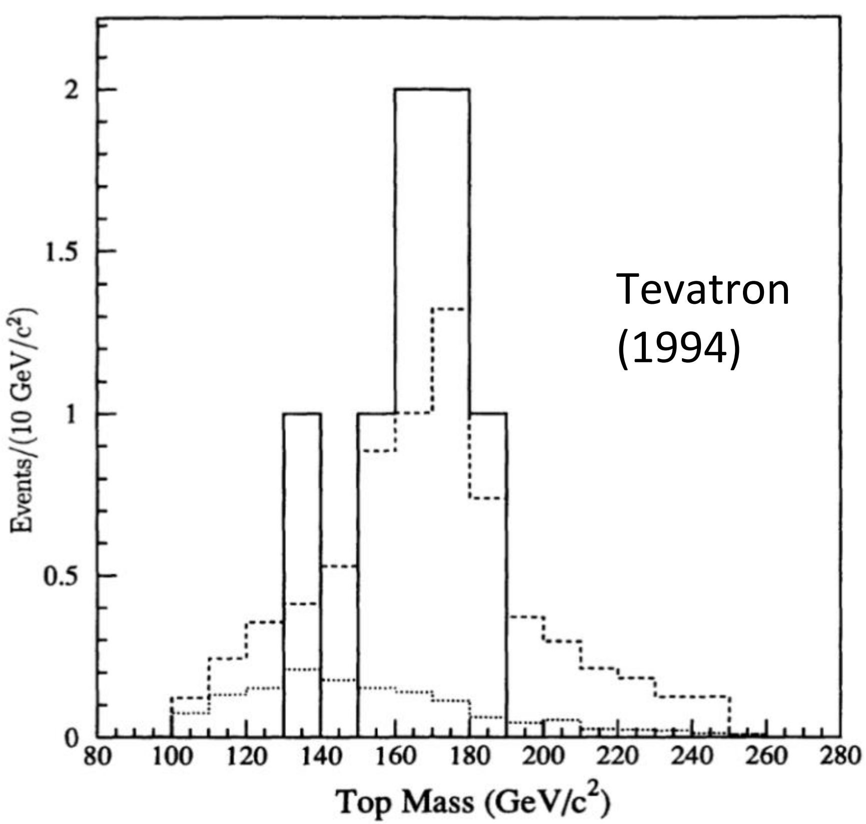


arXiv: 1709.07411

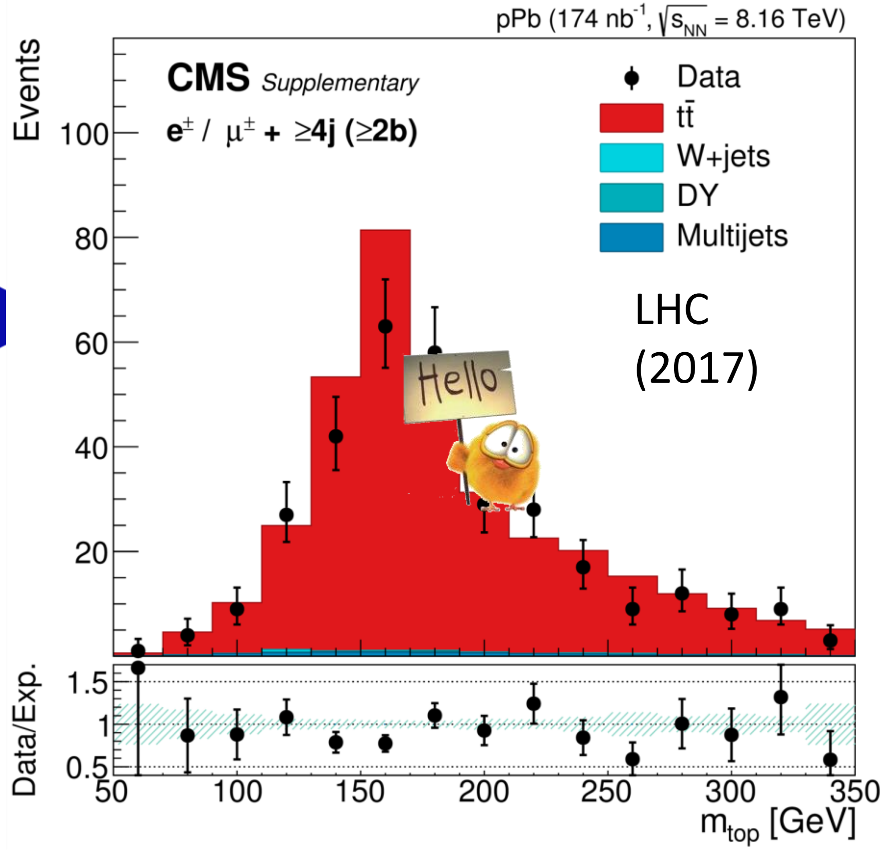
A peak is reconstructed close to top mass

- **First experimental observation** of the top quark in nuclear collisions
- Came after 25 years since Tevatron observation

Phys. Rev. Lett. **73** (1994) 225



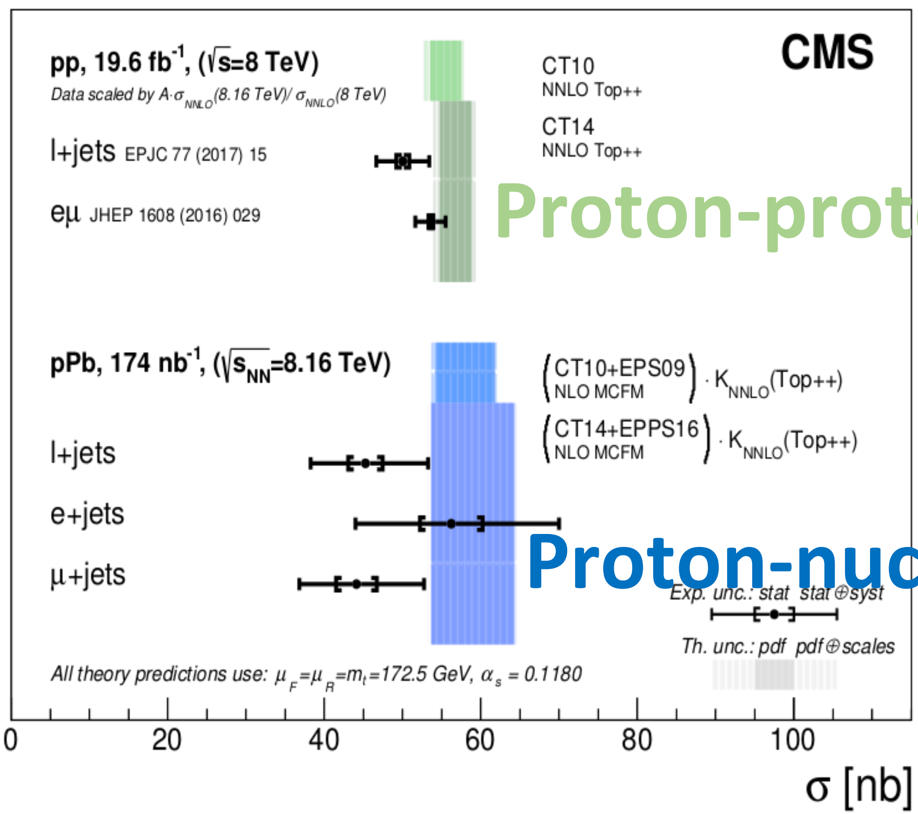
arXiv: 1709.07411
(Phys. Rev. Lett. **119** (2017) 242001)

