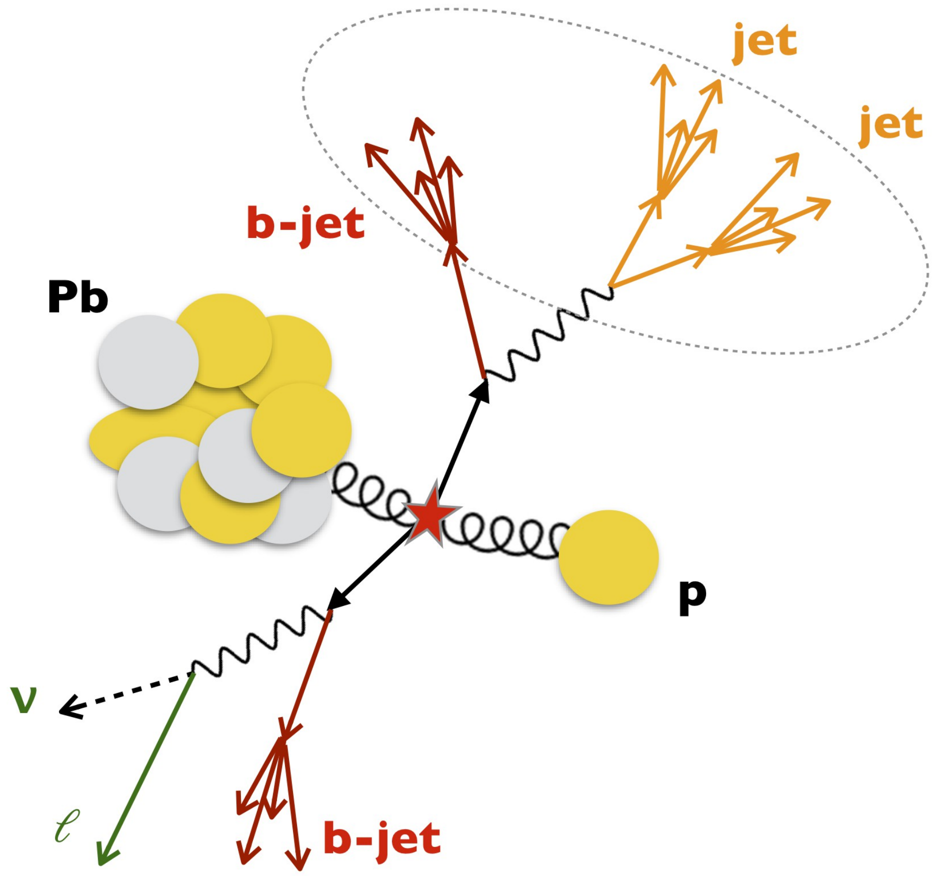
Top Nuclear Physics
and more fun with Heavy Ions



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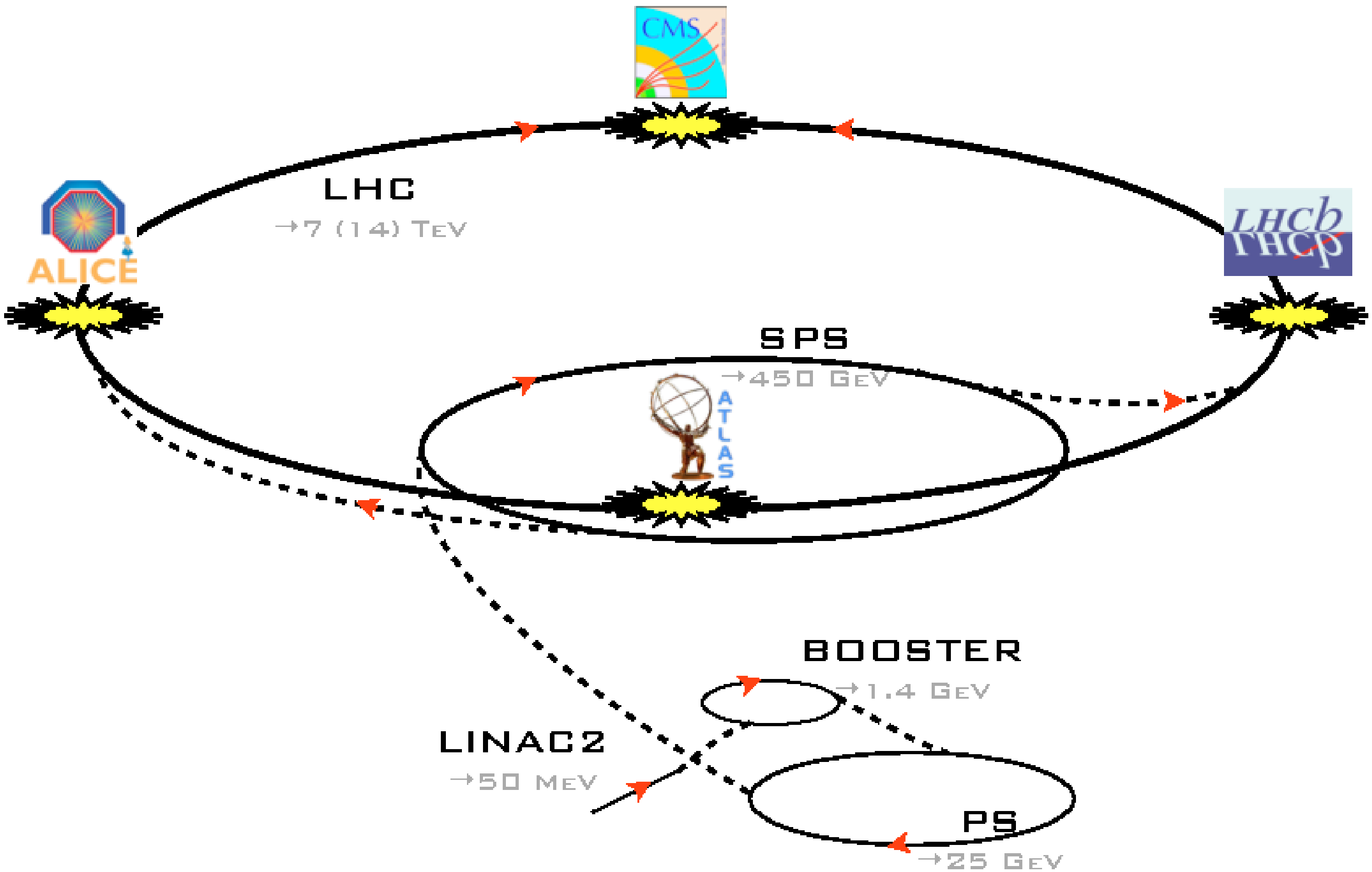
UCL, Louvain-la-Neuve, Belgium

1. Motivations

<u>Disclaimer</u>: I am not an expert in Heavy Ions, in the CMS *top @ HI* team I come from the *top* side

The Large Hadron Collider

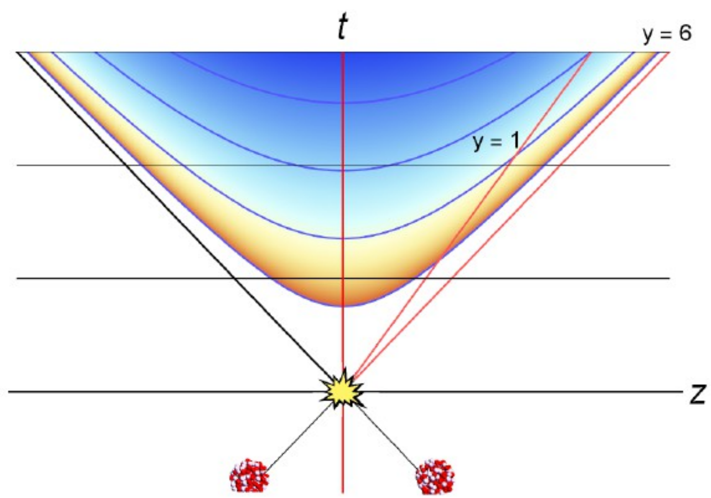


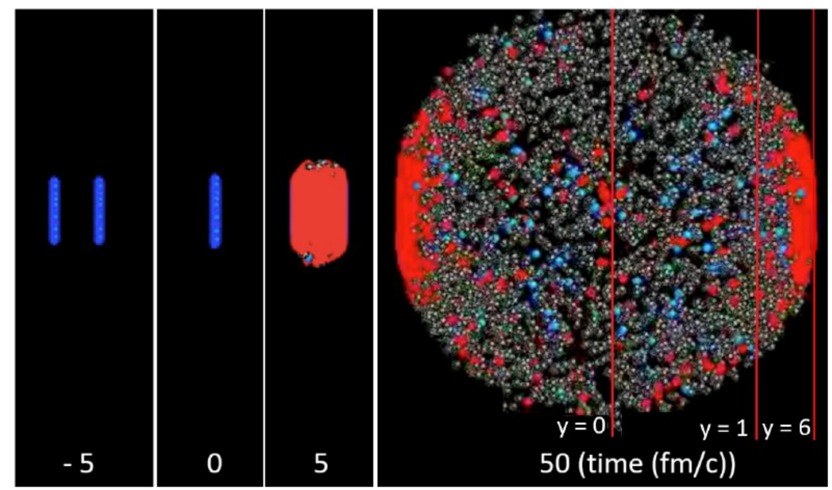
Picture taken from https://inspirehep.net/record/1119569

7 experiments take data at 4 collision points
(not shown here: LHCf, TOTEM and MoEDAL)
Most operation time is for **pp** collisions; 1 month per year of heavy ion run, mostly **pPb** and **PbPb** collisions

Why does LHC collide Heavy Ions?

From: Busza, Rajagopal, van der Schee, Ann.Rev.Nucl.Part.Sci. 68 (2018) 1





Quark Gluon Plasma (QGP) indicated in red

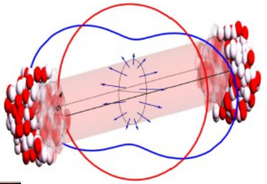
The study of QGP is relevant for:

- Understanding QCD (phase diagram) in a regime of free partons
- Emergence of quantum matter: QGP is the **simplest** form of **complex** matter
- Cosmology: in its first microseconds, Universe's temperature was >>Λ_{QCD}

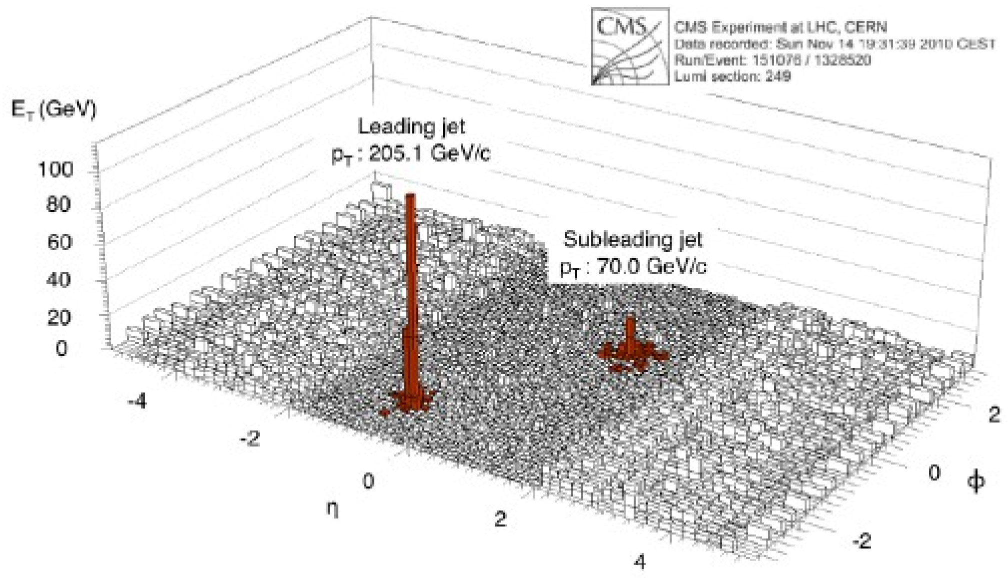
Many QGP properties already established (e.g., it is a liquid), many questions still open, some new puzzles appeared with LHC data

Some signatures of QGP

From: Busza, Rajagopal, van der Schee, Ann.Rev.Nucl.Part.Sci. 68 (2018) 1



Jet quenching:



Anisotropies:

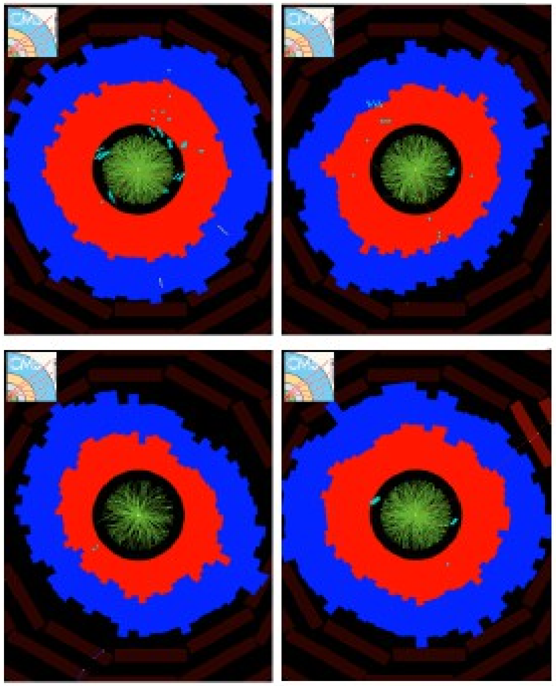
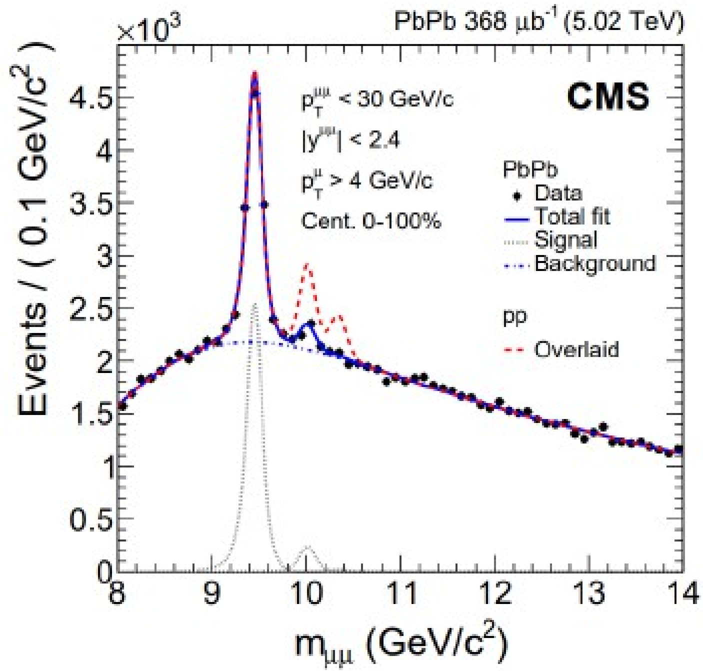


Figure 4

(left) This event display (86) shows energy deposited in the CMS calorimeter in a heavy ion collision as a function of azimuthal angle ϕ and pseudorapidity η, a proxy for rapidity which is more easily measured. Two jets of very different energies are apparent, suggesting that one jet lost more energy as it traversed the droplet of QGP. (right) CMS event displays showing azimuthal distribution of charged tracks (green) and energy in the electromagnetic and hadronic calorimeters (red and blue respectively) from four heavy ion collision events as seen by the CMS detector. The azimuthal anisotropies are apparent, with the upper-right and lower-left events showing marked ellipticity and the bottom-right event showing a substantial anisotropy in a higher harmonic. It is remarkable that the strongly coupled character (left) and the liquid nature (right) of the QGP formed in these collisions can be seen so clearly in individual events.

Some signatures of QGP

Melting of quarkonia:



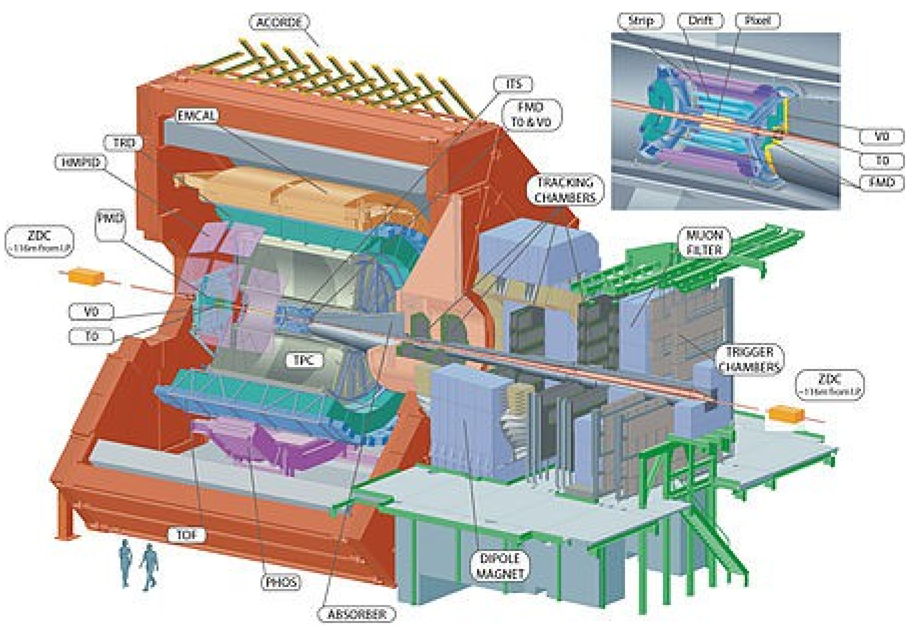
CMS coll, PRL 120 (2018) 142301

The larger / less bound resonances melt more readily in the QGP.
Note the need for **reference data** with pp collisions at 5.02 TeV!

(There are also other QGP-sensitive studies:
strangeness production, „the ridge“, etc.)