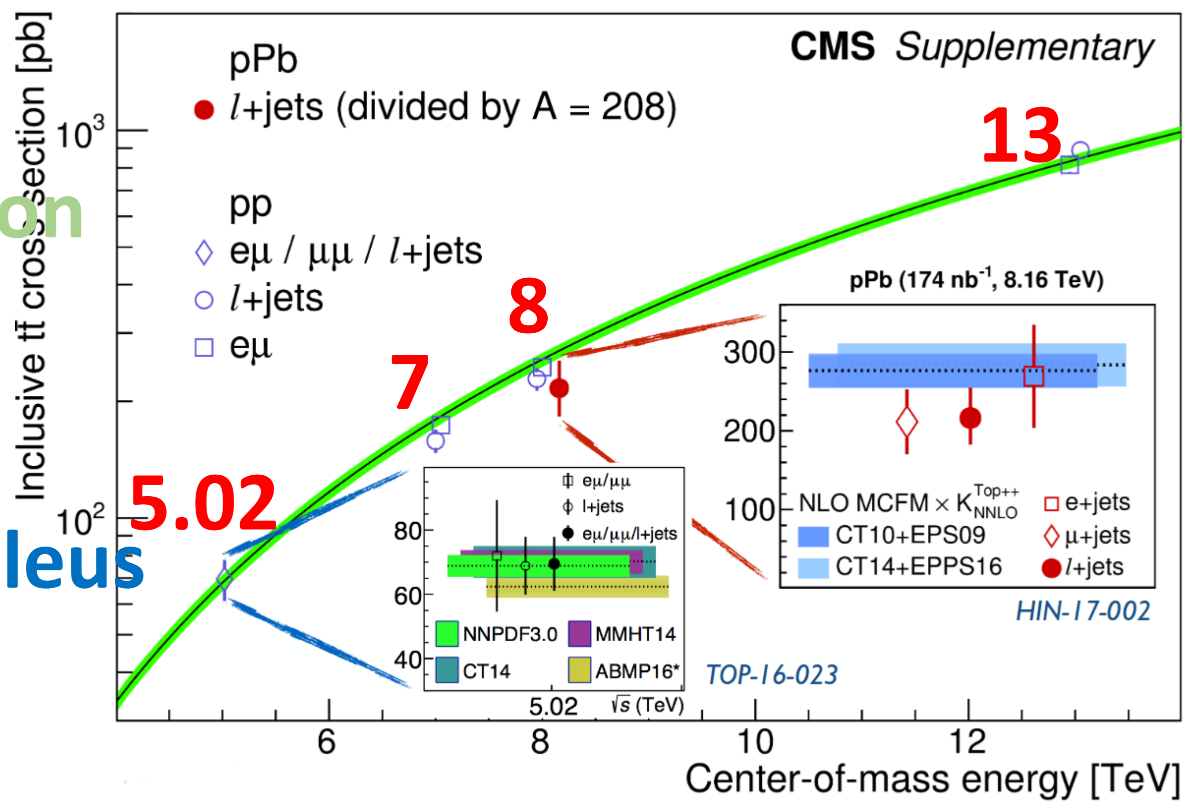


Updated compilation: 4 $\sqrt{s_{NN}}$ & 2 systems @ LHC!

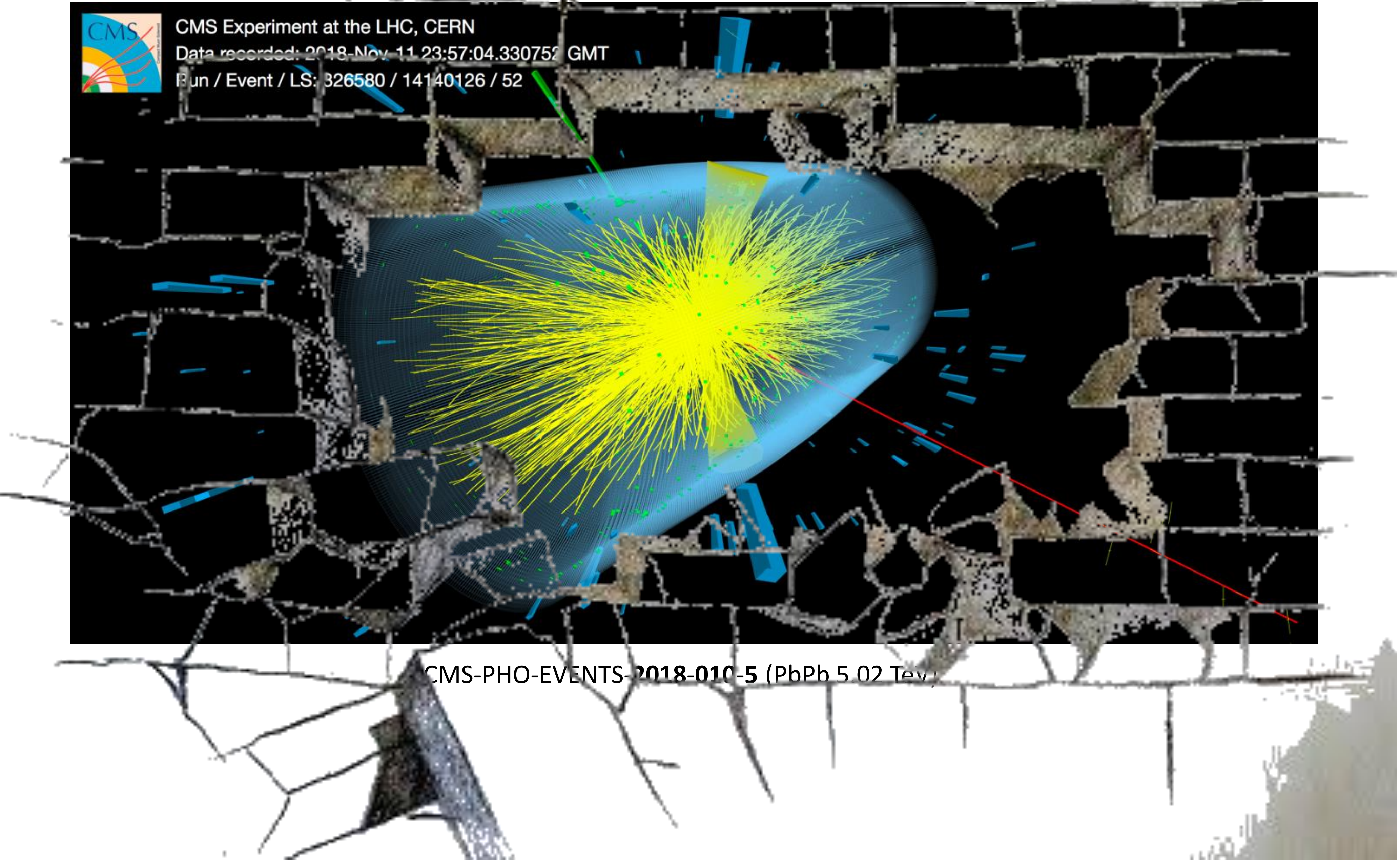
- CMS is **the first&only experiment** to measure *tt* inclusively in **2 collision systems**
- The measurement **paved the way** for dedicated nuclear studies

arXiv: 1709.07411





The road was finally open

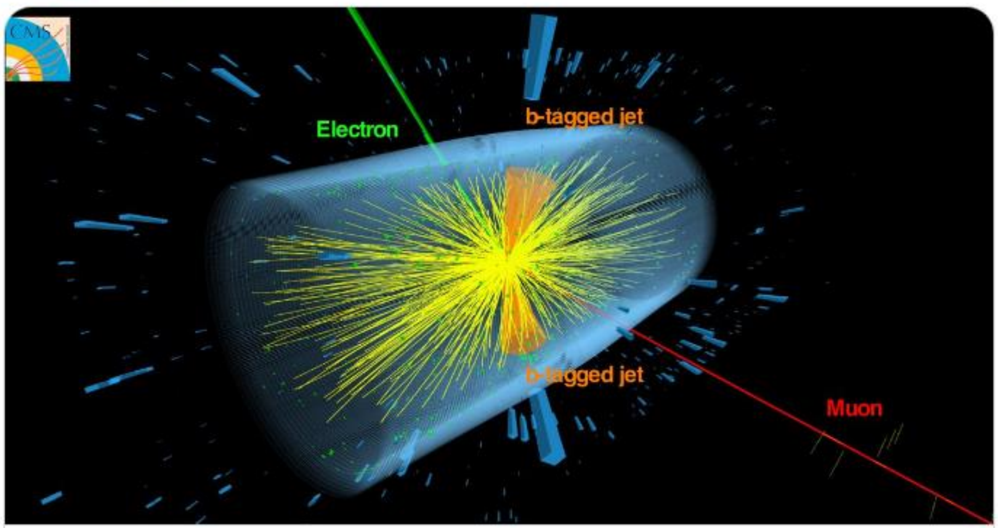


CMS-PHO-EVENTS-**2018-010-5** (PbPb 5.02 TeV)

"Heavy metal hits the top"

CERN @CERN

This result from @CMSExperiment, opens the path to study in a new and unique way the extreme state of matter that is thought to have existed shortly after the #BigBang.