Specialized vs multipurpose

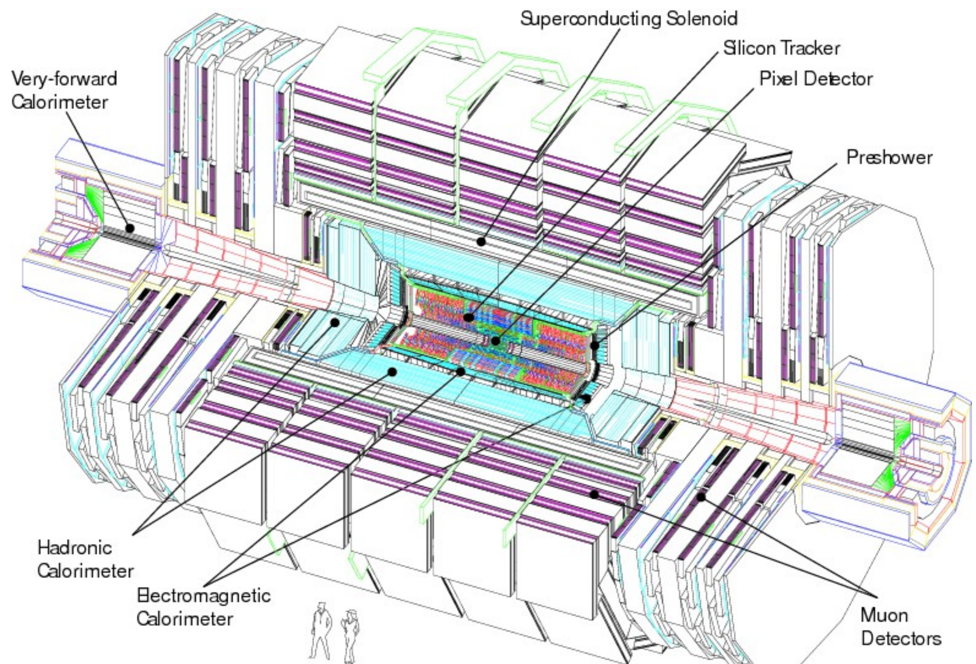
ALICE:



A Large Ion Collider Experiment

- Extremely precise tracking required for HI physics → TPC
- TPC → slow response → limit on the instantaneous luminosity that ALICE can handle; not a problem for PbPb collisions (low lumi anyway)
- Excellent hadron ID
- Non-hermetic for μ,e,γ and jets

CMS:

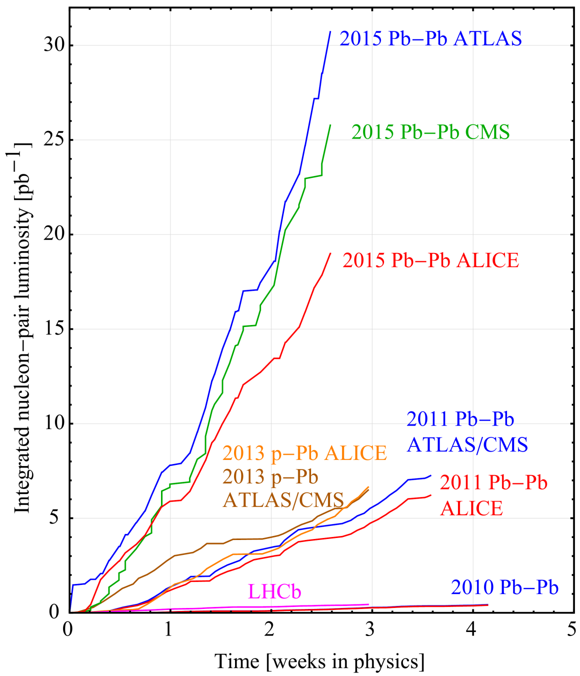


Compact Muon Solenoid

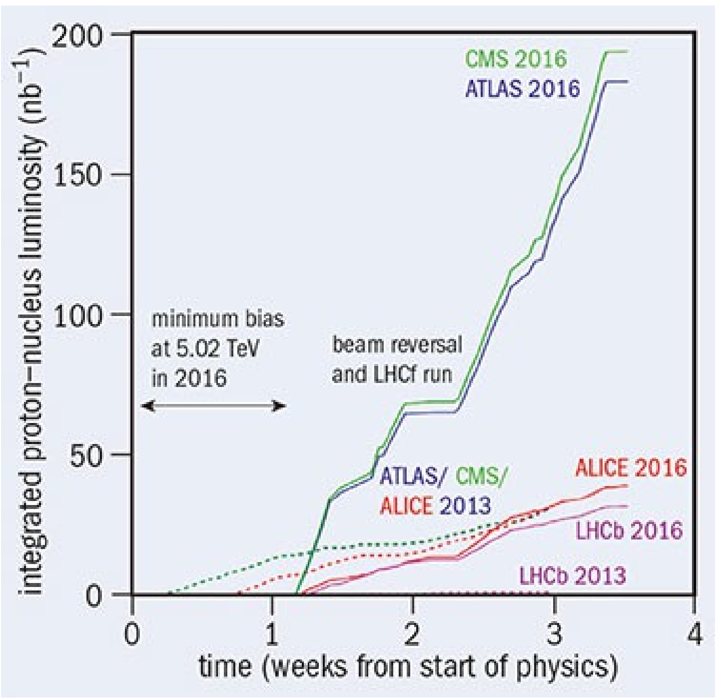
- Aims to accumulate as many data as LHC can deliver → fast tracking → pixel & microstrip detectors
- Very limited hadron ID; not a problem for most of its analyses
- Excellent coverage for μ,e,γ and jets, can use missing energy for ν

LHC Heavy Ion runs so far

PbPb:



pPb:

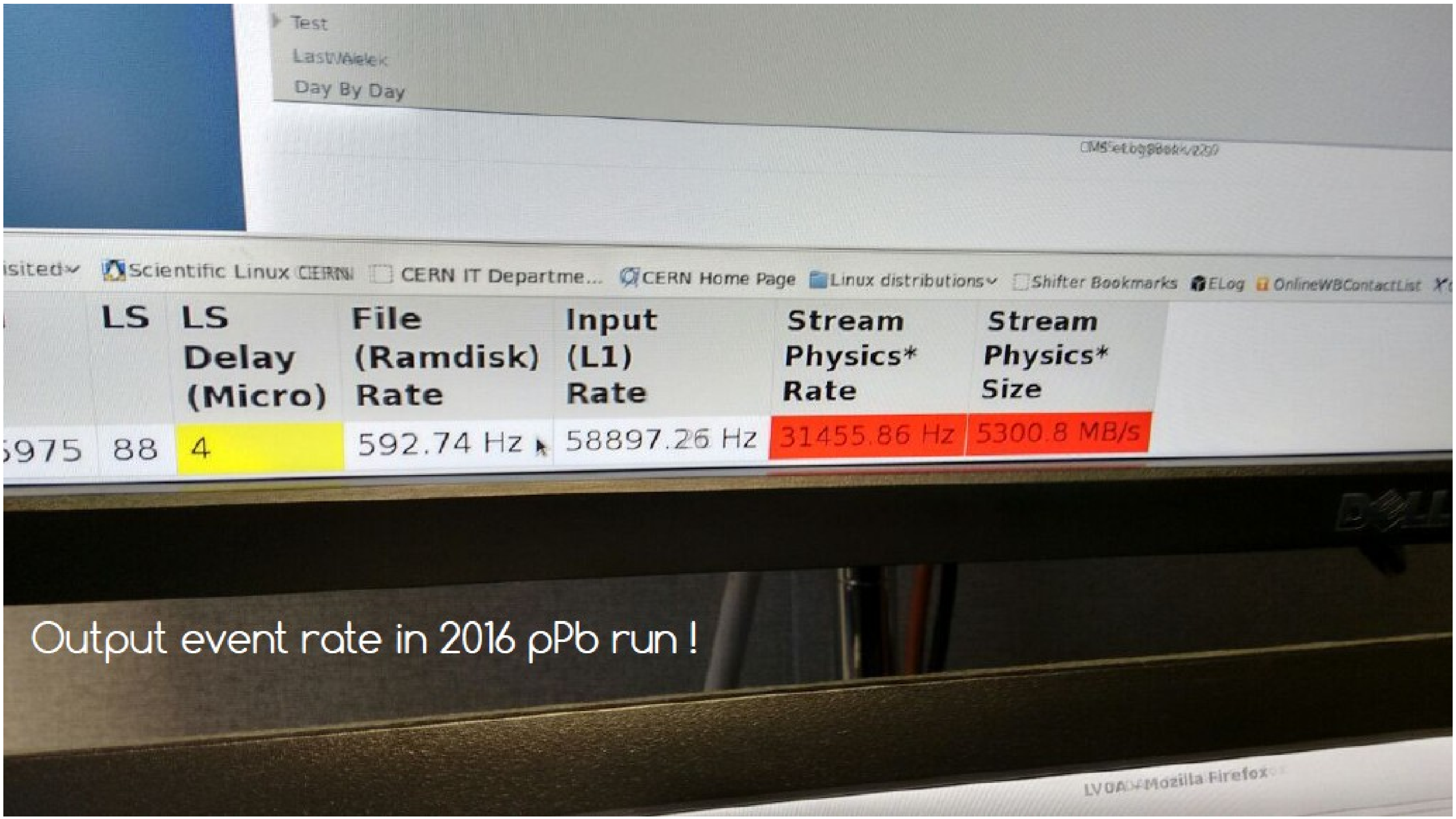


pp : pPb : PbPb = baseline : cold nuclear modification effects : QGP.

Side remark: LHC was originally intended for equal beams; the possibility of asymmetric collisions was an afterthought that required some ingenuity by the LHC machine people

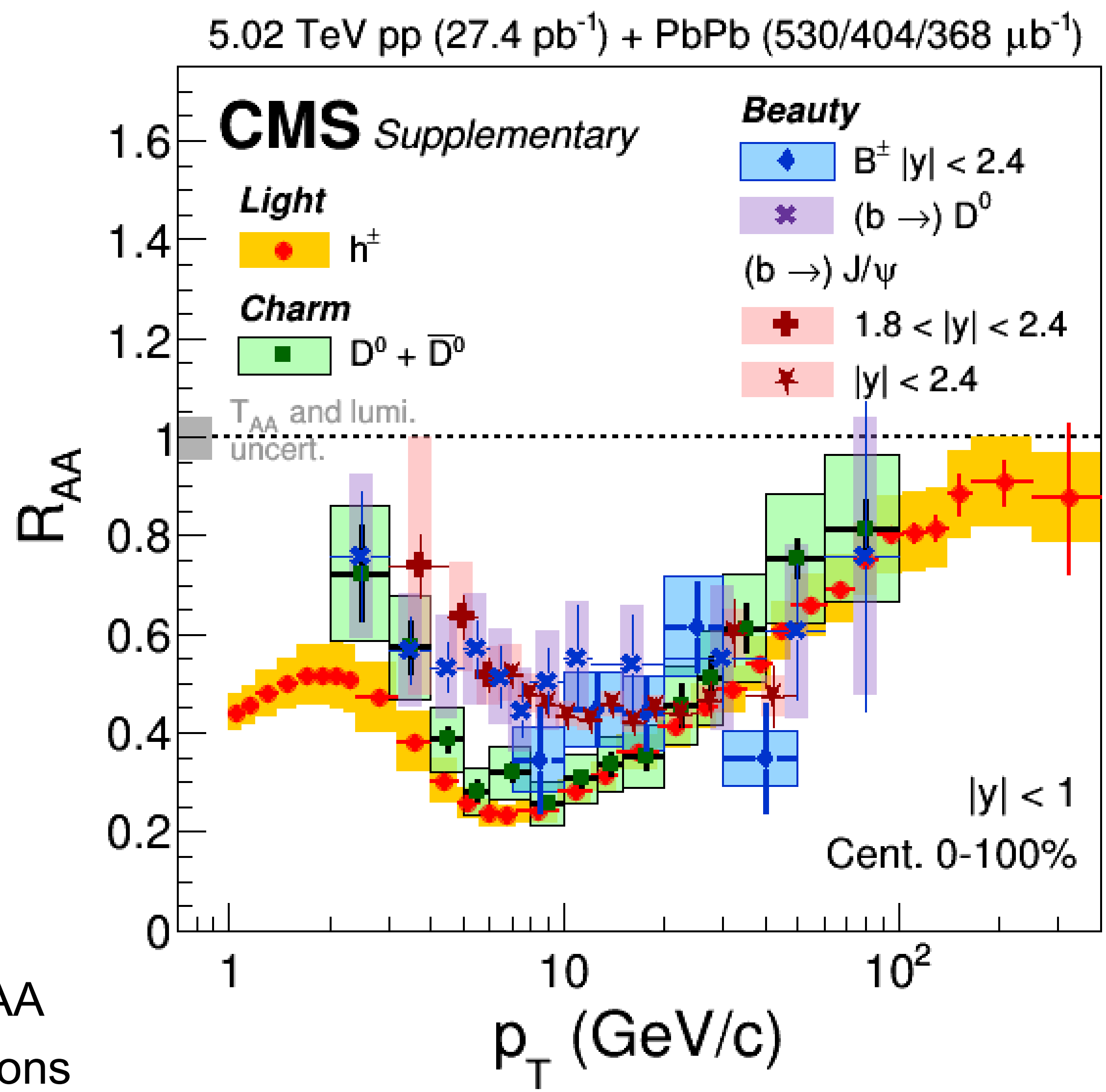
Plots from proceedings of the IPAC 2016 (left) and IPAC 2017 (right) conferences

Stressful conditions
for the multipurpose detectors



Courtesy of Georgios Krintiras

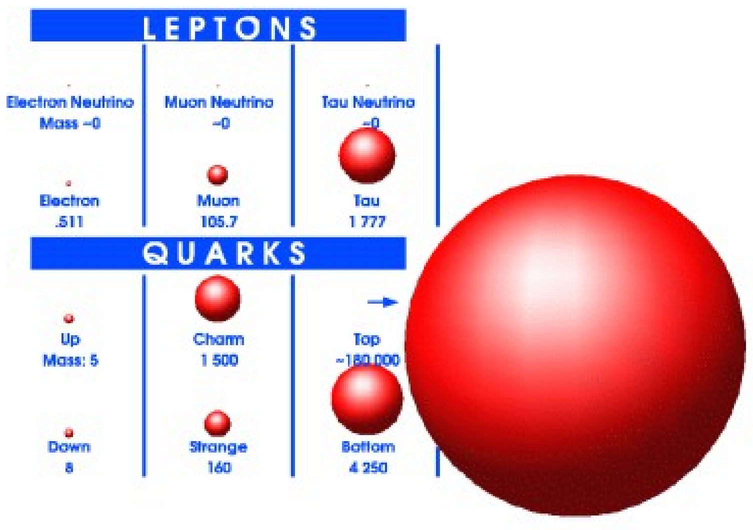
Heavy quarks in Heavy Ions



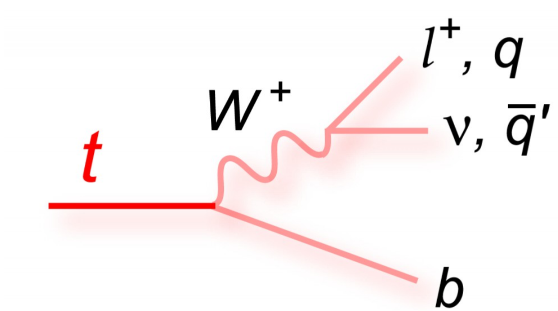
R_{AA}: ratio between AA (A=Pb) and pp collisions

From https://twiki.cern.ch/twiki/bin/view/CMS/HardProbes2018

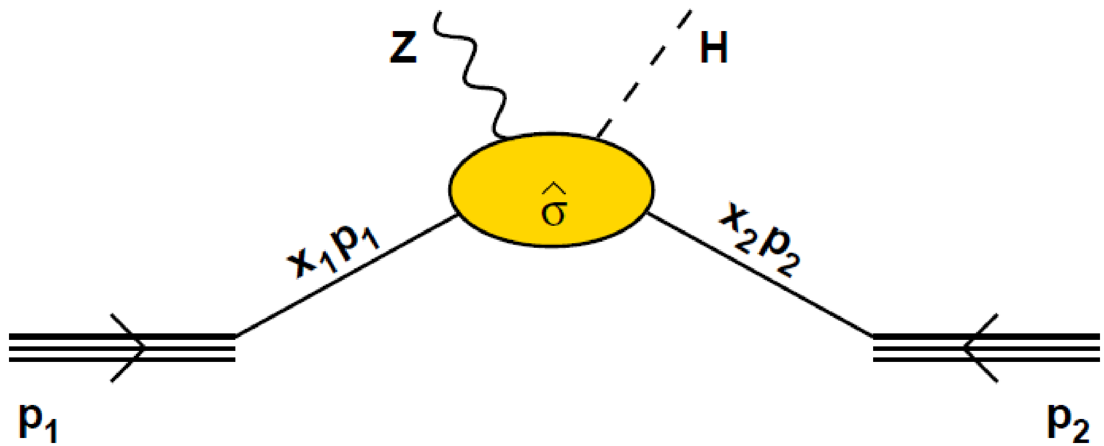
The heaviest possible probe



Heavy as a gold atom



Parton Density Functions



Factorization theorem:

$$\sigma = \int dx_1 f_{q/p}(x_1, \mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2, \mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)\,, \qquad \hat{s} = x_1 x_2 s$$

Total cross section (pp)

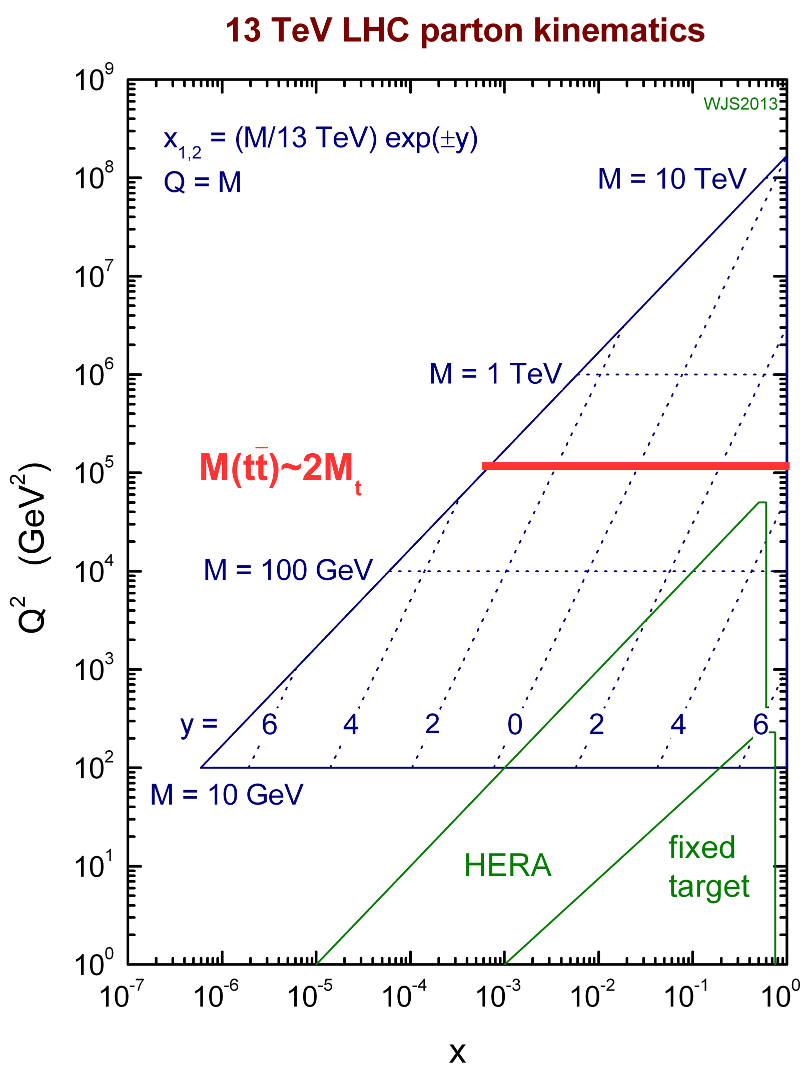
Parton density functions of partons 1 and 2;
x: fraction of proton momentum;
μ (or Q): momentum exchange

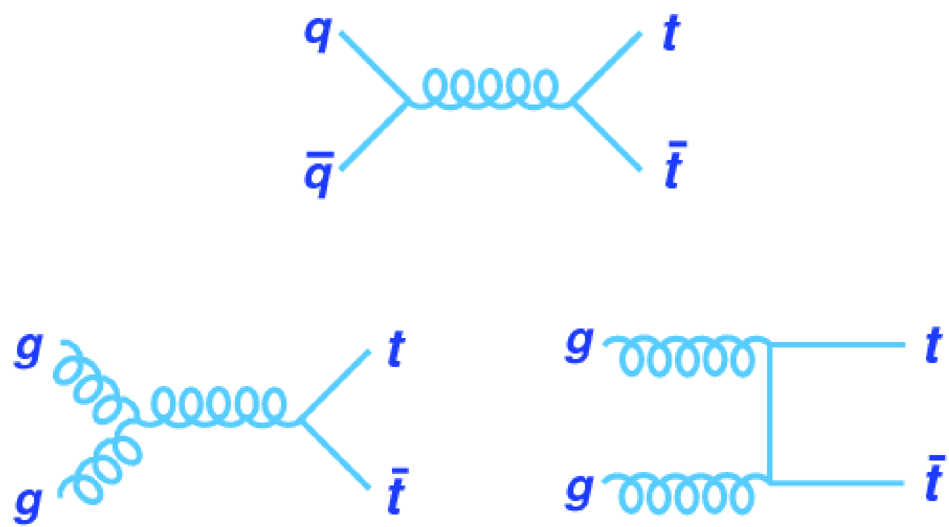
Partonic cross section

Plot and formula from Gavin Salam's lecture:
https://gsalam.web.cern.ch/gsalam/repository/talks/2009-Bautzen-lecture2.pdf