CMS sees evidence of top quarks in collisions between heavy nuclei
The CMS collaboration has seen evidence of top quarks in collisions between heavy nuclei at the Large Hadron Collider (LHC). This isn't the first time this ...
home.cern

CERN press release

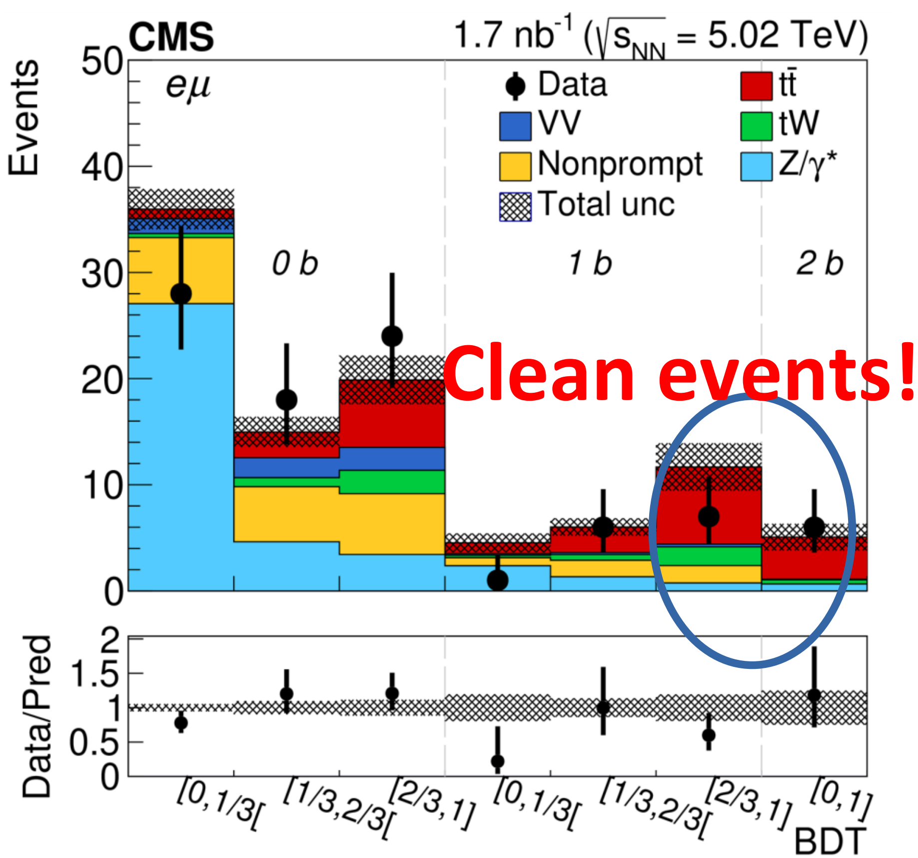
CMS Experiment at CERN
October 9 at 9:08 AM

For the first time the CMS Collaboration demonstrates evidence that top quarks are produced in nucleus-nucleus collisions! Read more how the top quark interacts with the heavy metal 🎸💥🎸 of the lead-lead collisions in this CMS physics briefing: ➡️ https://cms.cern/news/heavy-metal-hits-top

arXiv: 2006.11110
(Phys Rev Lett **125** (2020) 222001)

First evidence of top quarks in nucleus-nucleus collisions

- CMS **the first&only experiment** to measure *tt* inclusively in **3 collision systems**
- **A new tool** for probing bound gluons as well as the QGP properties



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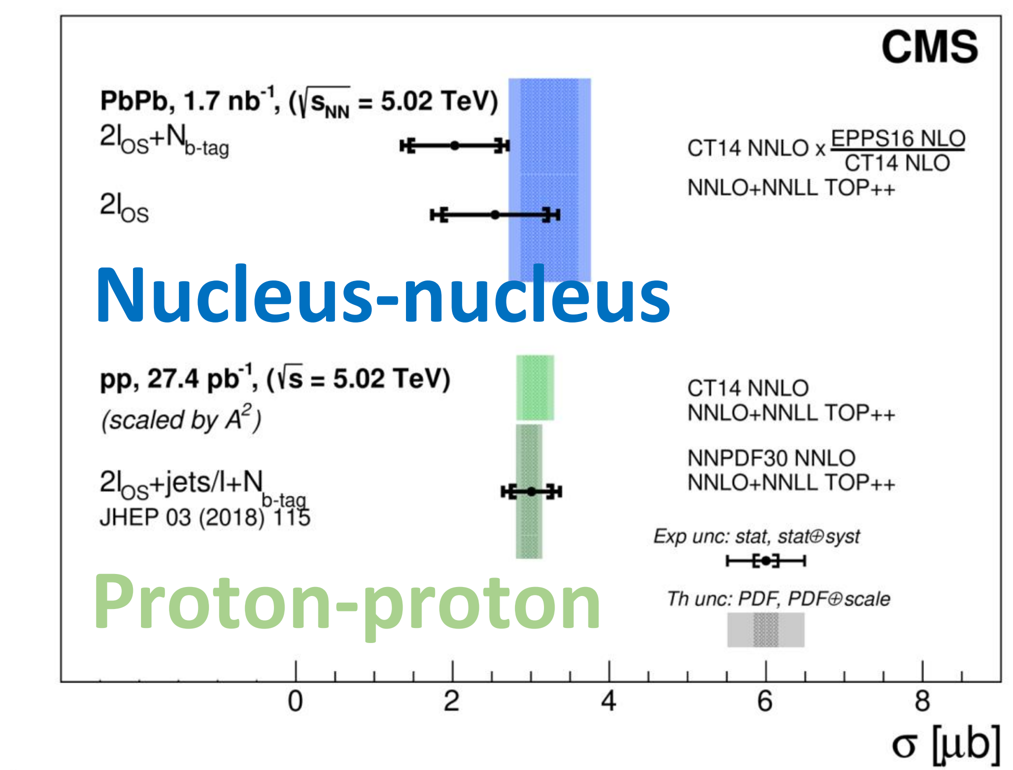
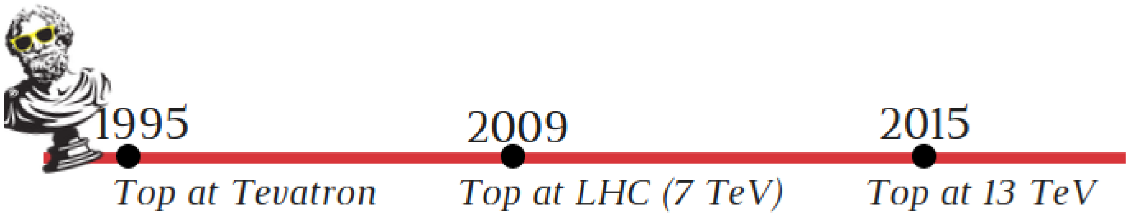


Outlook

- Top quark first **observed** at Tevatron 25 years ago
- Studied **in detail** in pp collisions at LHC



Outlook

- Top quark first **observed** at Tevatron 25 years ago
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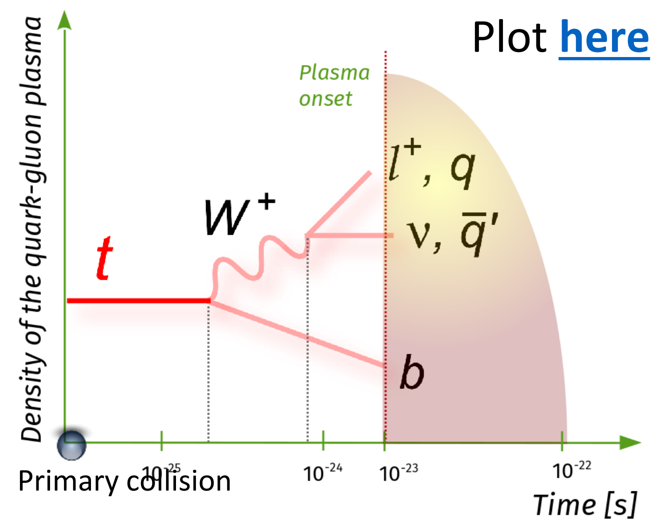
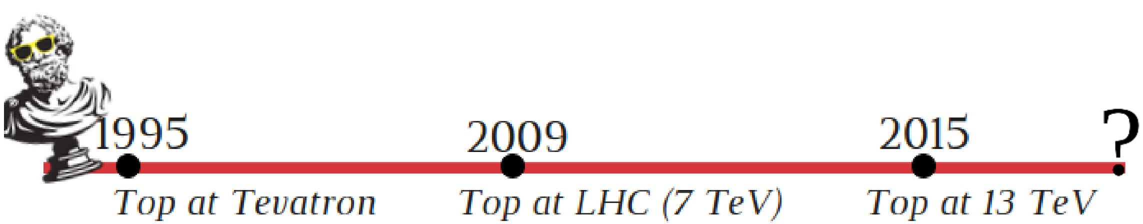
- Nuclear collisions are used to study **quark-gluon plasma**, a strongly-interacting form of matter
- What is the arrangement of quarks and gluons inside heavy nuclei?
- Could top quarks provide successive time snapshots of QGP?

Plot here





Outlook

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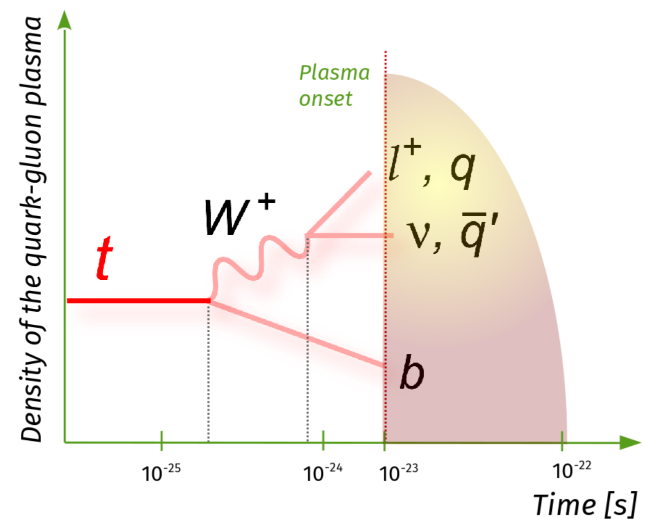
  - What is the arrangement of quarks and gluons inside heavy nuclei?
  - Could top quarks provide successive time snapshots of QGP?
- A dedicated study program of $t\bar{t}$ in the “Little Bang Standard Model”
  - going from “reference” **pp** → **pPb** → **PbPb**
- Luminosity is relatively low for those data sets
  - great **prospects** at Runs 3–4 & beyond



1995 — Top at Tevatron
2009 — Top at LHC (7 TeV)
2015 — Top at 13 TeV
2016 — Top at 5.02 TeV
2017 — Top in pPb
2020 — Top in PbPb
?

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

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

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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

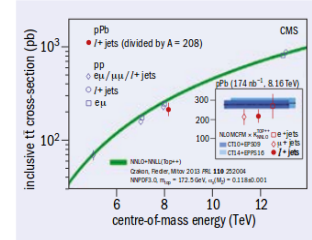
CERN Courier, Nov 2017

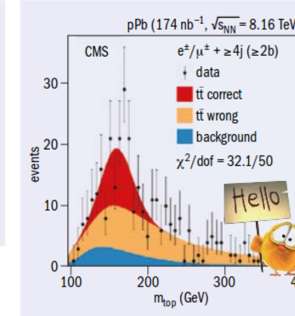
CMS observes top quarks in proton–nucleus collisions

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





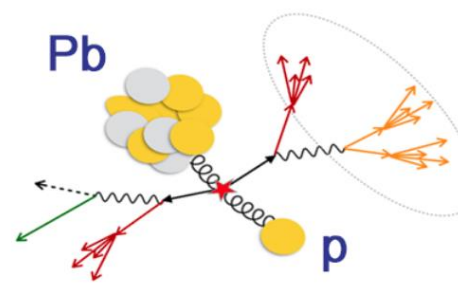
(Above) Top-quark pair-production cross-section in pp and pPb collisions as a function of the centre-of-mass energy per nucleon pair. (Right) Invariant mass distribution of the hadronic top-quark candidates in selected events with two b-tagged jets.

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.



JANUARY 7, 2021 FEATURE

The first evidence of top quark production in nucleus-nucleus collisions

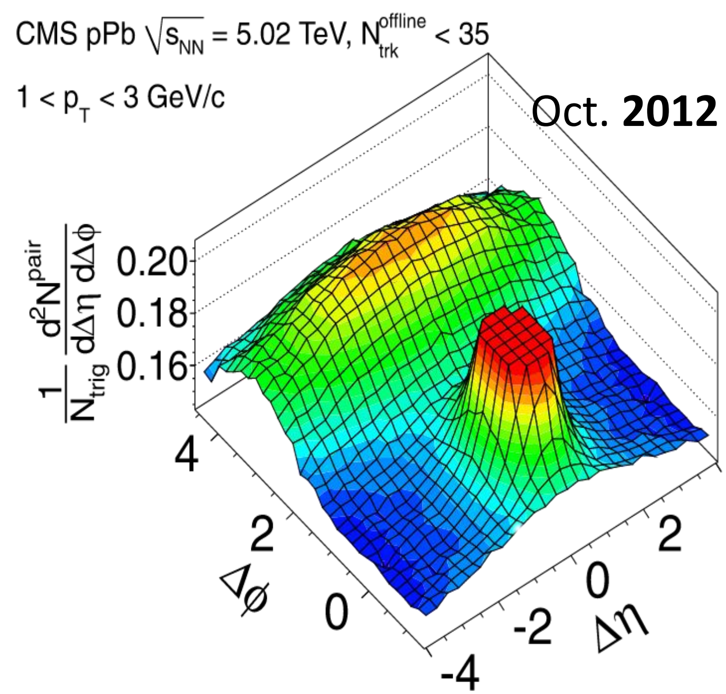
by Ingrid Fadelli , Phys.org

Press coverage

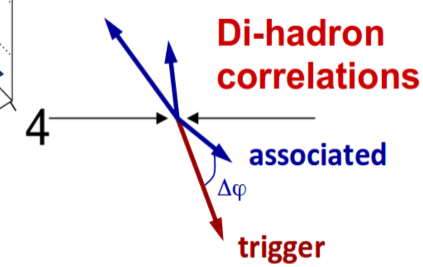
slides

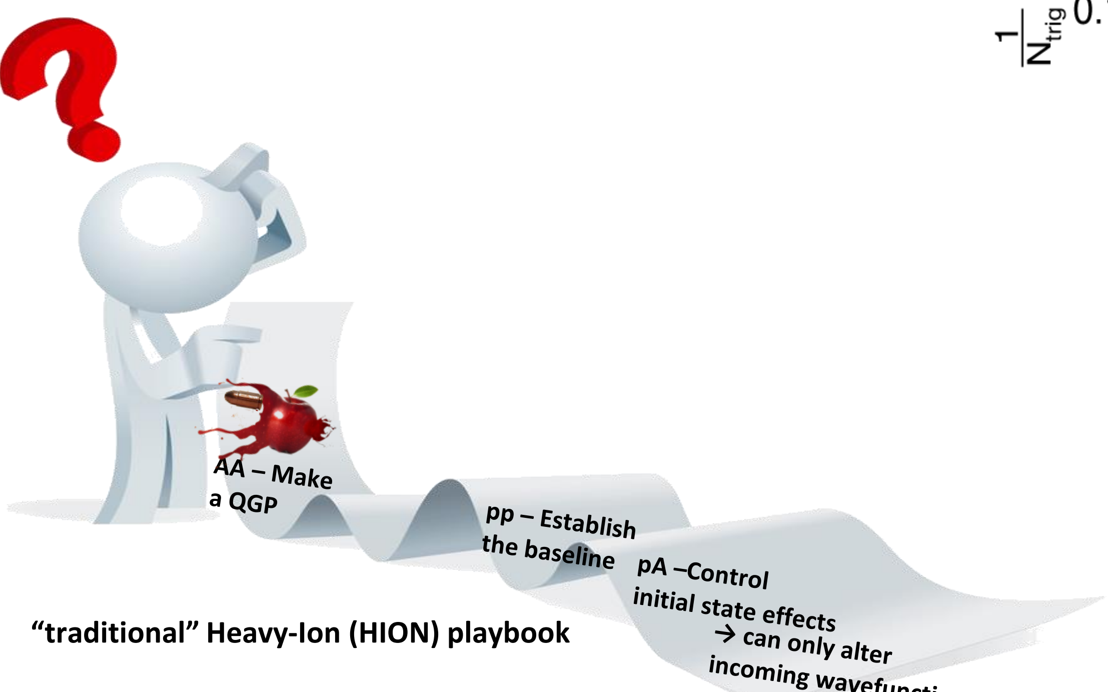
Throwing a bullet through an apple... Why?

- 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!)