Probe of the high-x gluon density

Adapted from W.J. Stirling



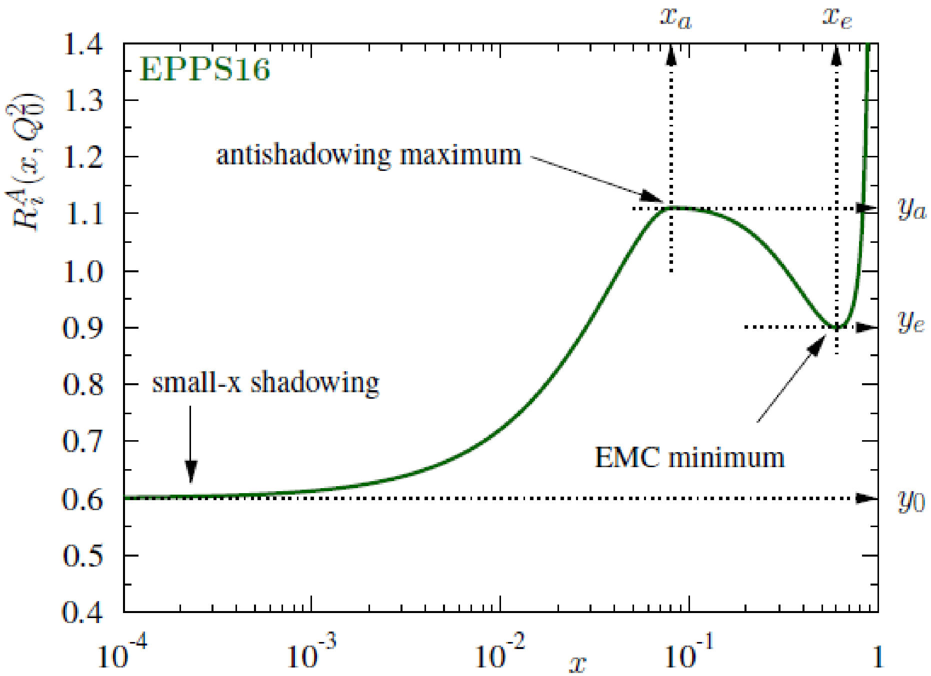


Diagrams for $t\bar{t}$ from D0 webpage

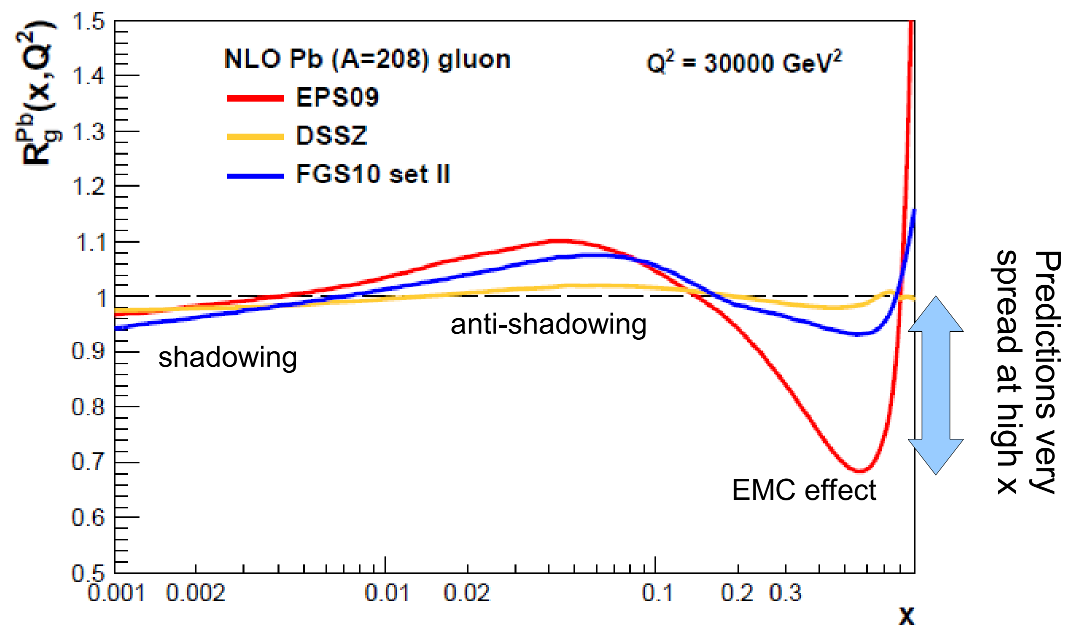
- Not many clean probes of the gluon PDF at high x
- The dominant production mechanism is pair production ($t\bar{t}$), high-x because of large top mass
- Mostly $gg \rightarrow t\bar{t}$ (~85-90% at 7-13 TeV)

The nuclear PDF

K.Eskola, P.Paakkinen, H.Paukkunen, C.Salgado, EPJ C 77 (2017) 163

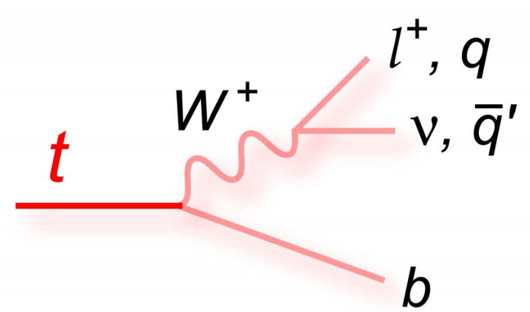


D.d'Enterria, arXiv:1706.09521 [hep-ph], in: J.Albacete et al., Nucl. Phys. A 972 (2018) 18



- Various data indicate that the gluon distribution inside a nucleon is modified if the nucleon is part of a nucleus
- R: ratio of the gluon PDF in Pb with respect to a free proton
- The high-x region is where models are less constrained
- We need more data; top-quark data would be ideal!

Naked



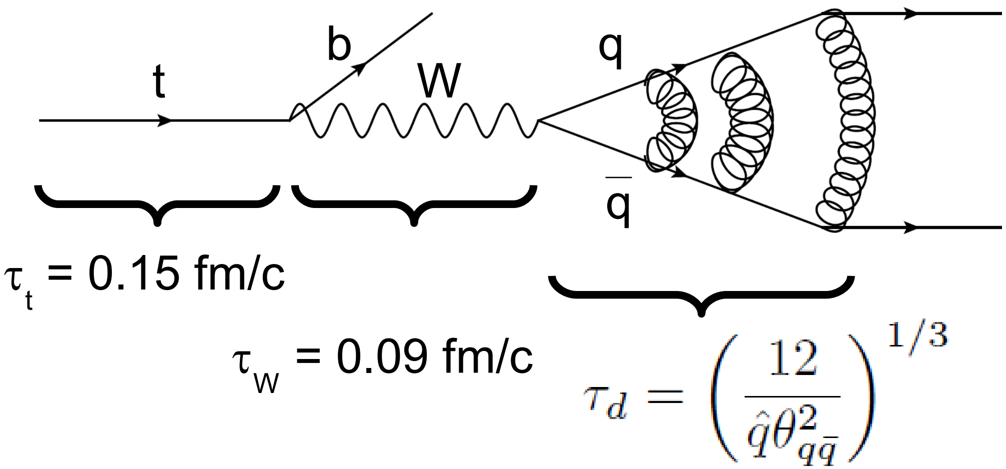
$$\Gamma_t \simeq \frac{G_F m_t^3 |V_{tb}|^2}{8\pi\sqrt{2}}$$

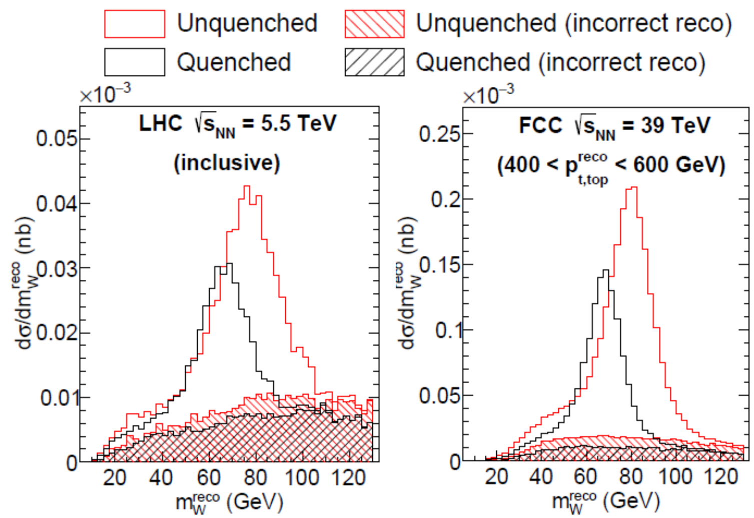
The only fermion heavier than the W ⇒ only case of two-body decay of a quark (*real* W) ⇒ top quark's *weak* decay is *fast*; the only weak decay that is faster than *strong*-force timescales:

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times10^{-24}\,s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times10^{-21}\,s << \tau_b \sim 10^{-12}\,s$$

Hadronization Spin decorrelation

A chronometer for the QGP?

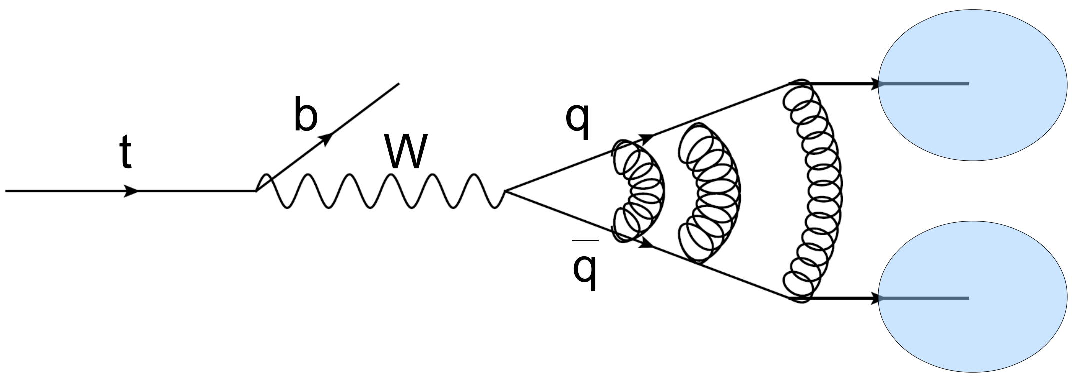




Apolinario, Milhano, Salam, Salgado,
PRL 120 (2018) 232301

- QGP expands and cools down in $O(10^{-22}$ s), i.e. O(10 fm/c)
- No direct access so far to **QGP's time evolution**, all measurements integrate over QGP lifetime from start to end
- Greater interest in **QGP size** since the discovery of collective effects also in pp and pPb collisions
- Idea: study quenching of jets from $t \to Wb \to q\bar{q}b$ chain

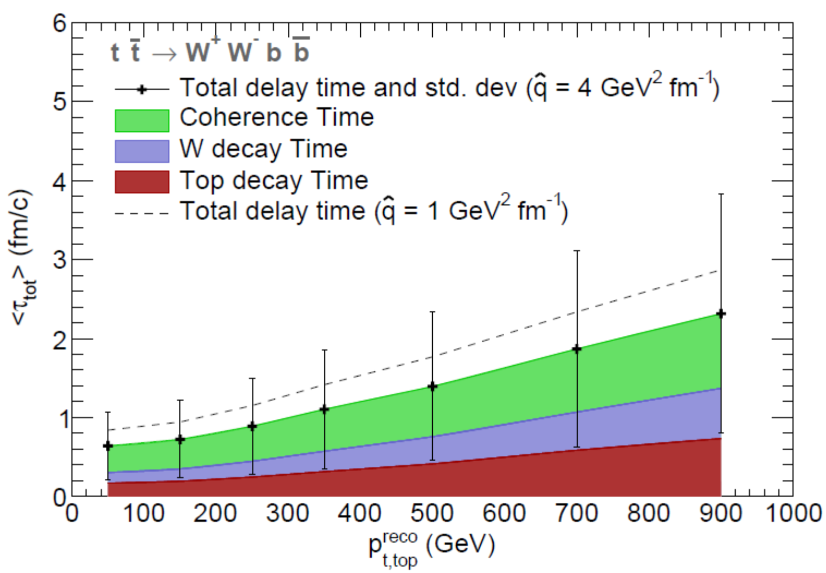
A chronometer for the QGP?

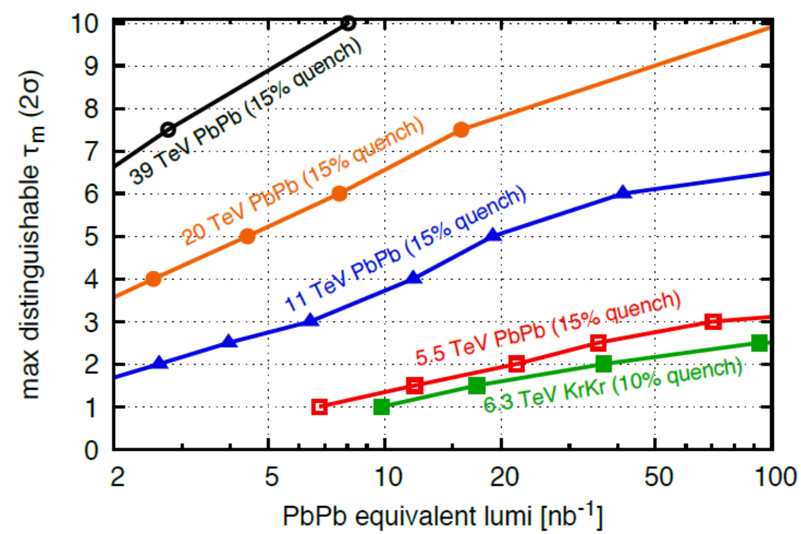


They start quenching due to the QGP as soon as they are not a colour singlet anymore ($t > \tau_d$)

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

$$\langle \tau_{\rm tot} \rangle (p_{t,\rm top}^{\rm reco}) \simeq (0.37 + 0.0022\, p_{t,\rm top}^{\rm reco}/\mathrm{GeV})\ \mathrm{fm}/c\,.$$

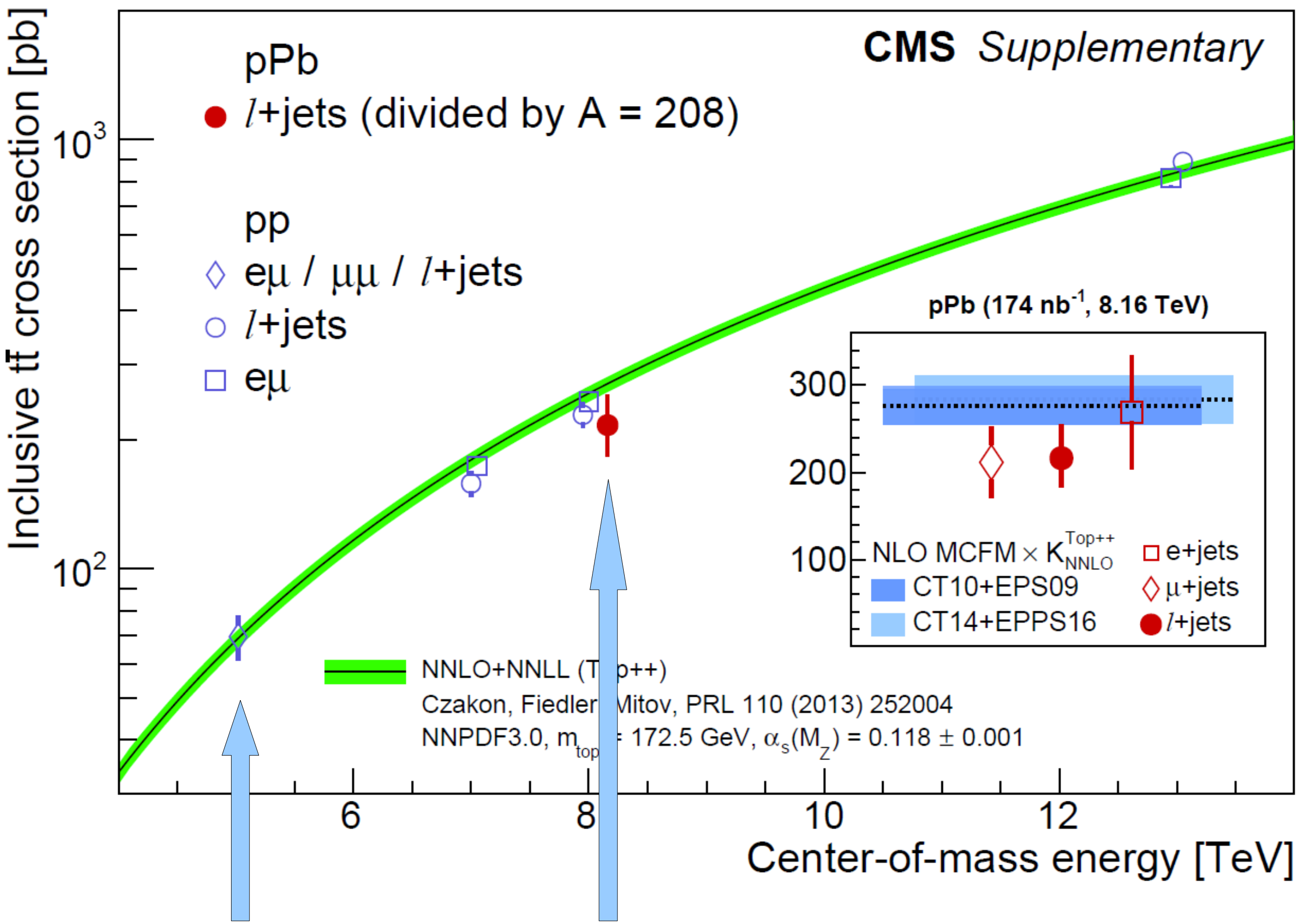




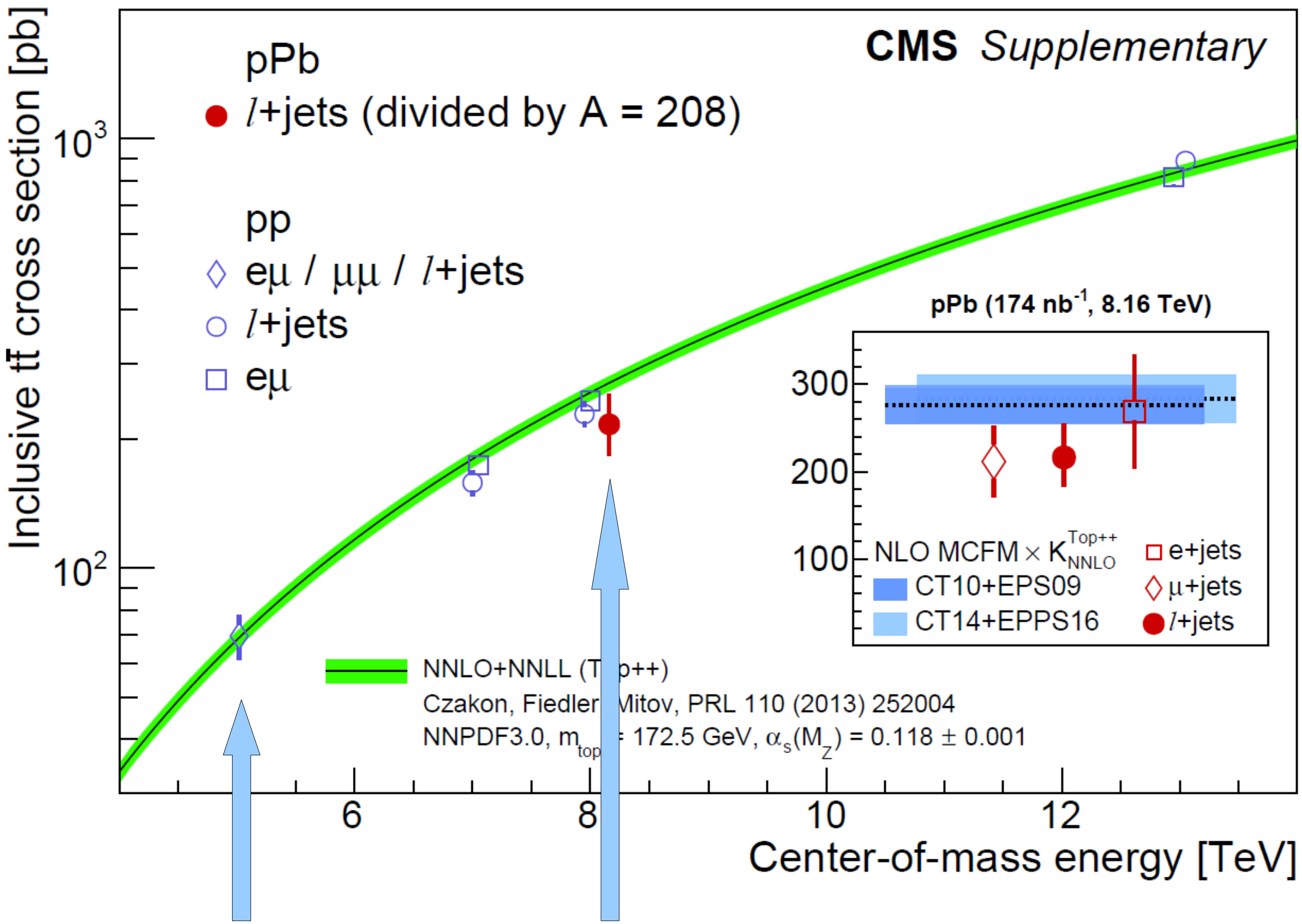
Apolinario, Milhano, Salam, Salgado PRL 120 (2018) 232301