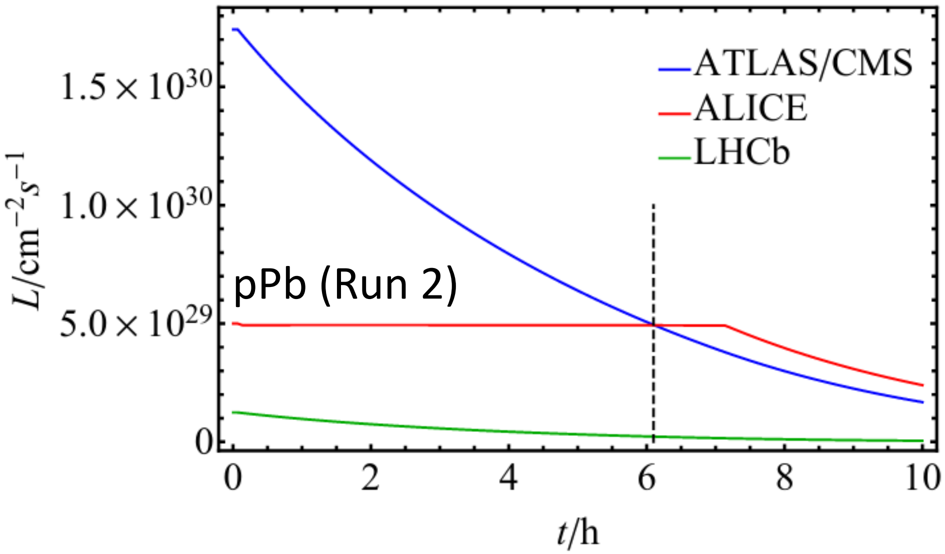
Phys. Lett. B **718** (2013) 795

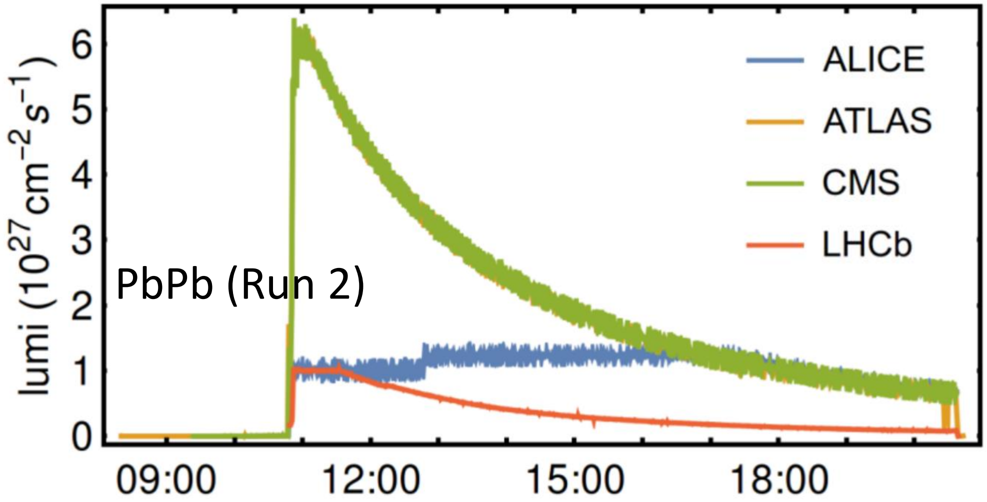




"traditional" Heavy-Ion (HION) playbook

HL-LHC operational scenarios for pPb and PbPb

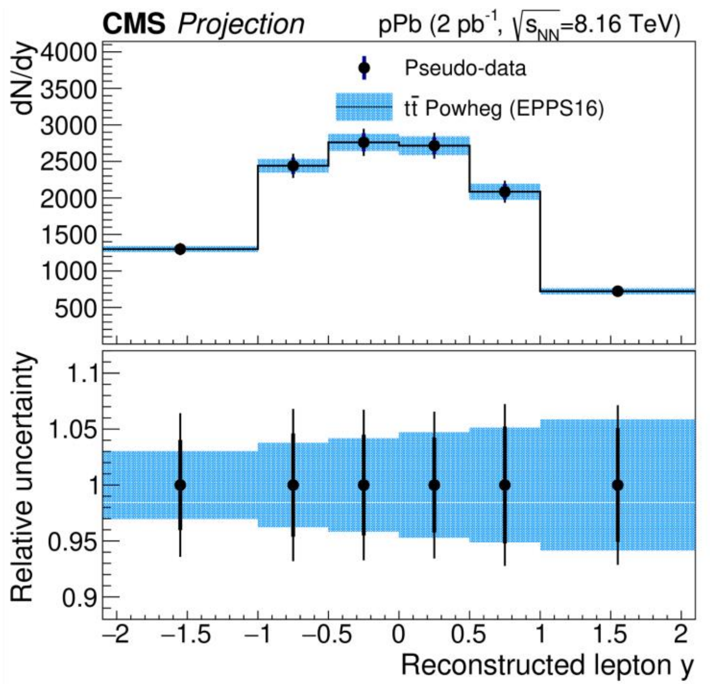


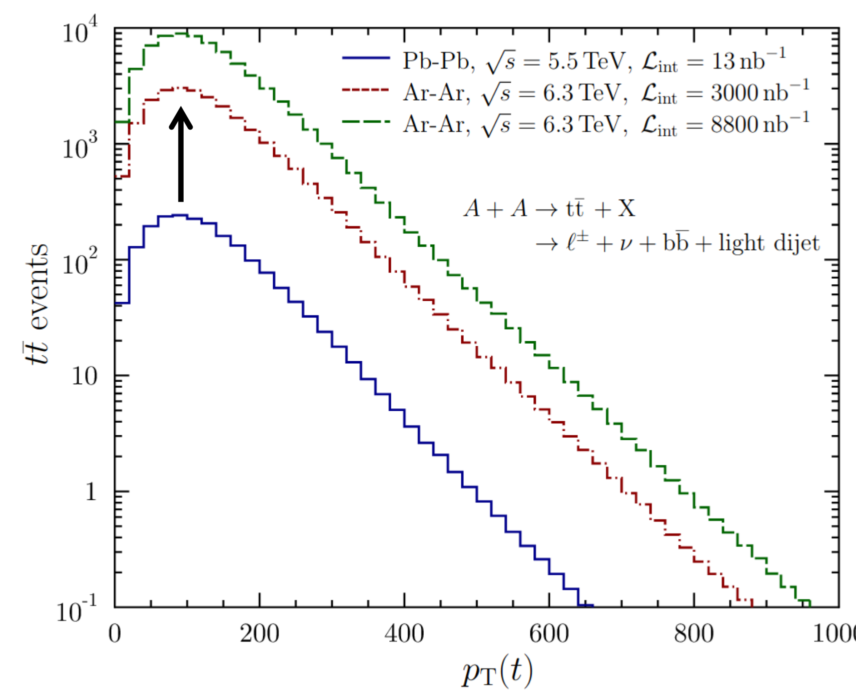


- Included in the YR and recently refined ([CERN-ACC-2020-0011])
  - scenarios are based on **benchmarked** models (actually agree remarkaly well with Run 2 LHC data)
  - ≈**five** one-month runs would be needed to reach 13 /nb of PbPb
  - ≈**two** one-month runs would be needed to reach 1.2 /pb of pPb
  - projections could be improved, e.g., due to operational efficiency (>50%), etc

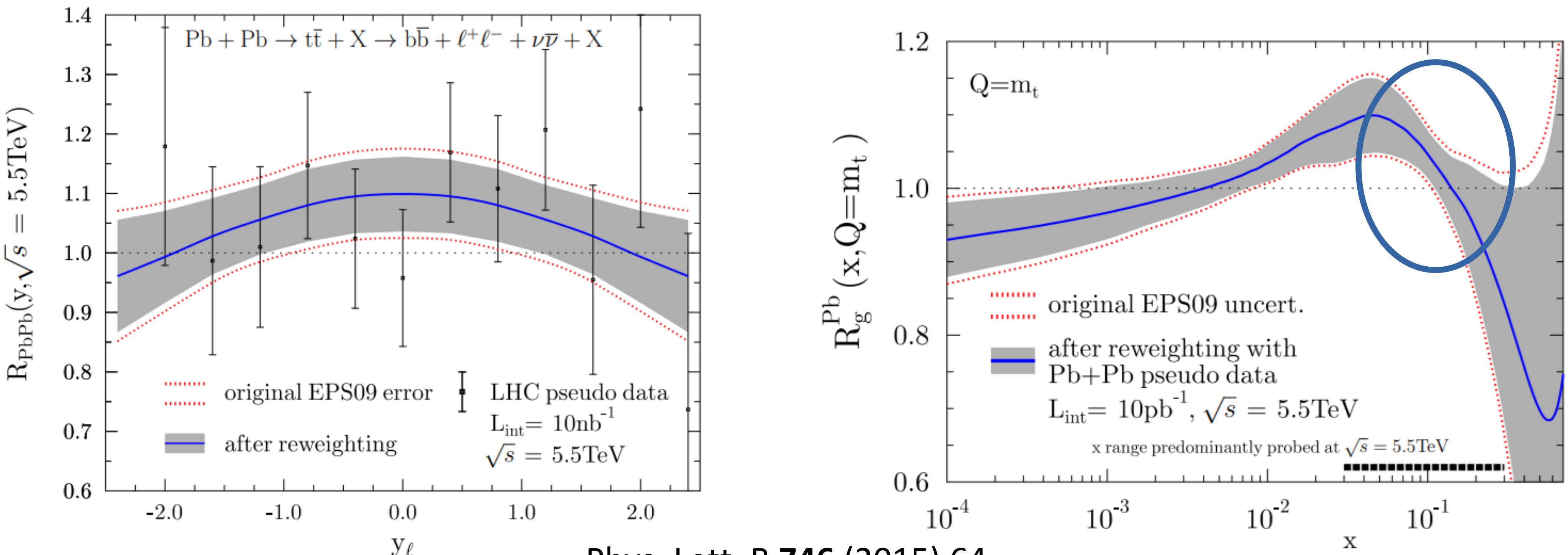
Prospects for top quark production at pA HL-LHC

- The y of the decay leptons sensitive probe of the nuclear gluon density
- **comparable** experimental and nPDF uncertainty with the pPb data set in Runs 3–4
- depending on the expected systematic error and bin-by-bin correlations
- to showcase **another potential**: In a pAr mode, the higher √s + lumonsity → increased tt̄ yield





Prospects for top quark production at **AA** HL-LHC

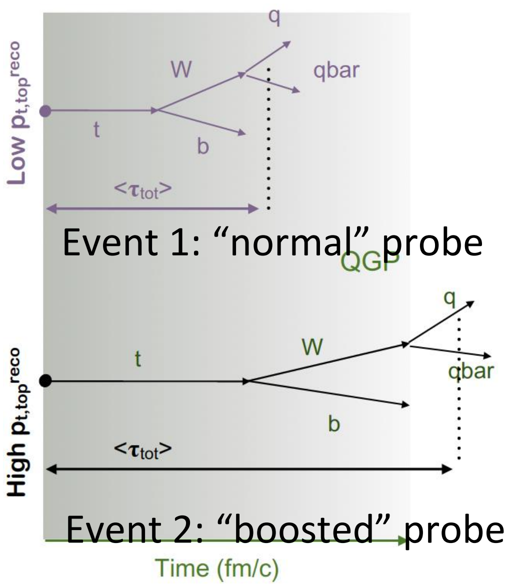


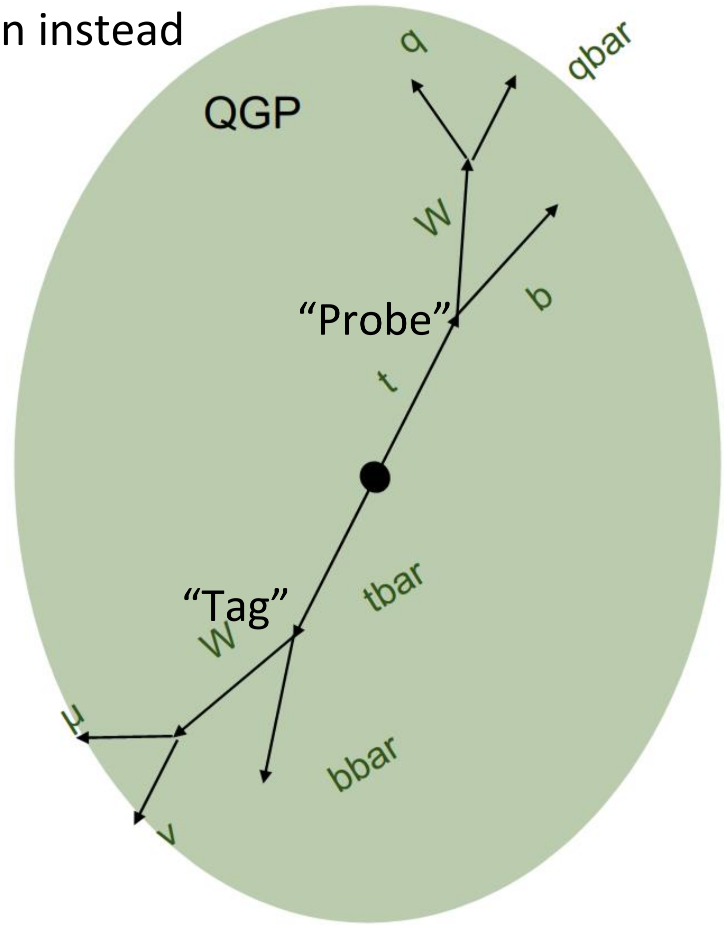
Phys. Lett. B **746** (2015) 64

- nPDF uncertainties increase at large *x* due to the **lack** of direct constraints
- the region where the predictions for R_g also **differ** between nPDF determinations
- some constraints from the current LHC dijet measurements (cf. backup)

Probing the "final state": the yoctosec QGP lifetime

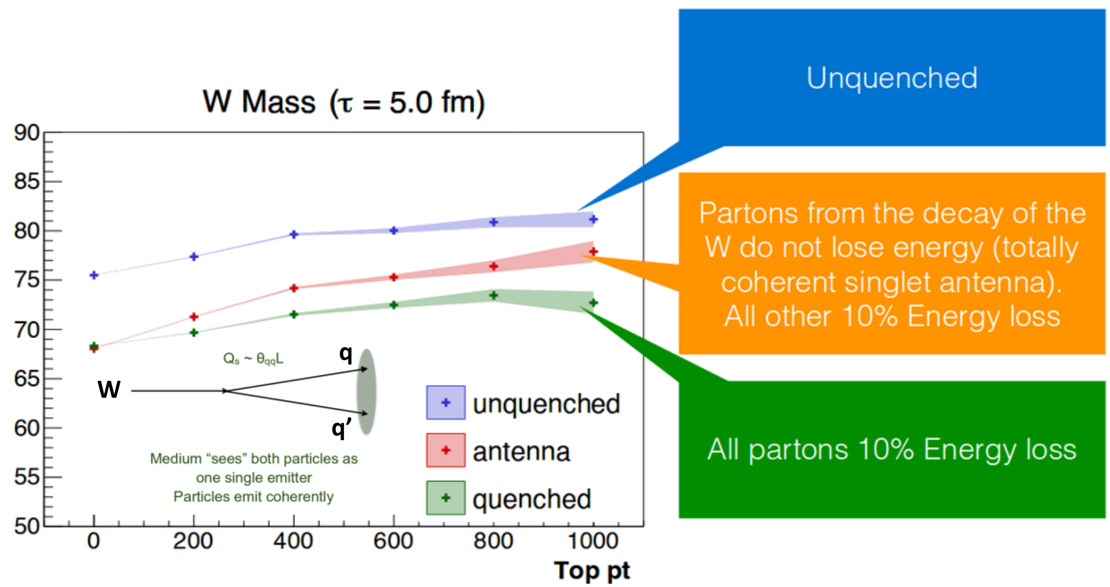
- Probes for jet quenching, e.g., dijets, Z/ɣ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead
- Leptonic & hadronic branches as "tag" & "probe"
- qq' start interacting with the medium at **later** times
- top p_T acts as the "trigger" on the onset of the interaction