2. Where we stand

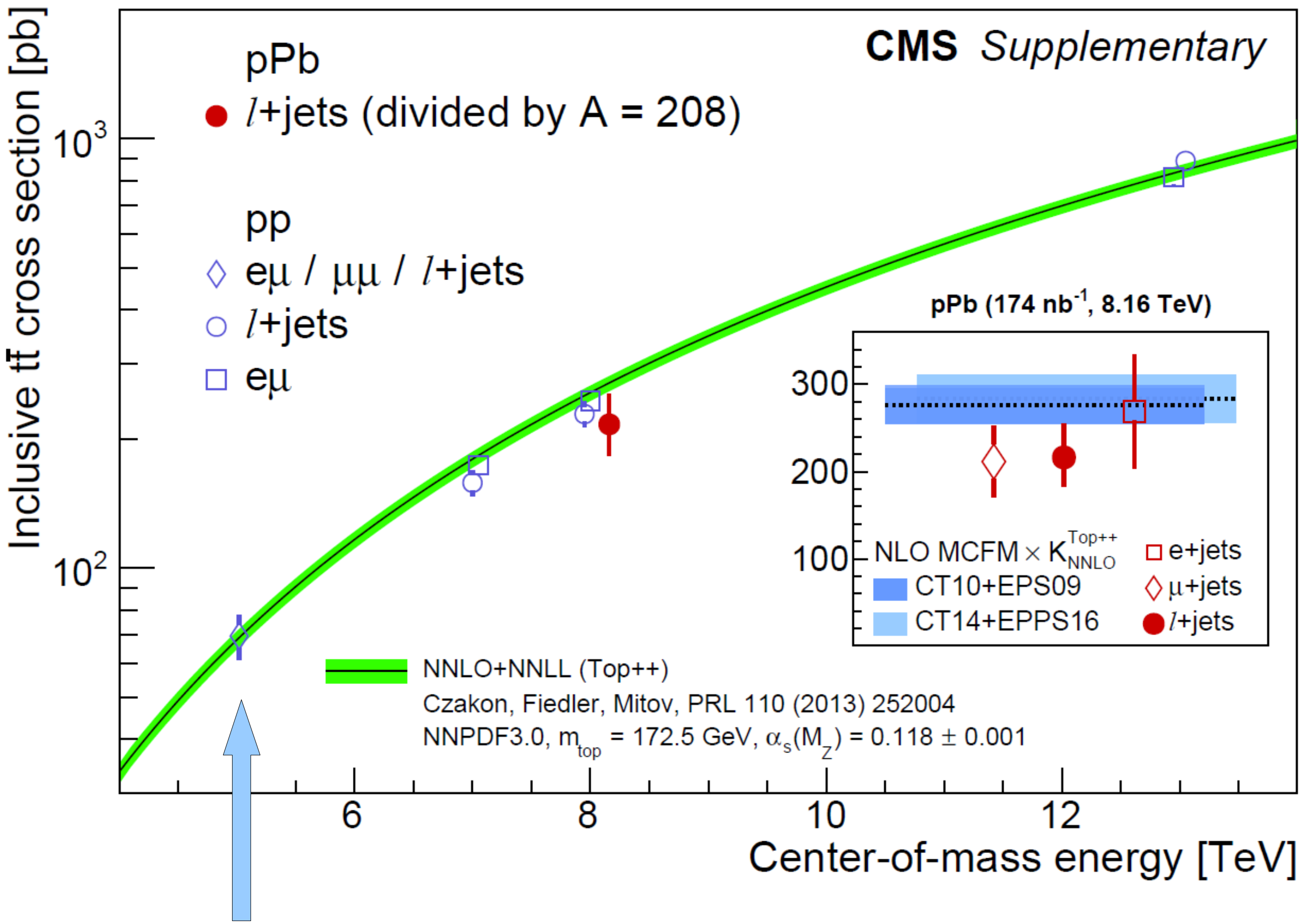
Top physics in "parasitic mode"



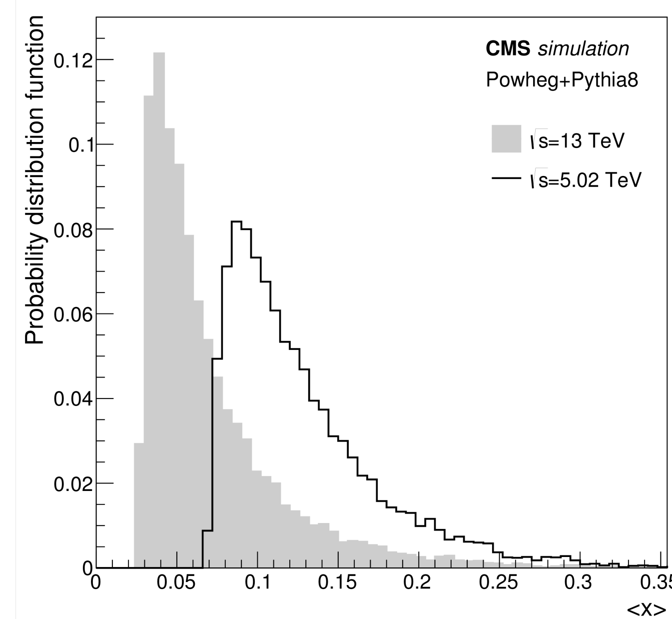
Two digressions from the beaten path
using data that were collected for other reasons



- Special Run of Nov.2015, **pp** @ $\sqrt{s}$ = 5.02 TeV
  - Few fills, preceding the PbPb run at the same NN energy (requested by the Heavy Ion community to normalize PbPb results to a reliable pp reference)
  - CMS recorded ~ 26/pb of good data
- Heavy Ion Run of Nov.2016, **pPb** @ $\sqrt{s_{NN}}$ = 8.16 TeV
  - CMS recorded ~ 0.174/pb of good data
  - In terms of pN collisions, it is equivalent to a pp lum. of 0.174*A ~ 36/pb



Long lever arm at the LHC, spanning from 5 to 13 TeV; opportunity for PDF fits (and α_S extraction!)

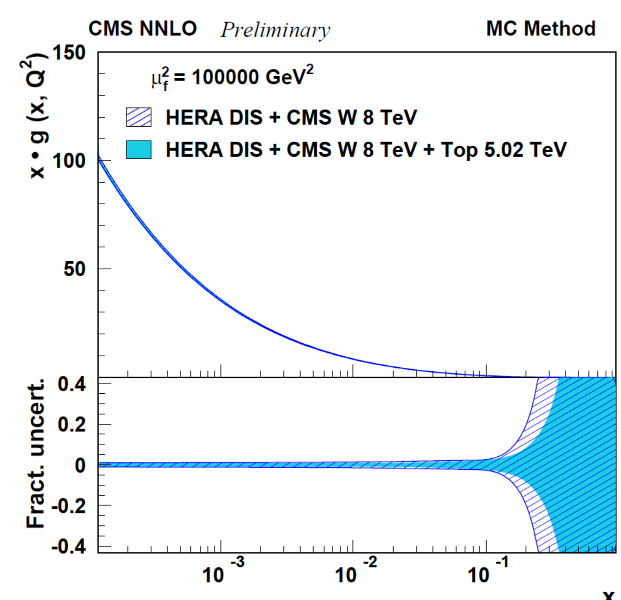


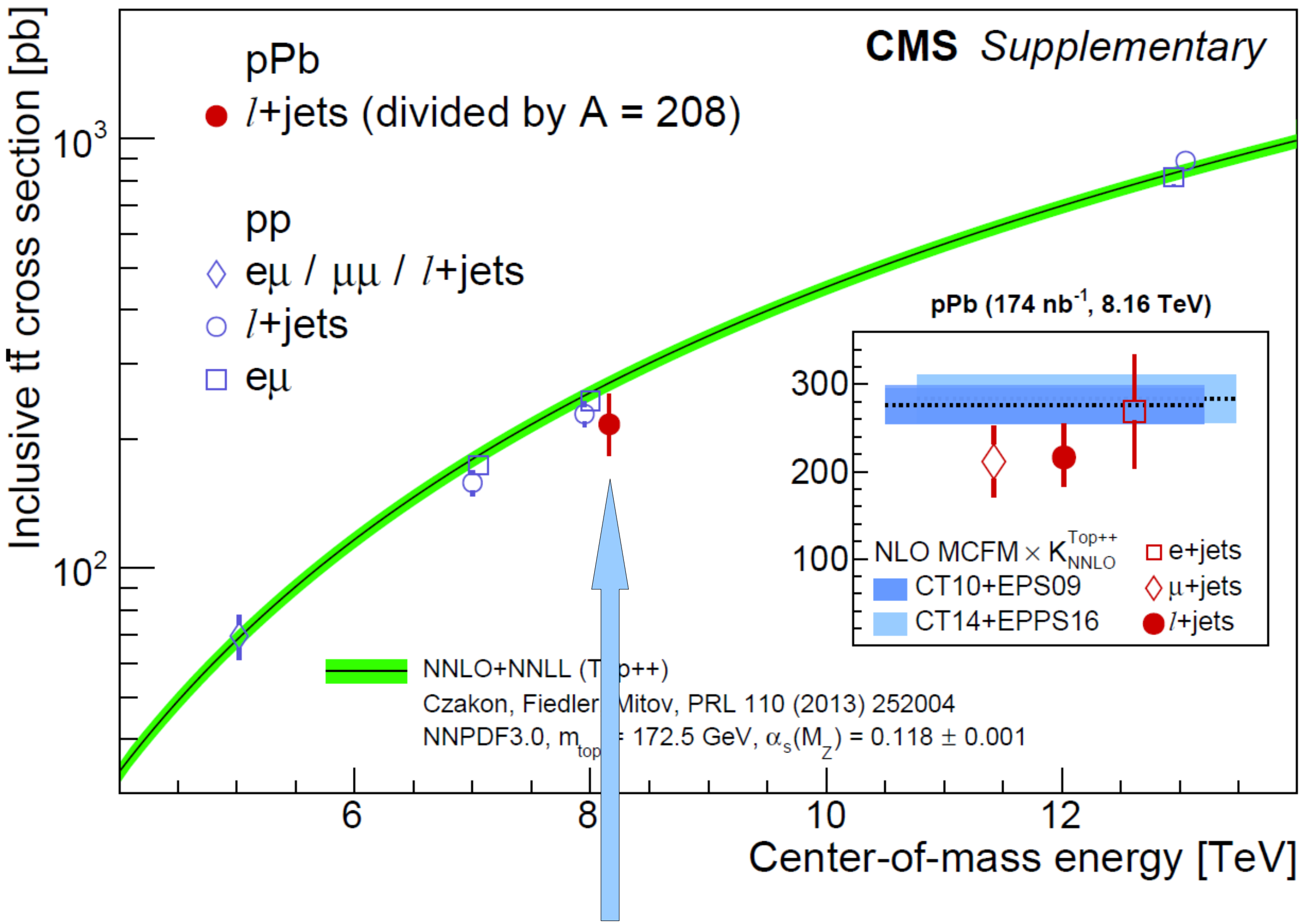
First measurement at 5 TeV

CMS coll., JHEP 1803 (2018) 115

Impact on gluon PDF is visible but not a game-changer, because of the small statistics

We took an order of magnitude more data at the end of 2017; expect an update...





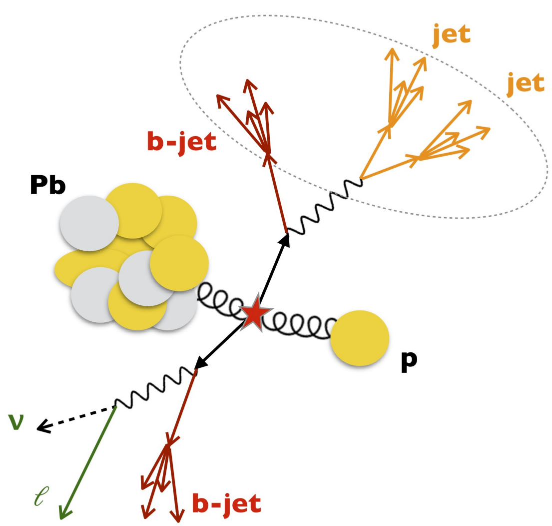
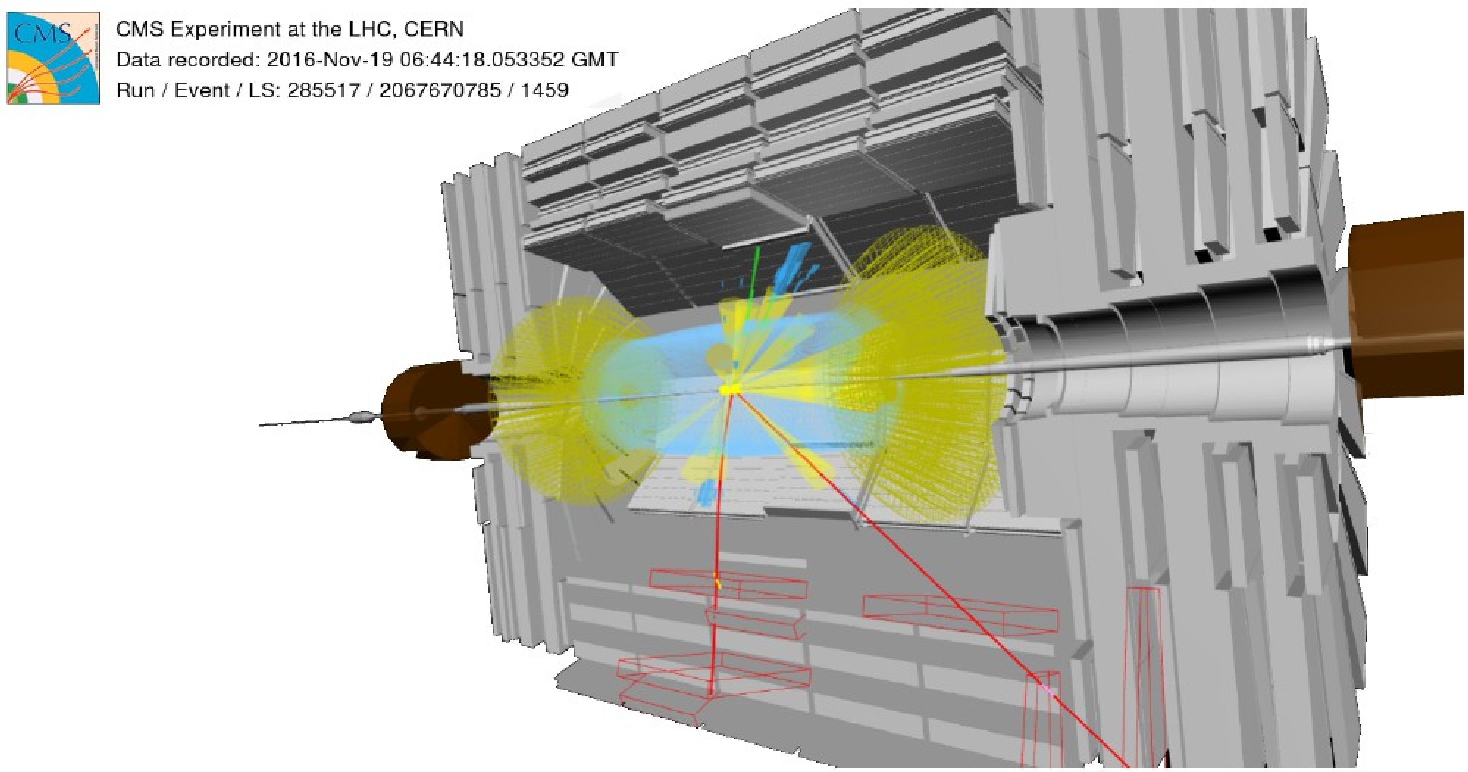


Image from Pedro Silva

First observation of top quarks in nuclear collisions

CMS coll., PRL 119 (2017) 242001

A top-pair candidate in pPb

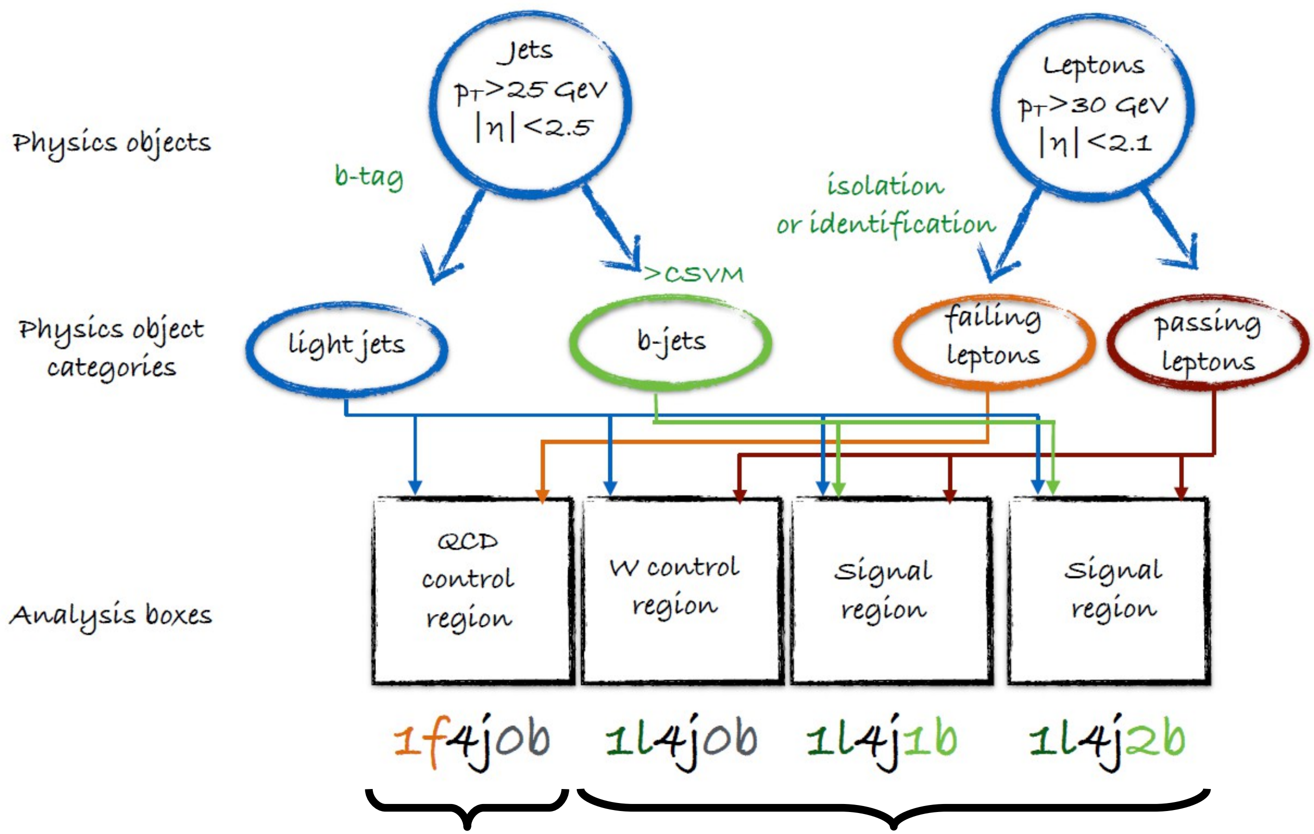


Event display by G.Krintiras with SketchUp

Beautiful dileptonic event:
electron + muon + 2 b-jets + missing energy

Very clean signature, but statistics insufficient for a serious measurement; we performed our analysis in l+jets instead

Selection (l+jets)

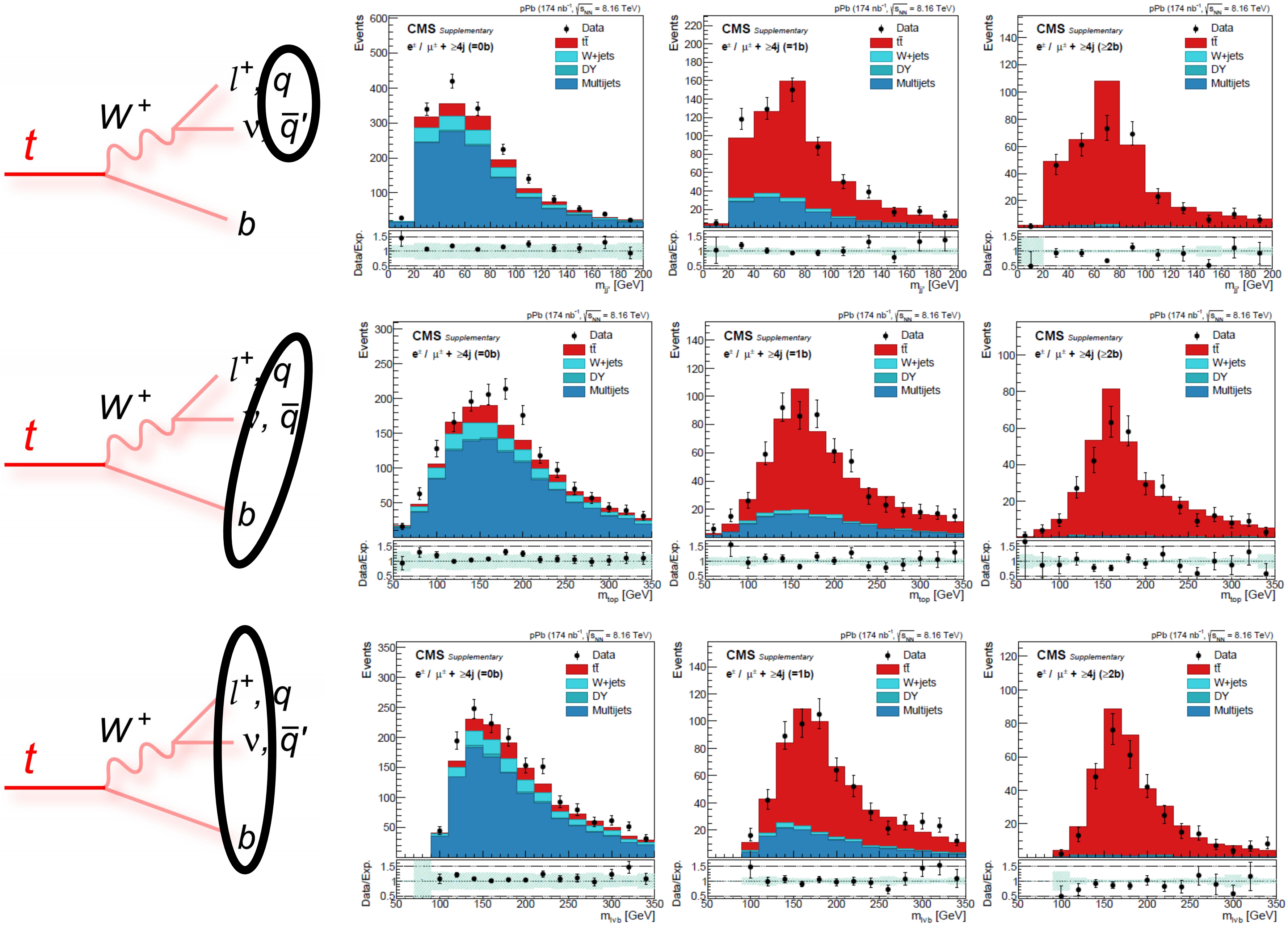


QCD
model fit

Simultaneous fit for signal
and bkg model parameters

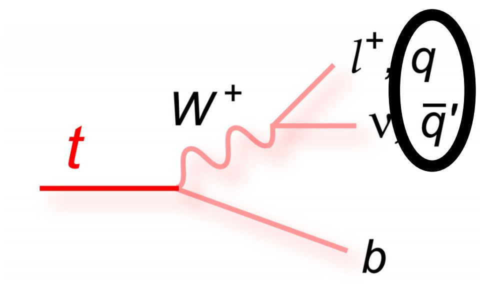
Illustration courtesy by P.Silva and G.Krintiras

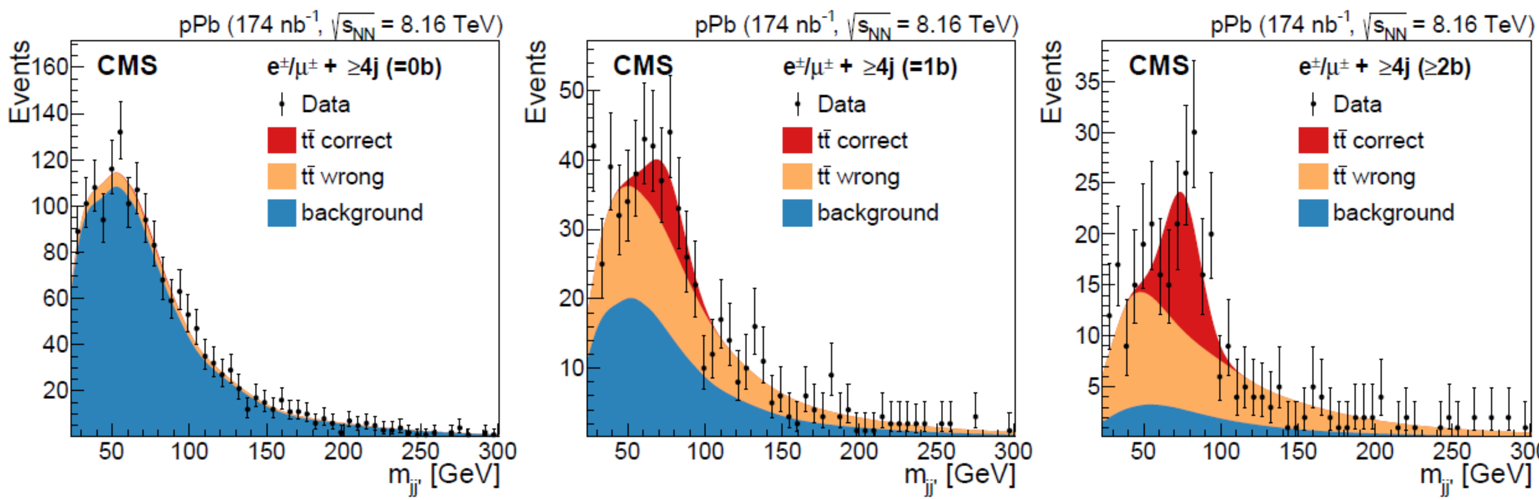
Three discriminating variables



Here the background predictions are from MC, pre-fit

Best fit

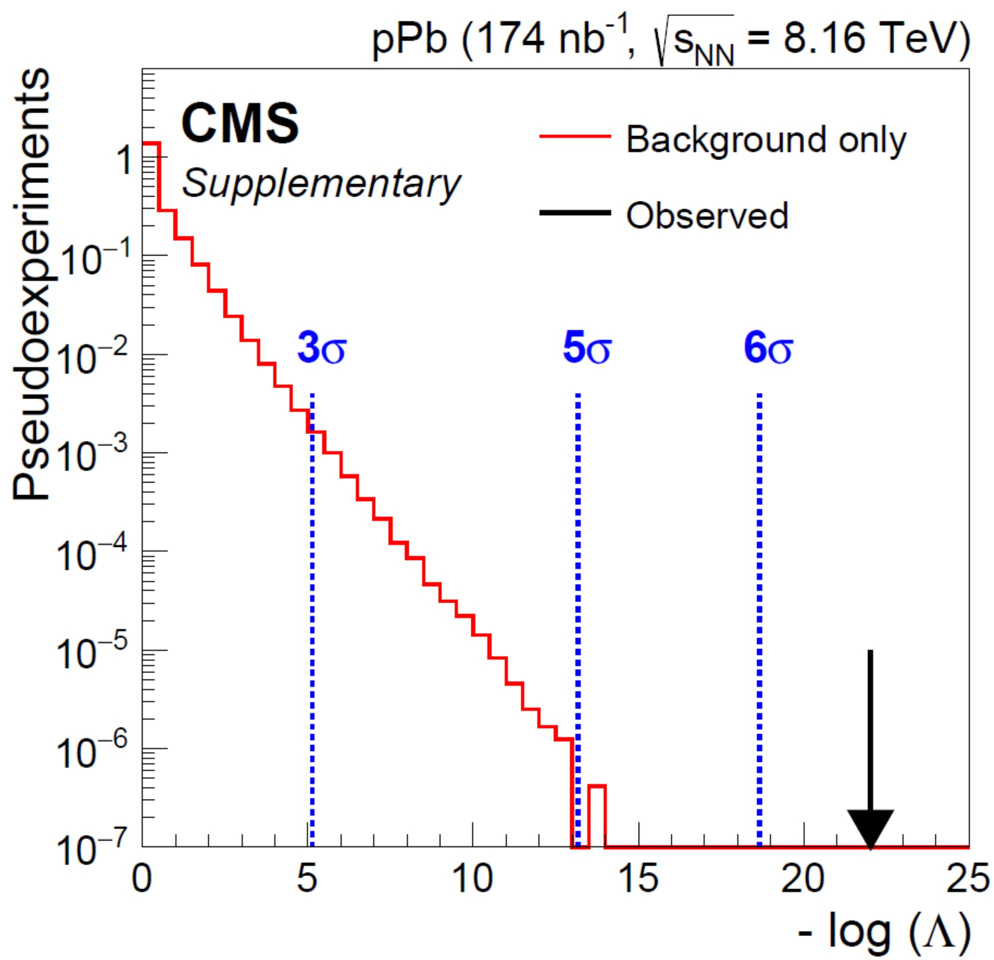




$$N_{\mathrm{k}}(m_{jj'}) = N_{\mathrm{k}}(\mathrm{t\bar{t}}) \cdot \mathrm{PDF}_{\mathrm{k}}^{\mathrm{t\bar{t}}}(m_{jj'}) + N_{\mathrm{k}}(\mathrm{bkg}) \cdot \left[\mathrm{PDF}_{\mathrm{k}}^{\mathrm{W+jets}}(m_{jj'}) + f_{\mathrm{k}} \cdot \mathrm{PDF}_{\mathrm{k}}^{\mathrm{QCD}}(m_{jj'})\right]$$

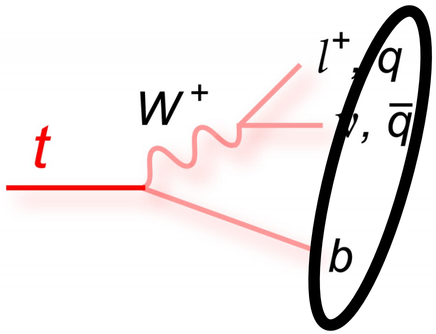
- We found the **W candidate (jj) mass** to be the most sensitive
  - Tried also combinations of 2 or 3 variables; more sensitive but we preferred the conceptual simplicity of fitting a single variable
- Result does not rely at all on MC for any of the backgrounds
  - MC samples used for signal (including theory systematics) and to validate the data-driven procedure for W and QCD in-situ estimations

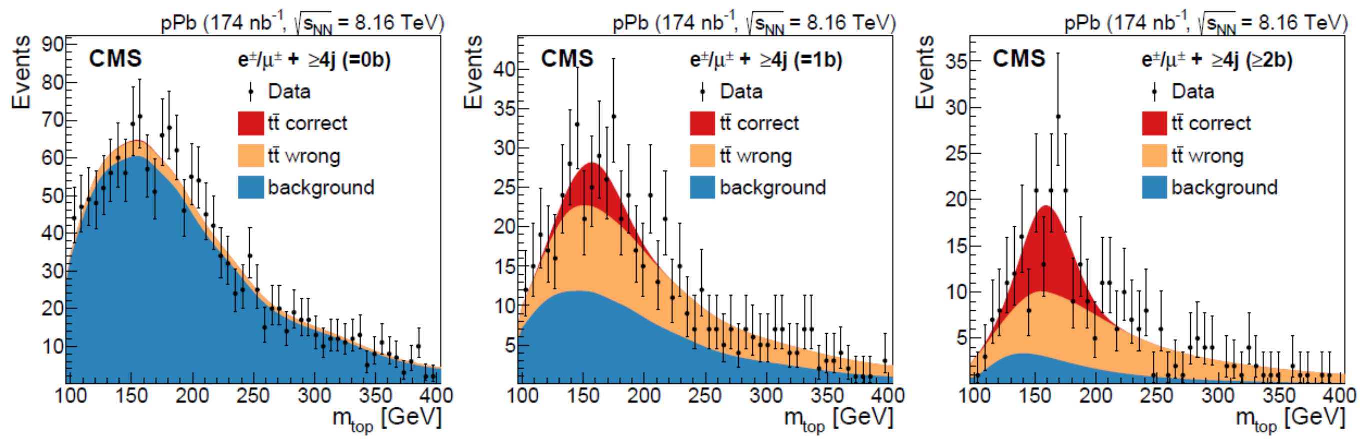
Significance



We cross-checked the fit with a few methods under many alternative assumptions, but no matter how extremely conservative we were, significance always came >> 5σ

The smoking gun

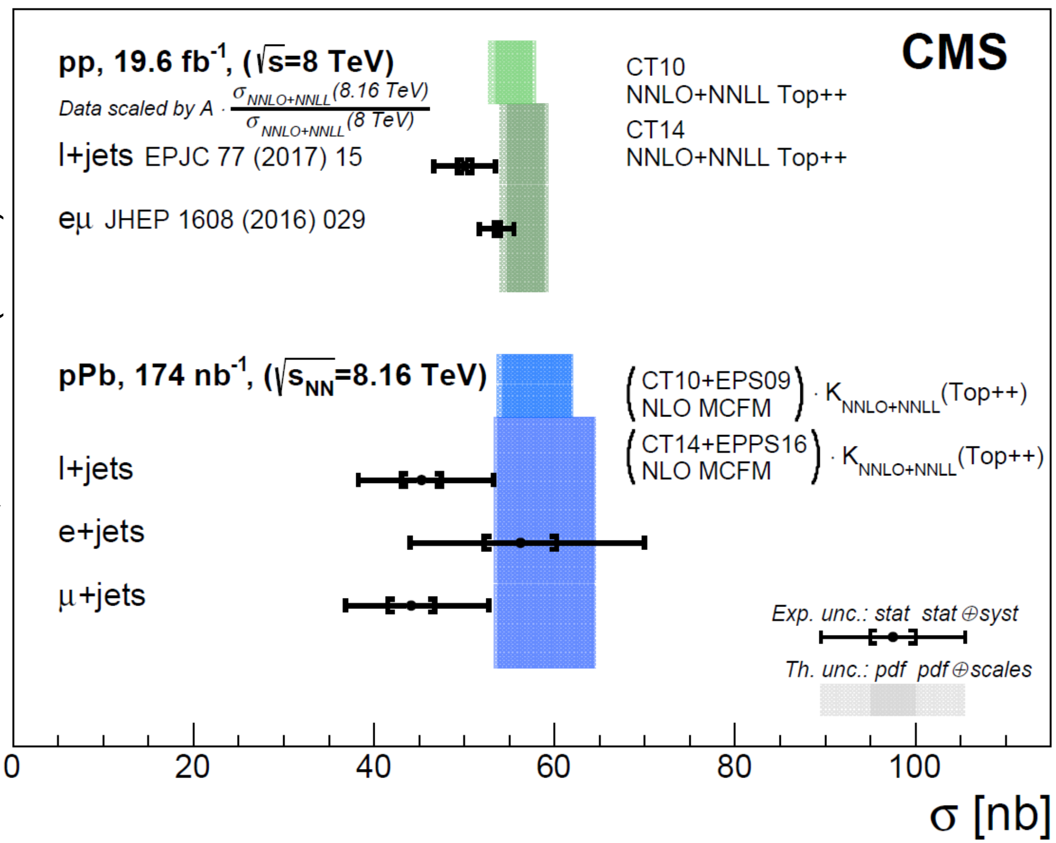




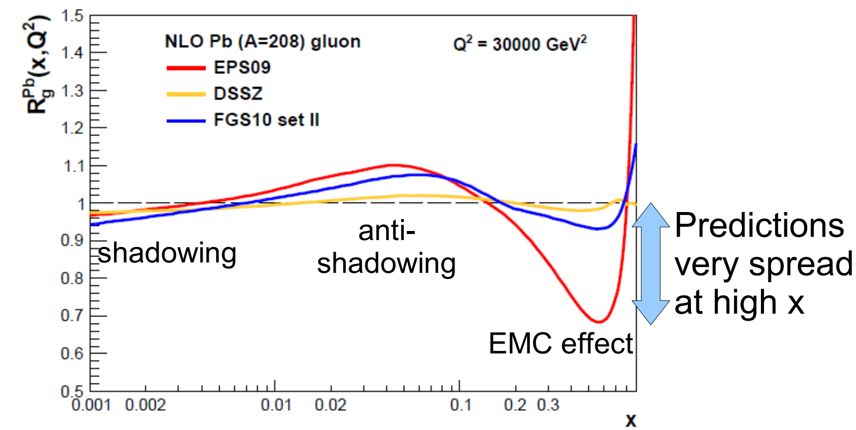
- Mass of the hadronic top candidate (bjj) where the choice of the b is based on a ΔR criterion when there is ambiguity (2b, 0b)
- A fit on this variable is less sensitive than the W mass
- However, we wanted to demonstrate that what we are selecting is really a sample dominated by top quarks
- In this page, the parameters from the main fit (W candidate mass) are applied to the normalization and shapes of the three curves ($t\bar{t}$ correct, $t\bar{t}$ wrong, background) to show the internal consistency of the fit results

Cross section

CMS coll., PRL 119 (2017) 242001



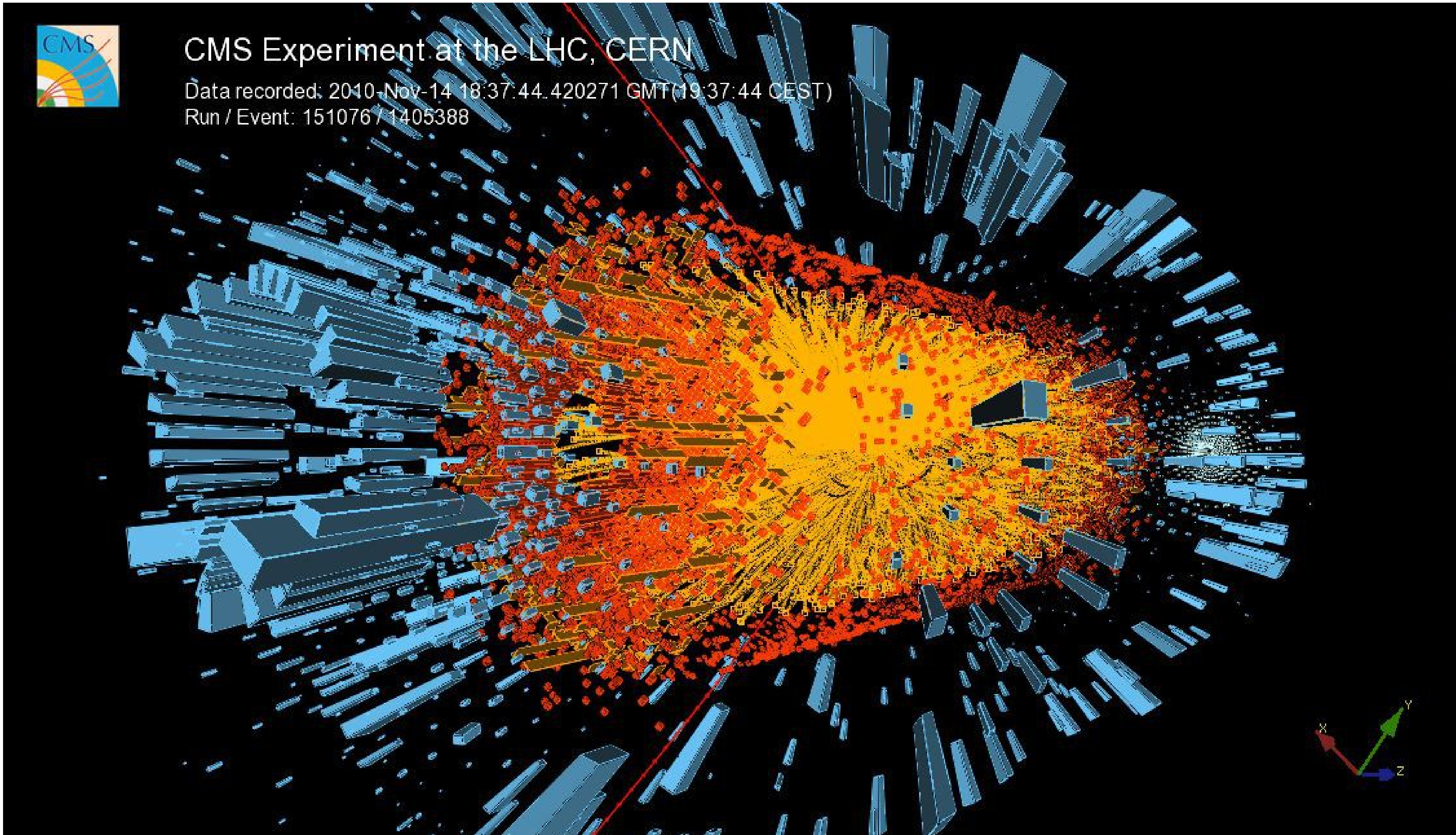
Nuclear modification for the gluon PDF:



D.d'Enterria, arXiv:1706.09521

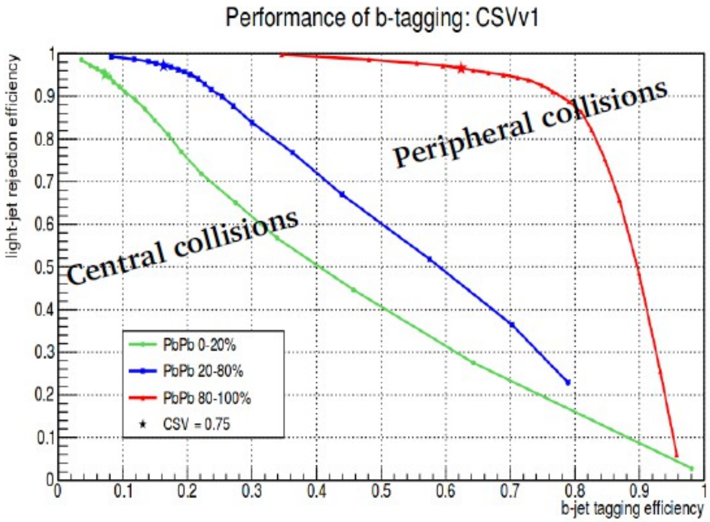
3. What is next

PbPb


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388

Top in PbPb: first attempt

- Last run in 2015: L=0.4/nb at 5.02 TeV/nucleon
  - Equivalent to a NN luminosity (L_{NN}) of ~17.5/pb
  - Not much smaller than pp @ 5 TeV (26/pb) and pPb at 8 TeV (36/pb)
- First attempt: L. Vermunt's summer project
  - Failure to observe signal; never published
  - Mostly blamed on collapse of standard b-tagging algorithm at extreme track multiplicity
  - Note: in pPb, instead, default b-tagging performs better than in pp data! Reason: no pileup, all tracks are from primary vertex

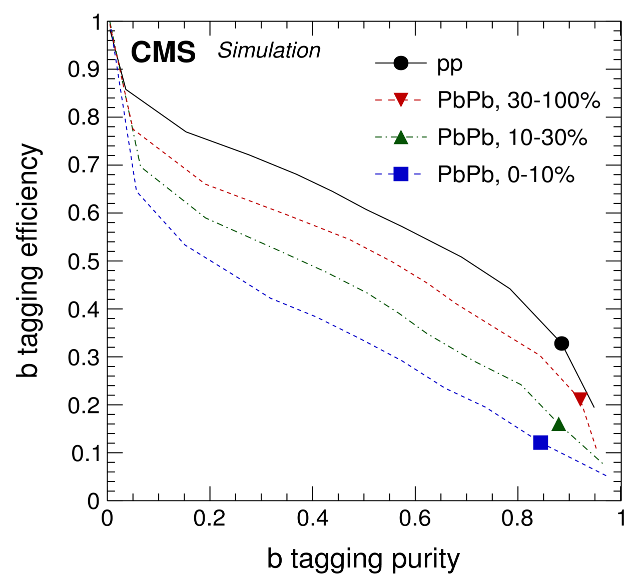


From Luuk Vertmunt's report:
https://cds.cern.ch/record/2210463

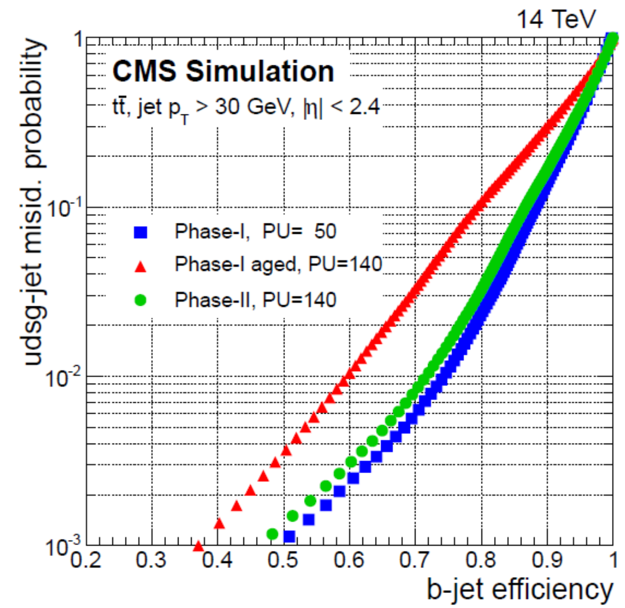
Top in PbPb: next attempts

- Last run in 2015: L=0.4/nb (L_{NN}~17.5/pb)
- Nov.-Dec.2018: L~1.2/nb (L_{NN}~50/pb)
  - Dedicated retraining of b-tagging is in the plans
- HL-LHC: L~10/nb (L_{NN}~0.4/fb) at 5.52 TeV/nucleon
  - Will profit from developments in detector and algorithms for very high pileup; track multiplicity of pp @ 14 TeV with <PU> ~ 200 is similar to PbPb @ 5.52 TeV/nucleon

CMS coll., JHEP 03 (2018) 181



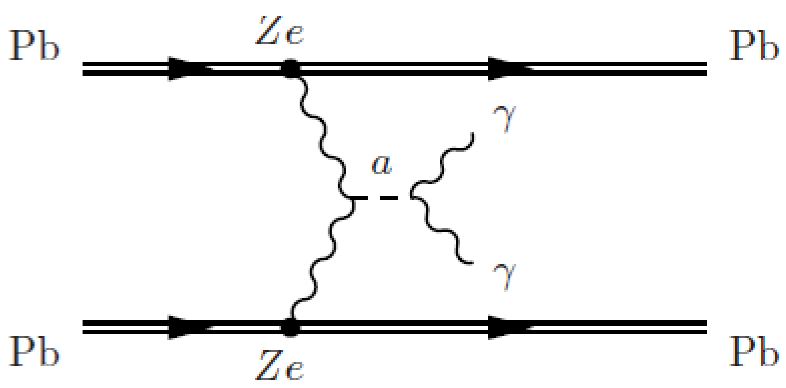
CMS Phase-II Upgrade TDR



4. Exotic searches?

Axion-like particles

Ultraperipheral collisions: projectiles stay unbroken, hard photons are emitted coherently



Key point: signal scales as Z^4; given Z=82, PbPb runs are competitive with pp

Proposed in:

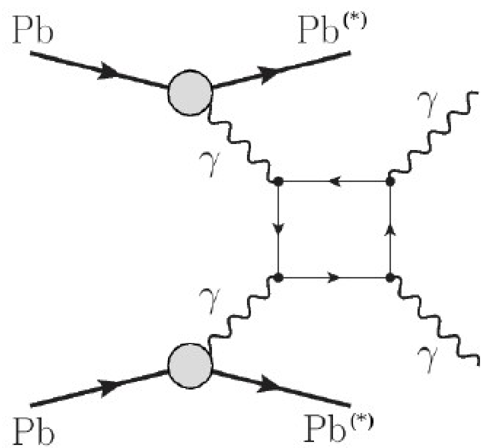
- Knapen, Lin, Lou, Melia, Phys.Rev.Lett. 118 (2017) 171801

Actually made in:

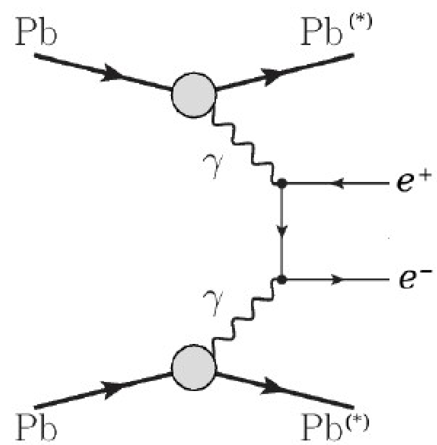
- CMS coll., arXiv:1810.04602 [hep-ex]

Backgrounds to ALP

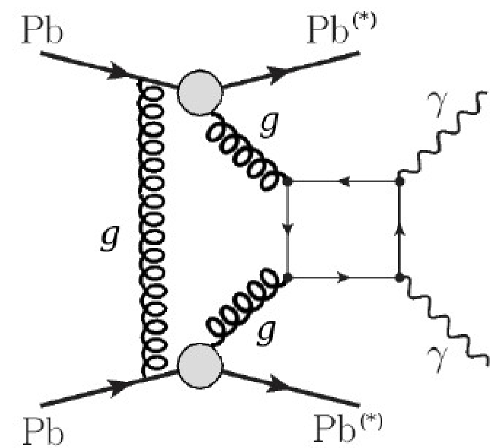
Light-by-light (LBL) scattering

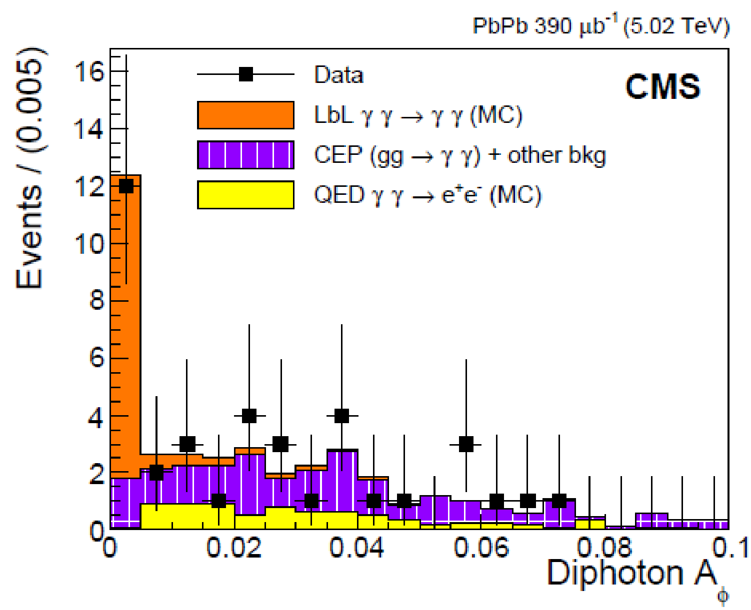


Fakes



Central Exclusive Production (CEP)





Analysis motivated by measurement of LBL (evidence at 4.1σ) with ALP search as byproduct

CMS coll., arXiv:1810.04602 [hep-ex]

Result of ALP search in PbPb

(released today!)

CMS coll., arXiv:1810.04602 [hep-ex]

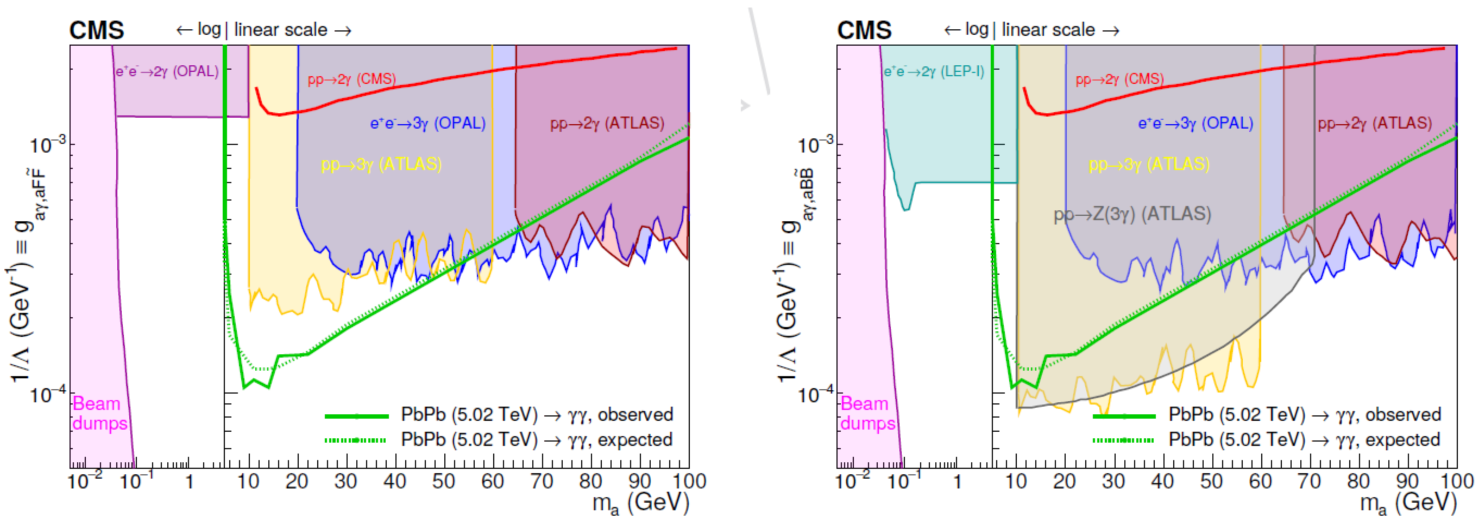


Figure 7: Exclusion limits at 95% CL in the ALP-photon coupling $g_{a\gamma}$ versus ALP mass m_a plane, for the operators $\frac{1}{4\Lambda}aF\tilde{F}$ (left, assuming ALP coupling to photons only) and $\frac{1}{4\Lambda\cos^2\theta_W}aB\tilde{B}$ (right, including also the hypercharge coupling, thus processes involving the Z boson) derived in Refs. [30, 55] from measurements at beam dumps [59], in e^+e^- collisions at LEP-I [55] and LEP-II [56], and in pp collisions at the LHC [13, 57, 58], and compared to the present PbPb limits.

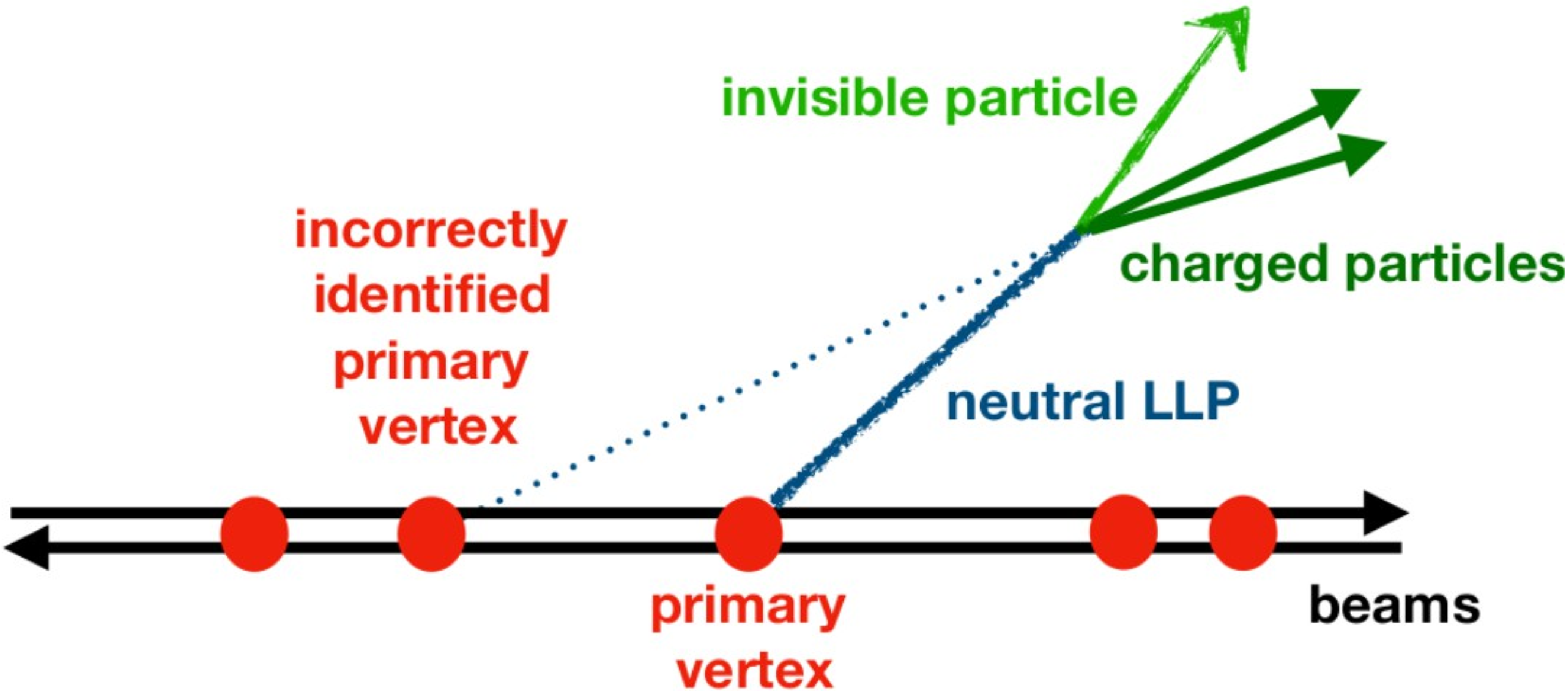
pp data:
CMS: 7 TeV
ATLAS: 8 TeV

- PbPb data @ 5.02 TeV (2015) are competitive with pp Run-1 data at 7 and 8 TeV up to large m_a values
- These data cover a blind spot at low m_a values

A new idea

- Very fresh result:
  - M. Drewes, A.G., J. Hajer, M. Lucente, O. Mattelaer, *"The Heavy Metal Path to New Physics"*, arXiv:1810.xxxx
- We started from some key facts:
  - No pileup in HI runs; this will stay true also in future runs
  - While in pp @ HL-LHC there will be <PU> ~ 200
  - Track multiplicity will be comparable in pp and HI runs
  - Trigger thresholds of pp runs will rise with respect to Run 2; while in HI the dimuon triggers will stay "thresholdless"

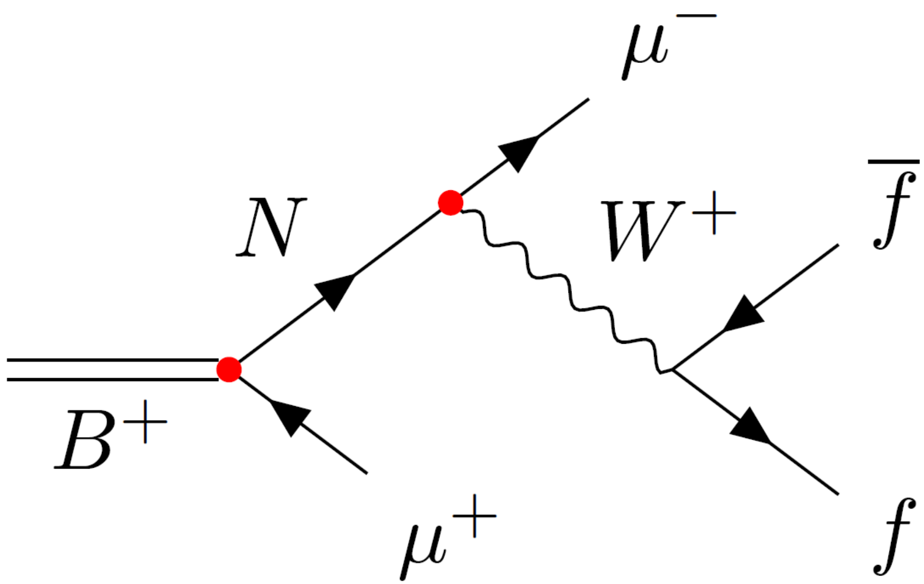
Long Lived Particles and PU



This kind of nuisance does not exist in HI runs, where there is no PU and therefore we always know with extreme precision where all particles are coming from

Representative model

(but any soft and clean displaced signature would do)



- Heavy neutrino (N), long-lived and lighter than the B mesons
- B mesons are abundantly produced; x-section depends on collision energy (disadvantage of HI collisions at ~5 TeV wrt pp collisions @ 13-14 TeV), but much less than for heavy particles
- Two muons are produced, one displaced → very clean signal
- Muon spectrum is very soft → very low muon thresholds are a key advantage of HI over pp runs

Early blunder

- When we had the idea, obviously we started from PbPb
  - PbPb is what LHC usually collides in HI runs
  - We hoped that A^2 enhancement compensated for low lumi
- But no, we "only" recover 4 orders of magnitude and we need one more to be competitive with pp @ HL-LHC
  - Not surprising: $(208)^2$ ~ 43k, L(PbPb) ~ $10^{29\rightarrow30}$ $cm^{-2}s^{-1}$, and L(pp) ~ $10^{34\rightarrow35}$ $cm^{-2}s^{-1}$
  - Of course if we could run 10 months instead of 1 per year...
  - .... but this will never happen!
- This made us curious: what is the limiting factor on the instantaneous PbPb luminosity?