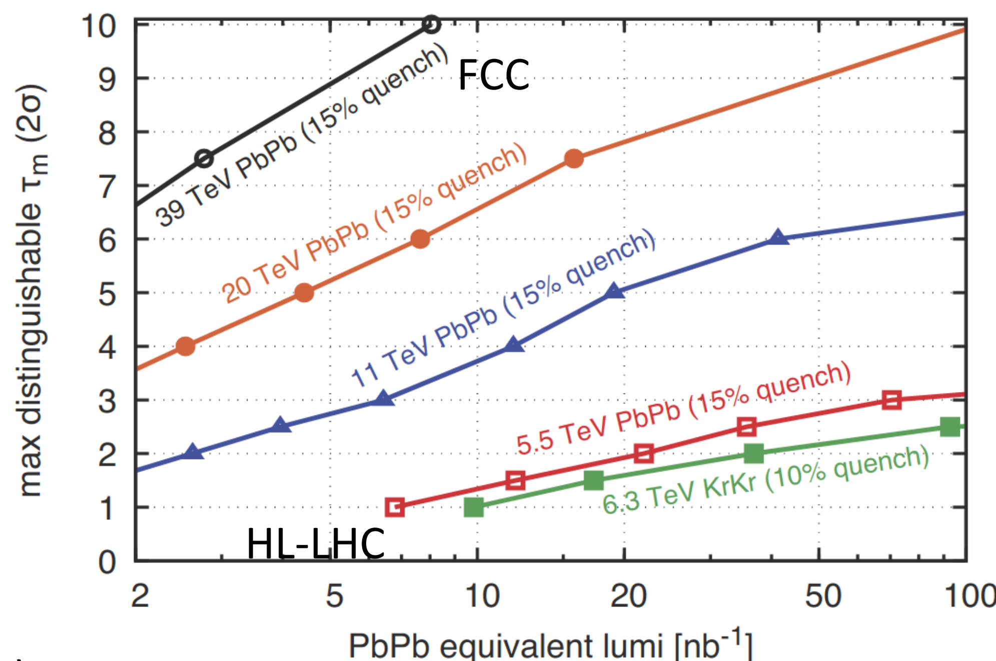




W mass vs top p_T and QGP lifetime reach

- What would be the observable to measure the amount of energy loss?
- By reconstructing **W mass vs top p_T** we can trace the quenching time dependence
- At HL-LHC, possible to distinguish low-duration scenarios (inclusively)
- At FCC, possible to assess the QGP density evolution (i.e., ‘triggering on’ top p_T)

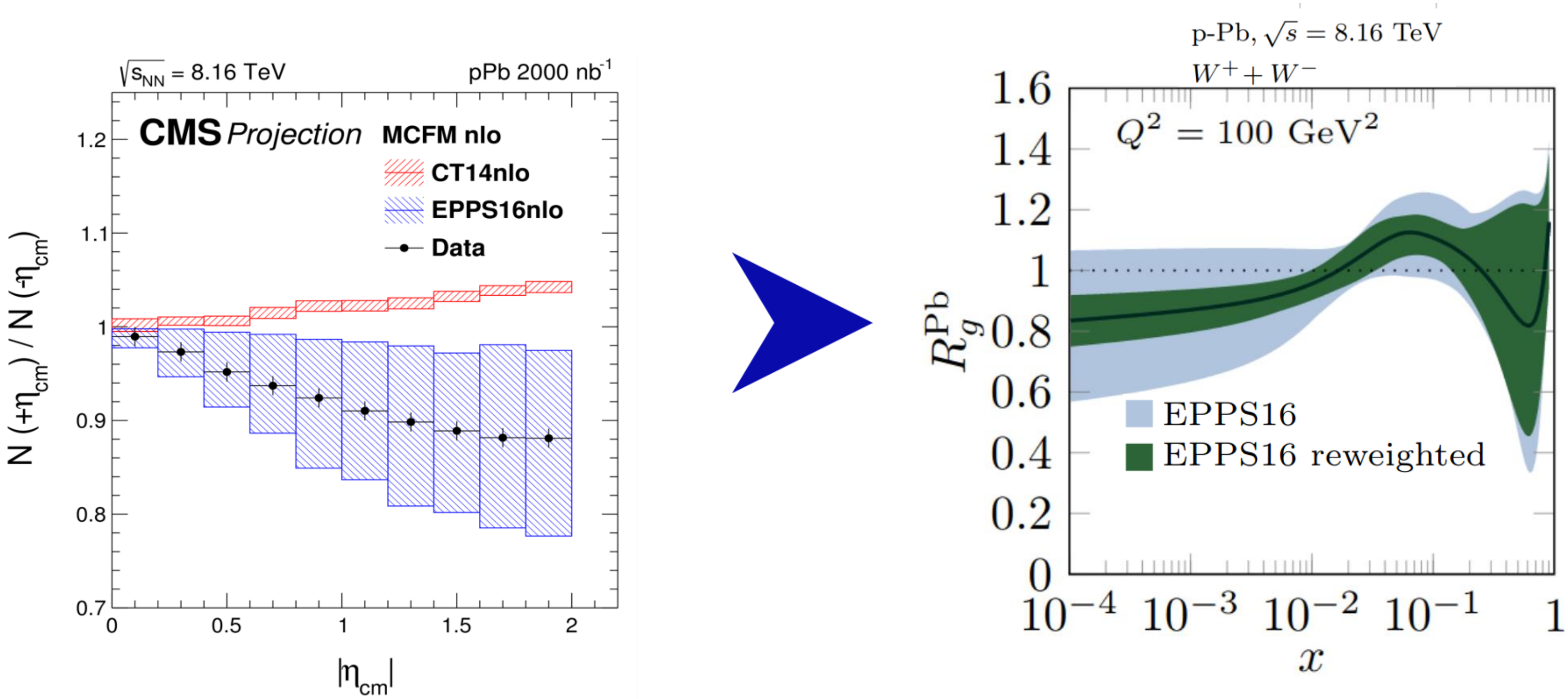




Phys. Rev. Lett. **120** (2018) 232301

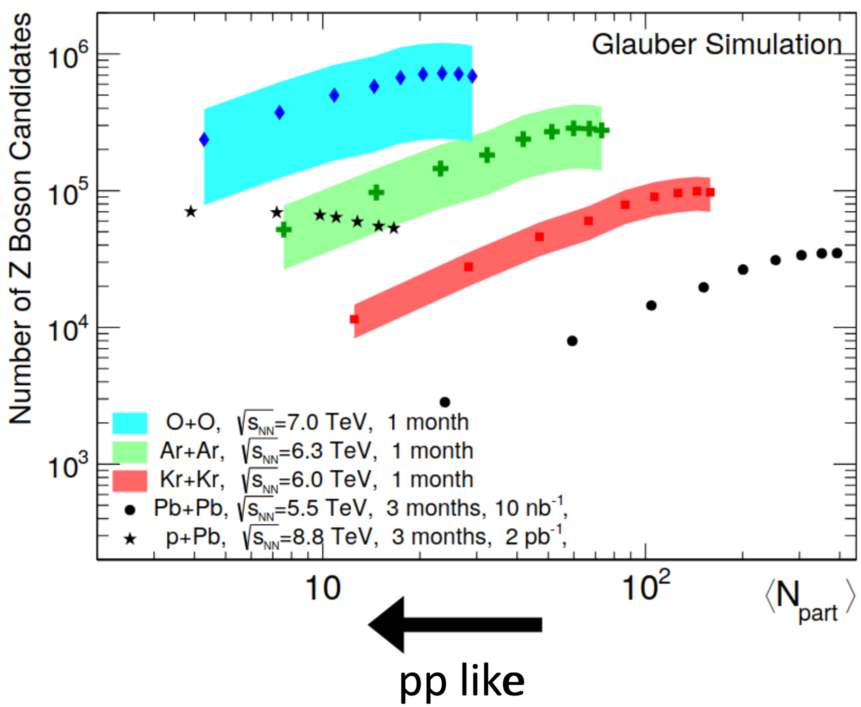
Prospects for W boson forward-to-backward ratios

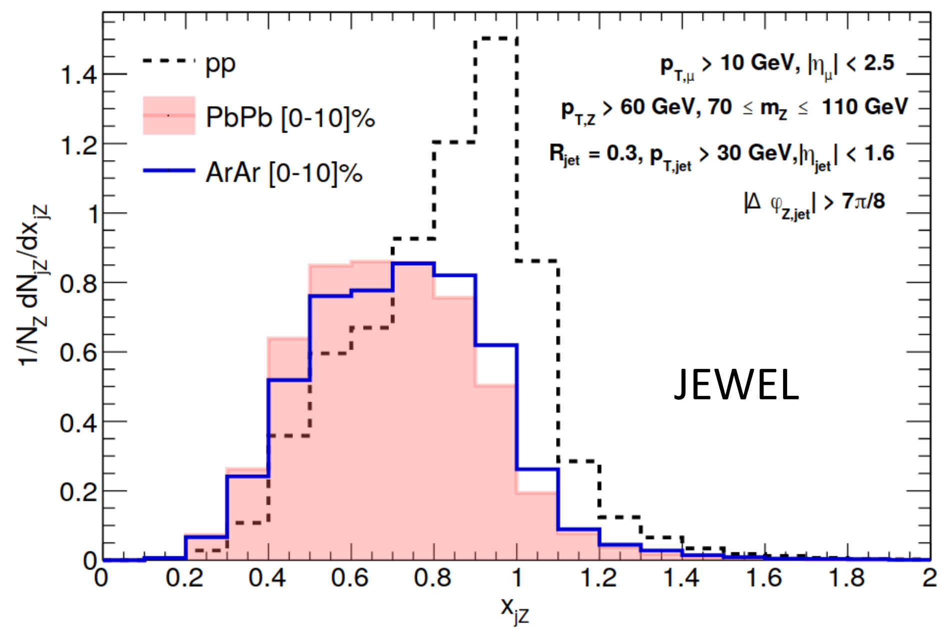
- Exploit the larger (× 10) pPb data set in Runs 3–4
- experimental uncertainties significantly **smaller** than the nPDF ones
- to showcase the potential: significant reduction of the uncertainties in the gluon nPDF
- the large-*x* (> 0.1) part is **not affected** though



Physics motivations for collisions with lighter ions

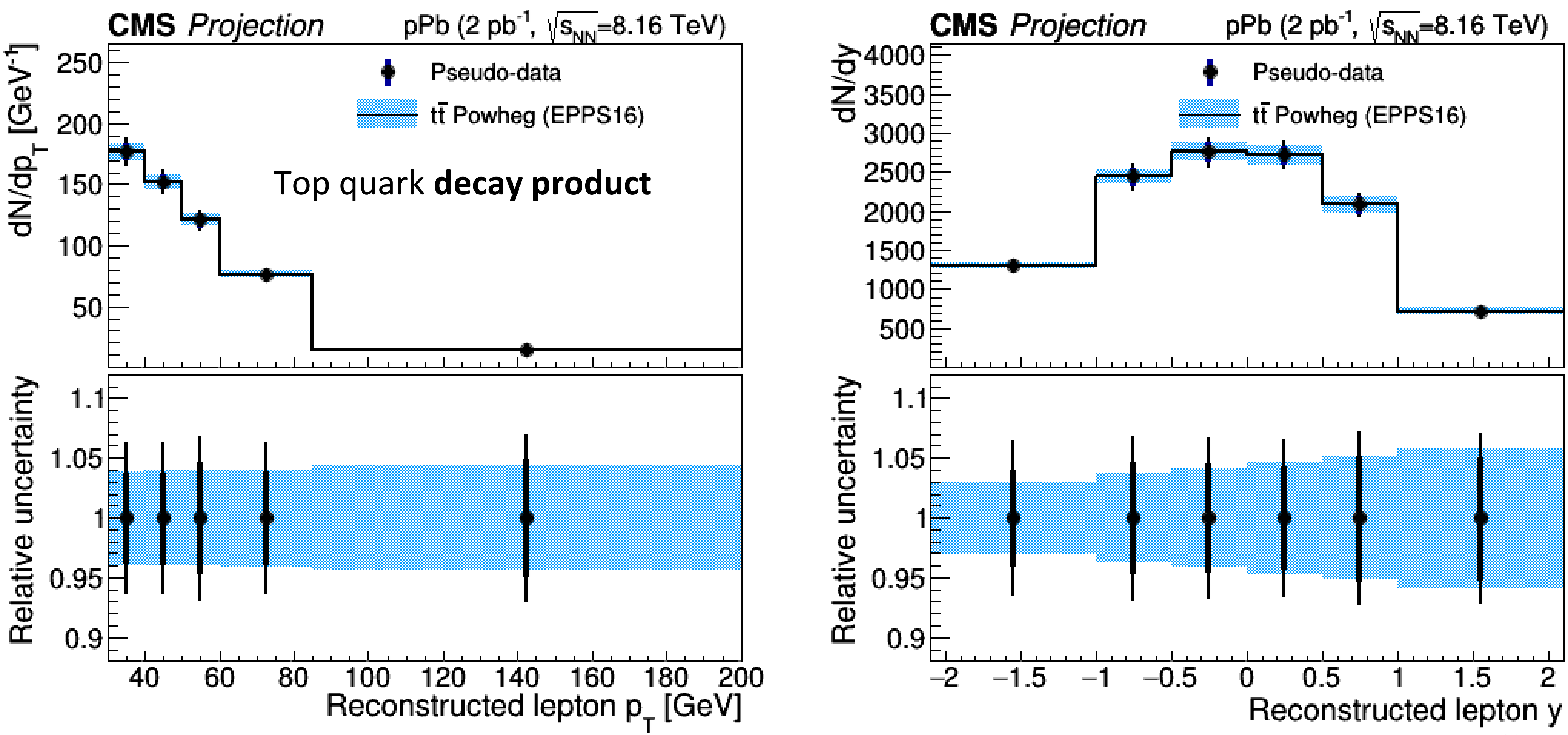
- **1 month** of ArAr > PbPb data set in Runs 3–4
- coverage of a much broader range in Z p_T → jet-energy differential studies of quenching
- case study: ratio of the jet to Z p_T expected **similar** in ArAr and PbPb collisions





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

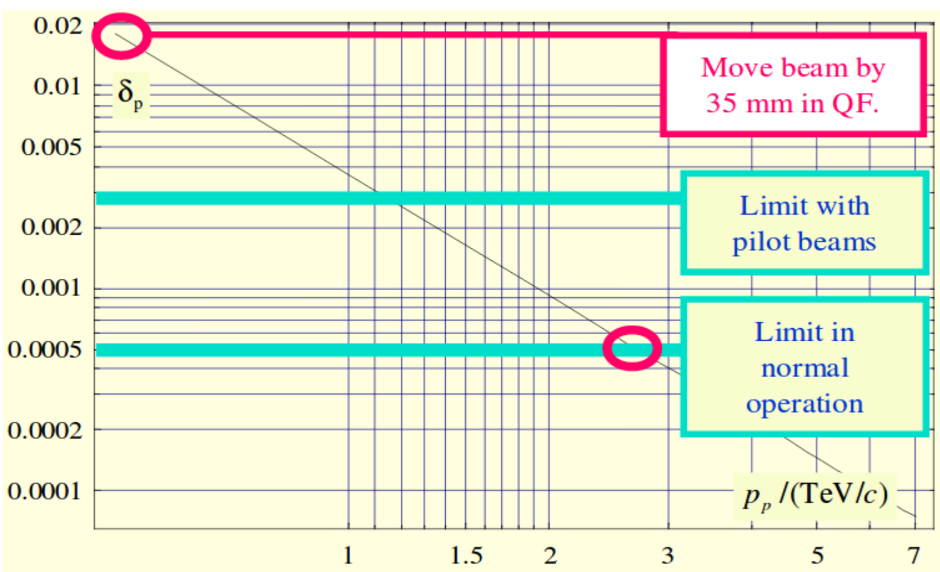


CMS-PAS-**FTR**-18-027
(High-Luminosity LHC Yellow Report)

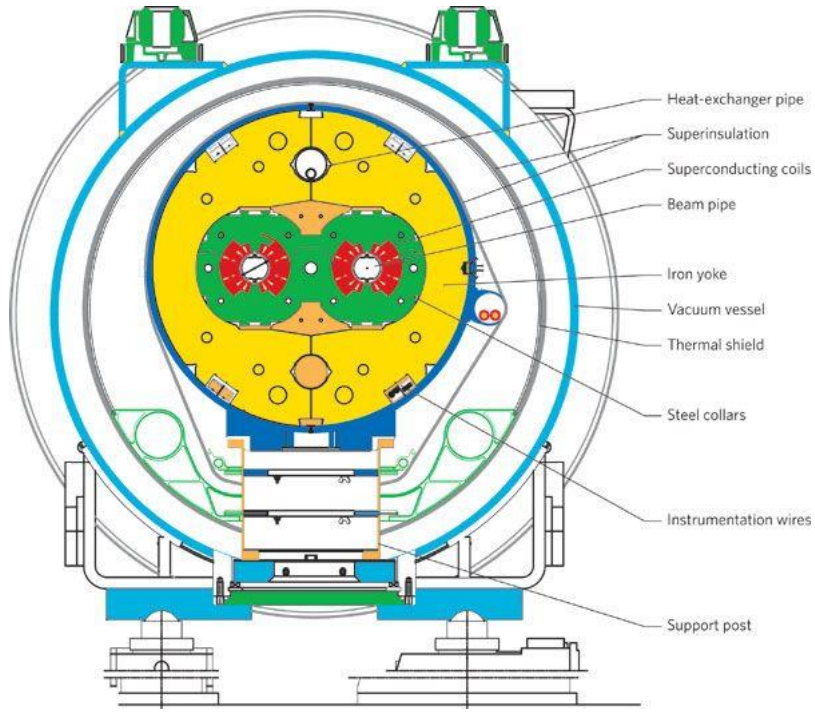
Throwing a bullet through an apple... How?

- 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