Secondary beams

Bound-Free Pair Production (BFPP): $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+}$

Electromagnetic dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}.$

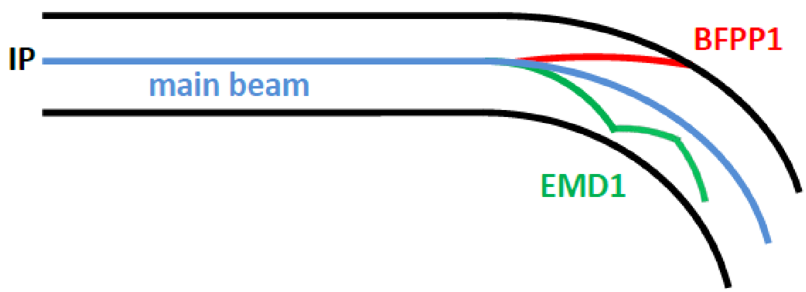


Figure 2.10.: Sketch of the separation of the secondary beams from the main beam in the curved beam pipe inside bending magnets.

	BFPP		EMD			Hadronic
Symbole	$\sigma_{c,\mathrm{BFPP1}}$	$\sigma_{c,\mathrm{BFPP2}}$	$\sigma_{c,\mathrm{EMD1}}$	$\sigma_{c,\mathrm{EMD2}}$	$\sum \sigma_{c,\mathrm{EMD}}$	$\sigma_{c,\mathrm{hadron}}$
Reference	[67]	[68]		[66]		[69]
Cross-section [b]	281	0.006	96	29	226	8

Table 2.3.: Cross-sections for electromagnetic interactions in Pb-Pb collisions at $E_b = 7Z$ TeV.

From Michaela Schaumann's thesis

Which ion is optimal?

$$\frac{dN}{dt} = -(\sigma_{\text{had}} + \sigma_{\text{EMD}} + \sigma_{\text{BFPP}})L - \frac{N}{\tau_{\text{other}}}, \qquad L = \frac{N^2 f_0}{4\pi\beta^* \varepsilon_{xn} k_c}$$

$$\sigma_{\text{EMD1}} \approx (3.42\ \mu b)\frac{(A-Z)Z^3}{A^{2/3}}\log(2\gamma^2 - 1),$$

$$\sigma_{\text{EMD}} \approx 1.95\ \sigma_{\text{EMD1}} \quad \text{(total for all EMD channels)}$$

$$\sigma_{\text{BFPP}} \approx Z^7(A\log(2\gamma^2 - 1) + B)$$

List of species are examples that are of interest.

Some species (e.g., Cu) are difficult to produce in the ECR heavy ion source.

Noble gases are particularly favourable.

Cross section scalings from papers by G. Baur et al, S. Klein, I. Pshenichnov, ….

Pb is worse in this respect because of high BFPP and EMD cross-sections.
Makes short fills, more time spend refilling, ramping, etc.

	γ	σ_{EMD} / b	σ_{BFPP} / b	σ_{had} / b	σ_{tot} / b
$^{16}O^{8+}$	3800.	0.074	0.000024	1.4	1.5
$^{40}Ar^{18+}$	3400.	1.2	0.0069	2.6	3.8
$^{40}Ca^{20+}$	3800.	1.6	0.014	2.6	4.2
$^{78}Kr^{36+}$	3500.	12.	0.88	4.1	17.
$^{84}Kr^{36+}$	3200.	13.	0.88	4.3	18.
$^{129}Xe^{54+}$	3100.	52.	15.	5.7	73.
Pb^{82+}	3000.	220.	280.	7.8	510.

Source: Jo Jowett, HL/HE-LHC workshop, June 2018 (updated), link

Which ion is optimal?

Initial luminosity gain wrt Pb-Pb

Species 2 vs species 1:

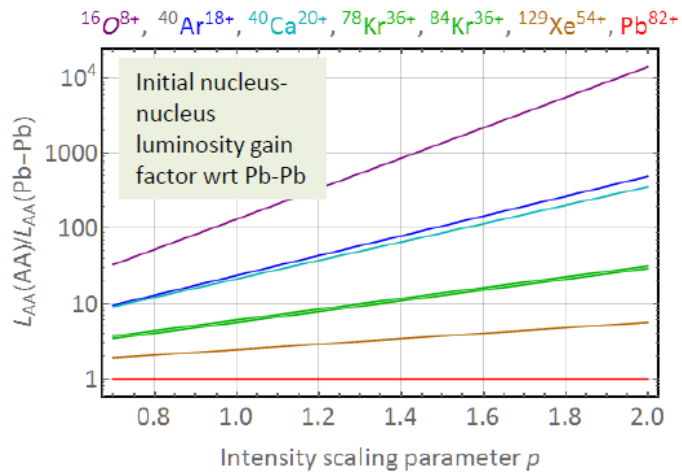
Beam size at IP: $\frac{\sigma_2^*}{\sigma_1^*} = \frac{\sqrt{A_2}\sqrt{Z_1}}{\sqrt{A_1}\sqrt{Z_2}}$

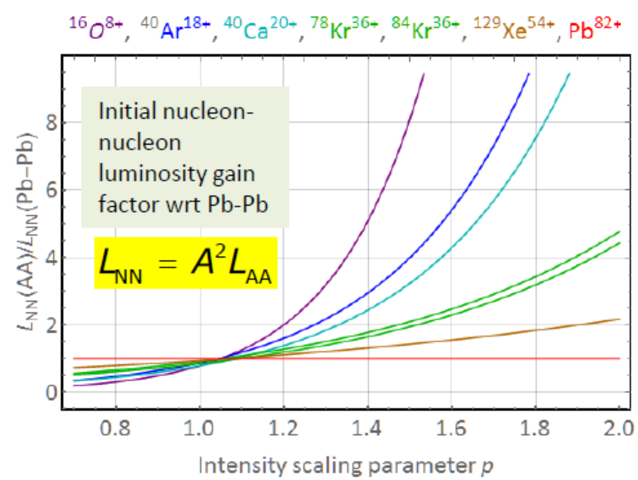
Initial luminosity $\frac{L_2}{L_1} = \frac{A_1 Z_1^{-1+2p}}{A_2 Z_2^{-1+2p}}$

Initial NN luminosity $\frac{L_2}{L_1} = \frac{A_2 Z_1^{-1+2p}}{A_1 Z_2^{-1+2p}}$

This assumes no luminosity levelling.

Formulas for integrated luminosity gains are much messier.





Source: Jo Jowett, HL/HE-LHC workshop, June 2018 (updated), link

Which ion is optimal?

Pessimistic "no-gain" scaling (p=1)

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{84}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3220.	3150.	2960.
$\sqrt{s_{NN}}$ /TeV	7.	6.3	7.	6.46	6.	5.86	5.52
σ_{had} /b	1.41	2.6	2.6	4.06	4.26	5.67	7.8
σ_{tot} /b	1.48	3.85	4.18	17.1	18.3	72.5	508.
N_b	1.95×10^{9}	8.66×10^{8}	7.79×10^{8}	4.33×10^{8}	4.33×10^{8}	2.89×10^{8}	1.9×10^{8}
ϵ_{xn} /μm	2.	1.8	2.	1.85	1.71	1.67	1.58
f_{IBS} /(m Hz)	0.0207	0.0419	0.0517	0.086	0.0798	0.117	0.167
W_b /MJ	21.5	21.5	21.5	21.5	21.5	21.5	21.5
L_{AA0} /cm^{-2}s^{-1}	1.43×10^{30}	2.82×10^{29}	2.29×10^{29}	7.06×10^{28}	7.06×10^{28}	3.14×10^{28}	1.36×10^{28}
L_{NN0} /cm^{-2}s^{-1}	3.66×10^{32}	4.52×10^{32}	3.66×10^{32}	4.3×10^{32}	4.98×10^{32}	5.22×10^{32}	5.88×10^{32}
P_{BFPP} /W	0.000302	0.0392	0.0738	2.51	2.51	28.6	350.
P_{EMD1} /W	0.485	3.63	4.12	17.8	19.2	50.5	141.
τ_{L0} /h	52.4	45.4	46.5	20.4	19.1	7.23	1.57
T_{opt} /h	16.2	15.1	15.2	10.1	9.78	6.01	2.8
$\langle L_{AA}\rangle$ /cm^{-2}s^{-1}	1.07×10^{30}	2.08×10^{29}	1.69×10^{29}	4.54×10^{28}	4.48×10^{28}	1.57×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle$ /cm^{-2}s^{-1}	2.74×10^{32}	3.33×10^{32}	2.7×10^{32}	2.76×10^{32}	3.16×10^{32}	2.6×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}\, dt$ /nb^{-1}	1390.	269.	219.	58.8	58.1	20.3	4.92
$\int_{month} L_{NN}\, dt$ /pb^{-1}	356.	431.	350.	358.	410.	338.	213.
R_{had} /kHz	2020.	734.	595.	286.	301.	178.	106.
μ	0.16	0.0583	0.0472	0.0227	0.0239	0.0141	0.00842

Stored energy in beam W_b is identical in this case $\Rightarrow$ Collimation risks ~ comparable.
f_{IBS} indicates strength of IBS emittance growth – all cases better than Pb.
Overestimates integrated luminosity for Pb-Pb wrt official values (since no levelling, etc).
Initial event rates are high! Much longer fills.

J.M. Jowett, HI-HE-LHC Physics Workshop, 18/6/2018 14

Source: Jo Jowett, HL/HE-LHC workshop, June 2018 (updated), link

Pilot Xe-Xe run, 13 Oct.2017

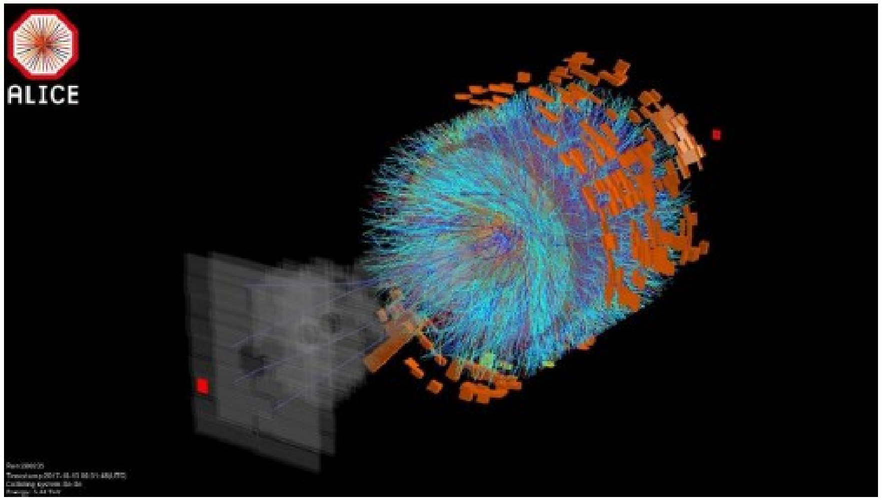


Table 1: Beam parameters at start of Stable Beams, fill 6295. Sets of three values correspond to the interaction points of ATLAS/CMS, ALICE, LHCb. Luminosity values are calculated from beam parameters.

Parameter	**Fill 6295**
Beam energy [Z TeV]	6.5
No. of bunches colliding	(8, 16, 8)
β^* [m]	(0.3, 10, 3)
Bunch intensity [10^8 ions]	2.87 ± 0.14
Normalized emittance (H, V) [μm]	(~1.5 / ~1.0)
Bunch length [cm]	9.1 ± 0.2
Luminosity [10^{27} cm^{-2}s^{-1}]	(0.28, 0.03, 0.04)
Rad. damping time (τ_z, $\tau_{x,y}$) [h]	(9.5, 18.9)
IBS growth time (τ_z, τ_x) [h]	(6.7, 13.1)

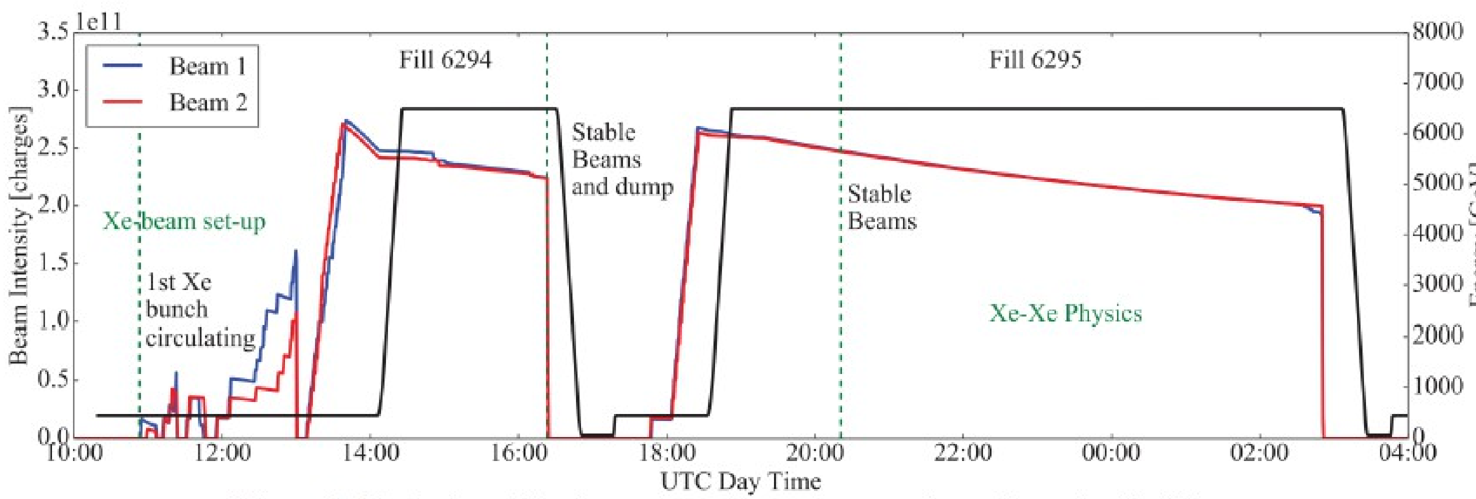
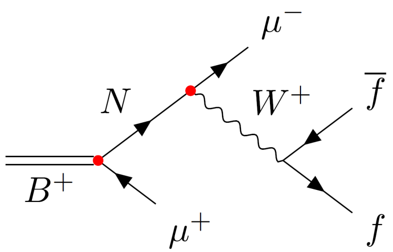
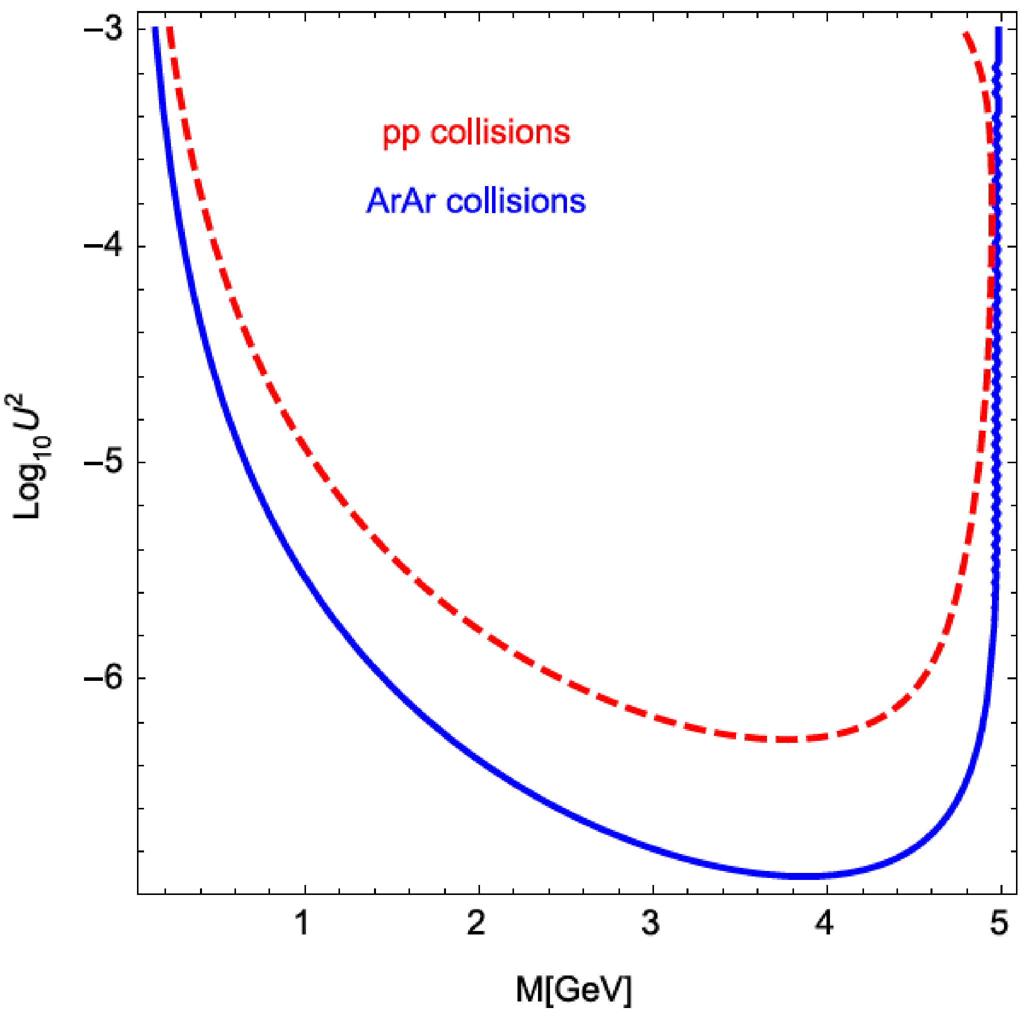


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

Source: Jo Jowett, HL/HE-LHC workshop, June 2018 (updated), link

Perspectives



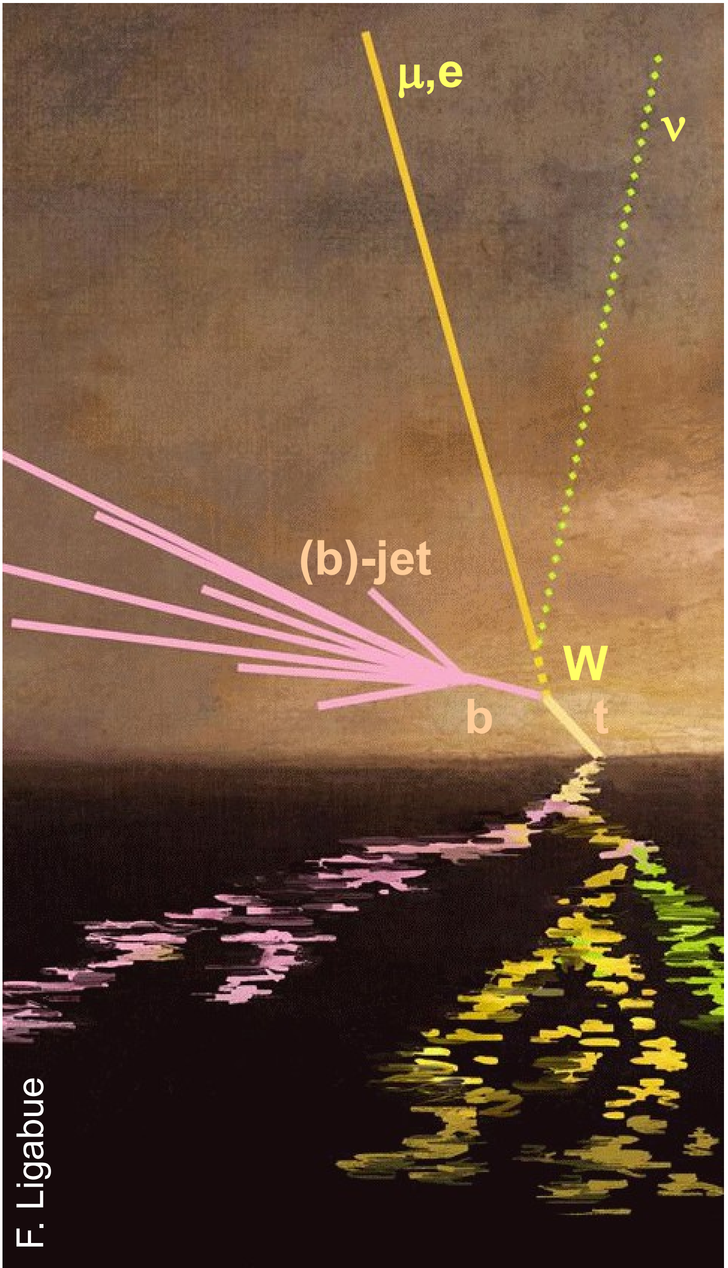


L(pp) = 100/fb
(1 year in Run 3)

L(ArAr) = 2.8/pb
(1 month)

M. Drewes, A.G., J. Hajer, M. Lucente, O. Mattelaer, arXiv:1810.xxxx

Conclusions



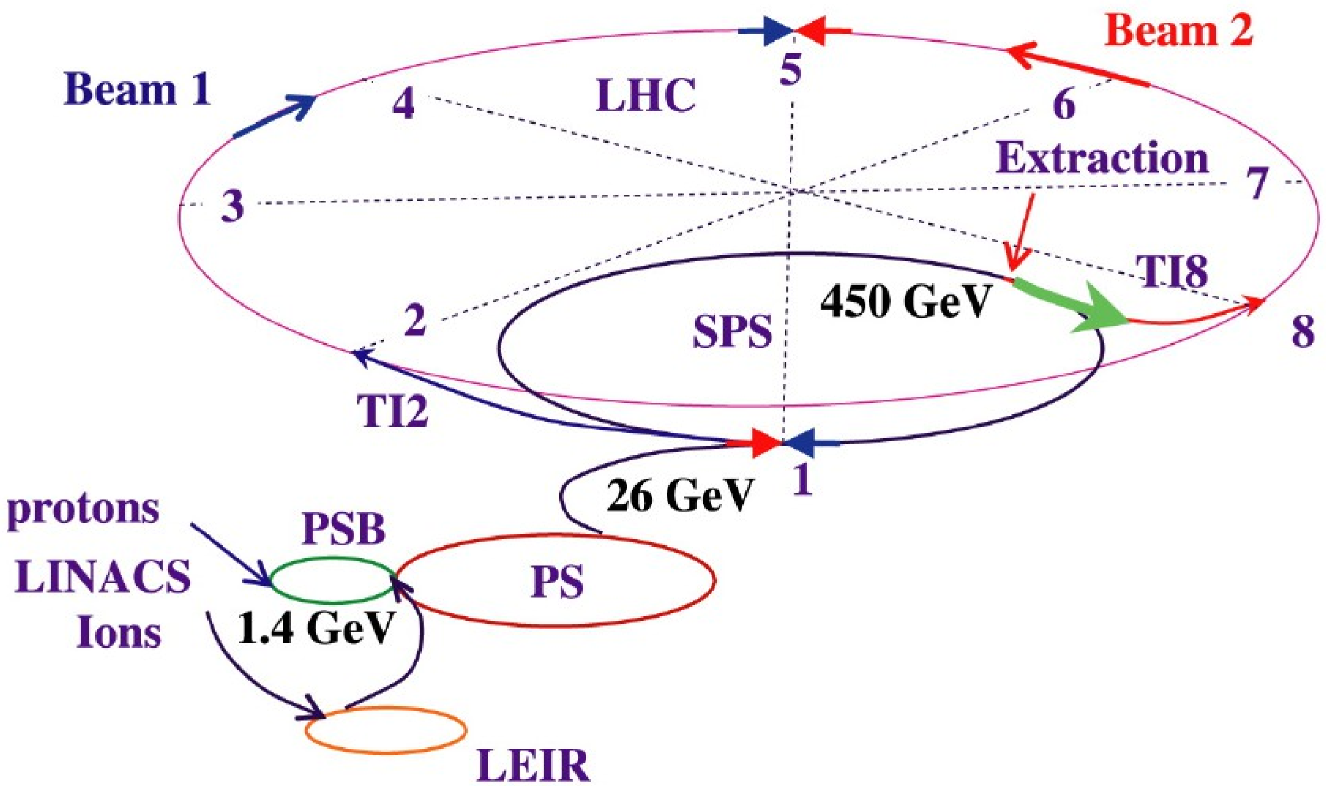
- The top quark is:
  - A new probe into the depths of nuclear matter
  - A chronometer with yoctosecond resolution
- Heavy Ion collisions are:
  - Useful data for more physics than they were planned for

Acknowledgments

I am indebted to my collaborators in **"top @ HI"**:
Georgios Krintiras, Pedro Silva, David D'Enterria,
Emilien Chapon, Marta Verweij, Martijn Mulders

And in **"LLP @ HI"**:
Jan Hajer, Marco Drewes, Michele Lucente,
Olivier Mattelaer
(with consultancy by Jo Jowett, Martino Borsato,
Georgios Krintiras, Emilien Chapon, Steven
Lowette, Albert De Roeck)

CERN accelerator complex

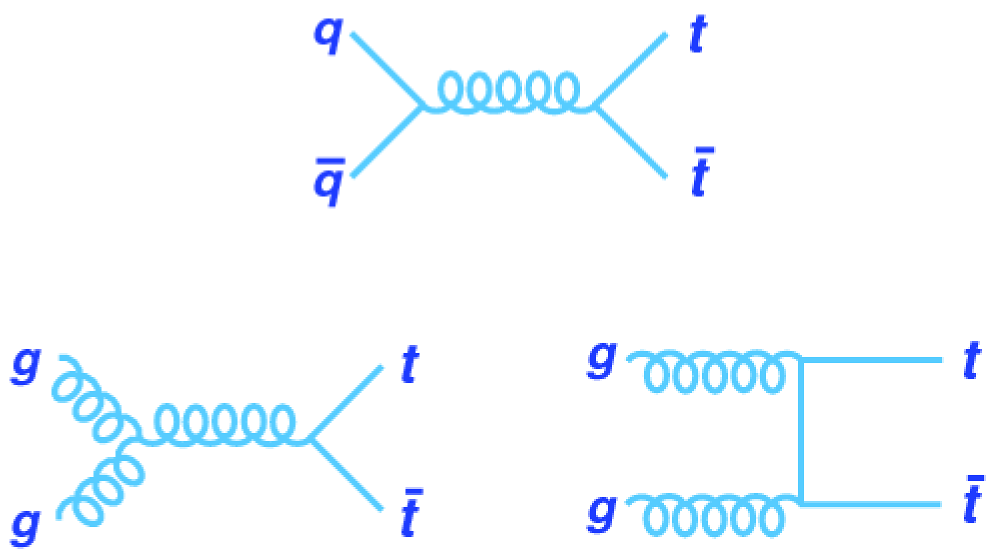


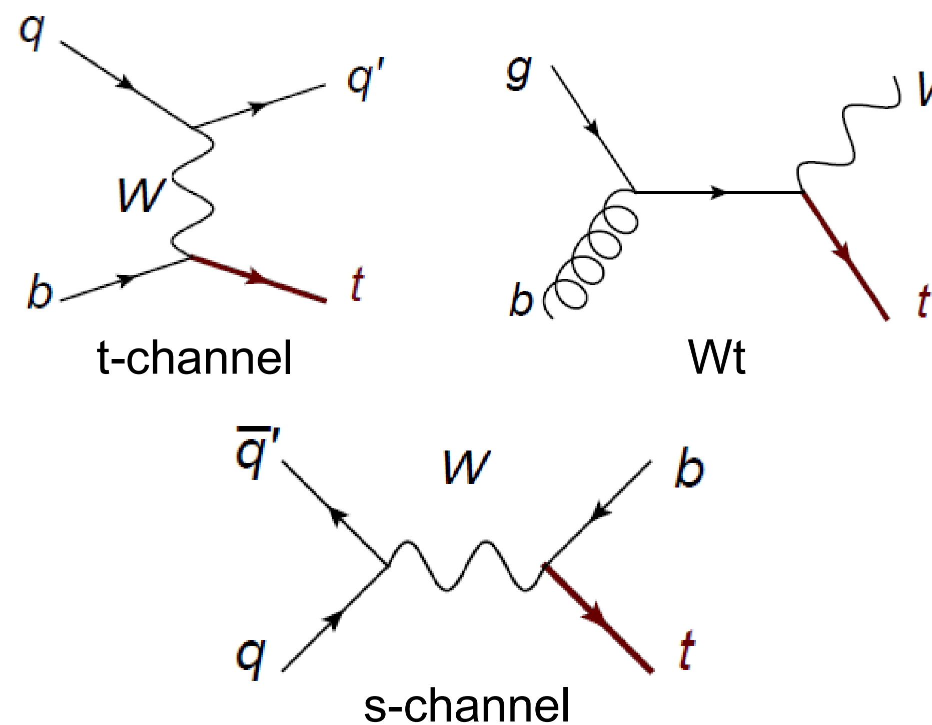
Systematics in pPb measurement

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)		
	e+jets	μ+jets	Combined
Statistical	± 7	± 6	± 5
Systematics			
Electron efficiency	4	-	4
Muon efficiency	-	4	4
b-finding efficiency	8	15	13
Jet energy scale	4	3	4
Jet energy resolution	<1	<1	<1
Background	21	8	7
Signal acceptance	4	4	4
Integrated luminosity	5	5	5
Total uncertainty	23	18	17

Main production mechanisms

Diagrams for $t\bar{t}$ from D0 webpage

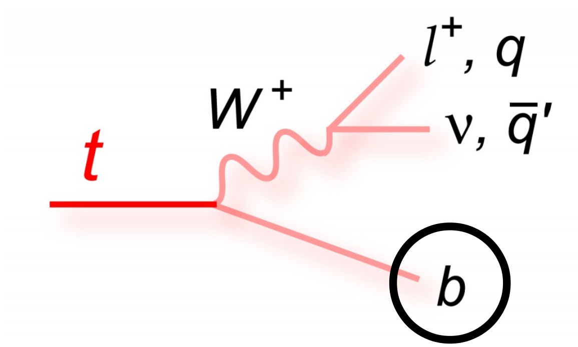




Diagrams for single top from AG & Schwienhorst, arXiv:1710.10699

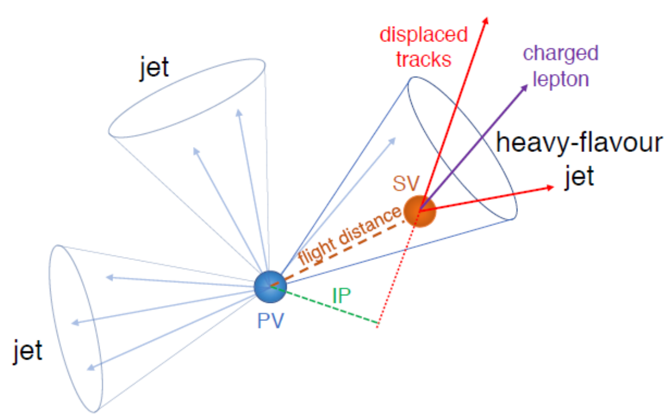
- The dominant production mechanism at LHC is pair production ($t\bar{t}$), mostly $gg \rightarrow t\bar{t}$ (~85-90% of $t\bar{t}$ at 7-13 TeV)
- Single-top processes more rare (weak-force production) but not so rare (~1/3 of $t\bar{t}$)

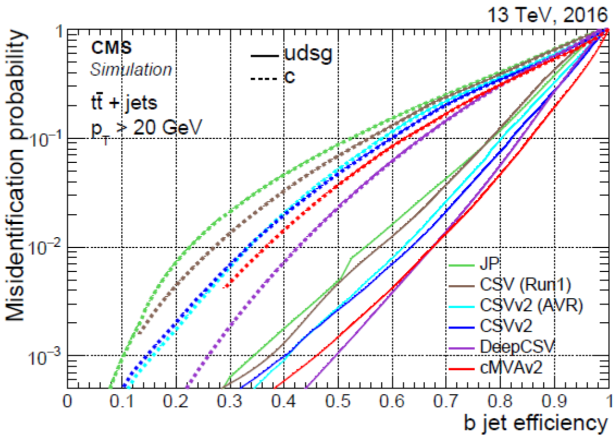
"b-tagging"



- The top quark decays almost always (~99.8%) in its isospin partner, the ***bottom***
- Background processes with bottom quarks are more rare than the same processes with lighter quarks

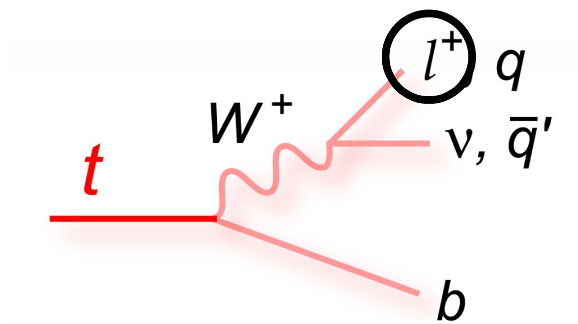
B hadrons have lifetimes of O(10^{-12} s) $\Rightarrow$ their decay vertex has a distance from the production vertex of O(1 mm) $\Rightarrow$ LHC trackers include few layers of pixel detectors with O(10 μm) hit resolution and distance of ≤ 10 cm from the center of the detector



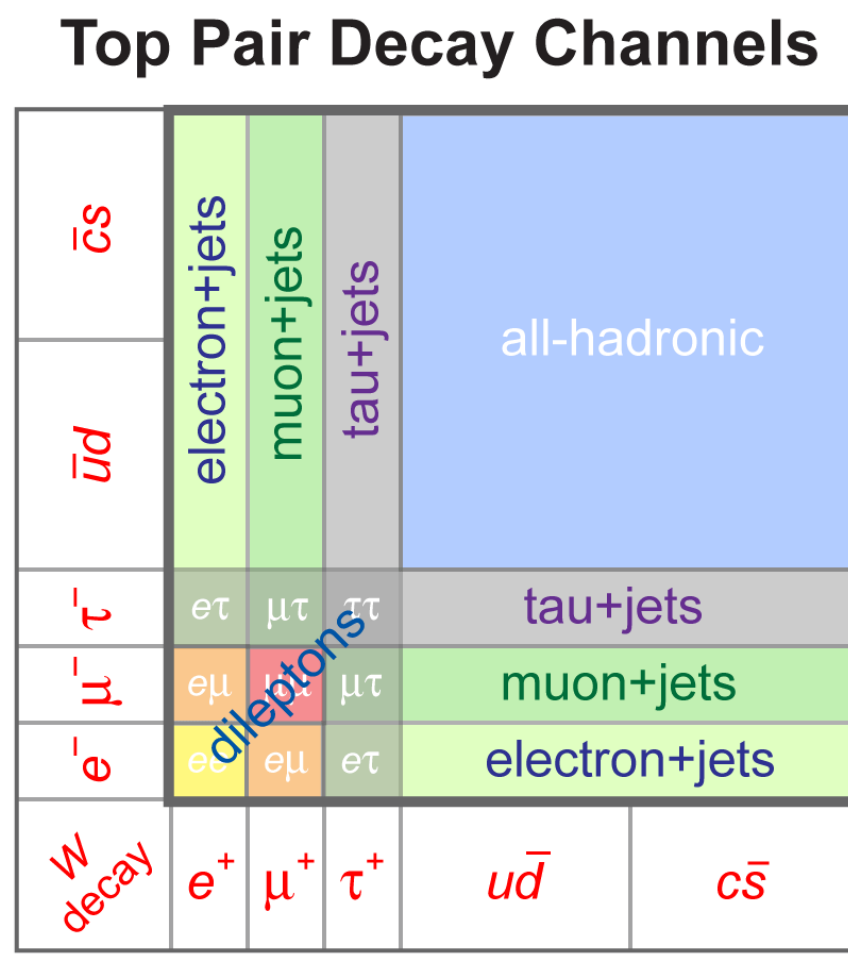


Sophisticated algorithms mostly exploit observables based on lifetime

Leptons in $t\bar{t}$



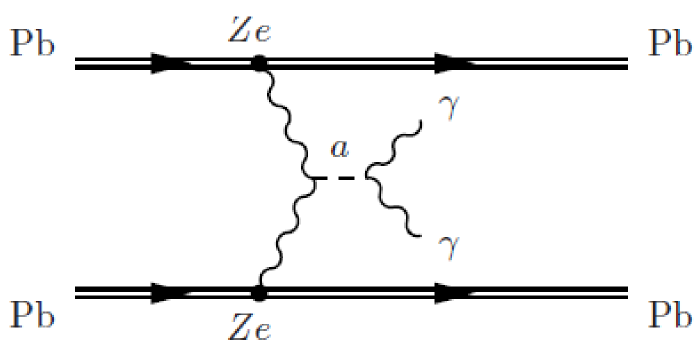
- Long-lived charged leptons (i.e., electron and muon) are rare in hadron collisions
- And they are relatively easy to discriminate from other particles
- All the largest LHC experiments have dedicated sub-detectors for electron and muon identification
- Selecting 1 or 2 high-momentum leptons per event rejects most of the backgrounds



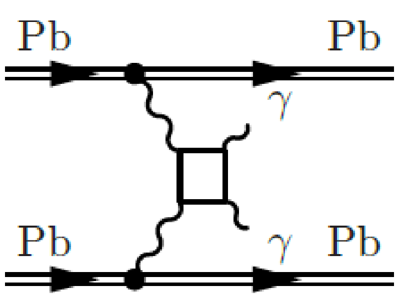
BR(W→eν) = BR(W→μν) ~ 1/9

Axion-like particles: expectations

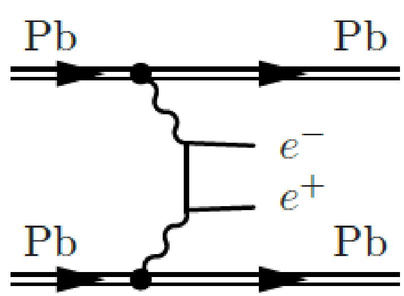
Signal:

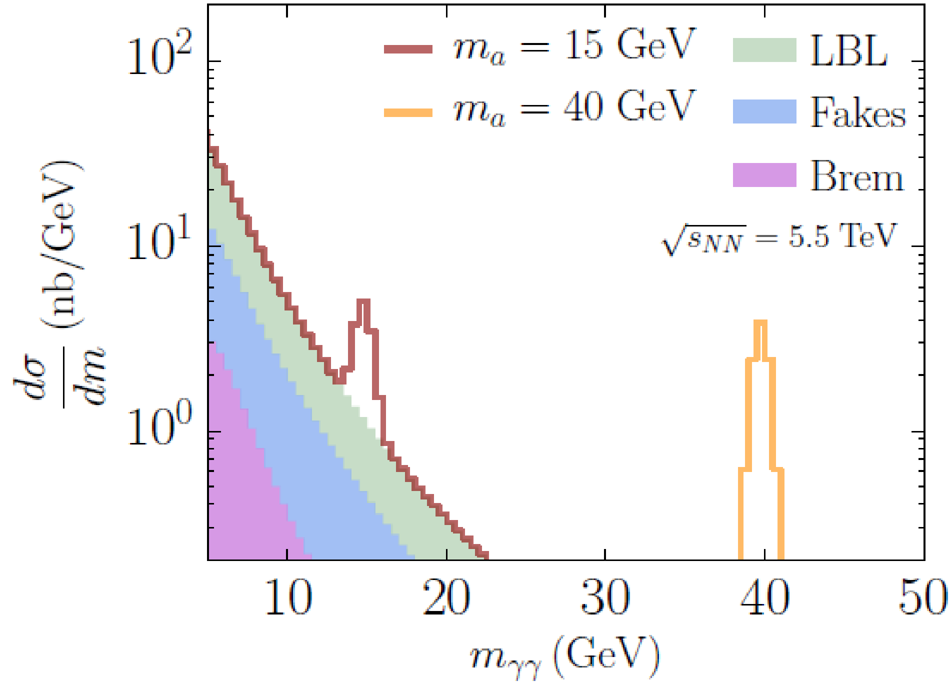


Light-by-light (LBL) scattering:



Fakes:





Knapen, Lin, Lou, Melia, Phys.Rev.Lett. 118 (2017) 171801

Axion-like particles: expectations

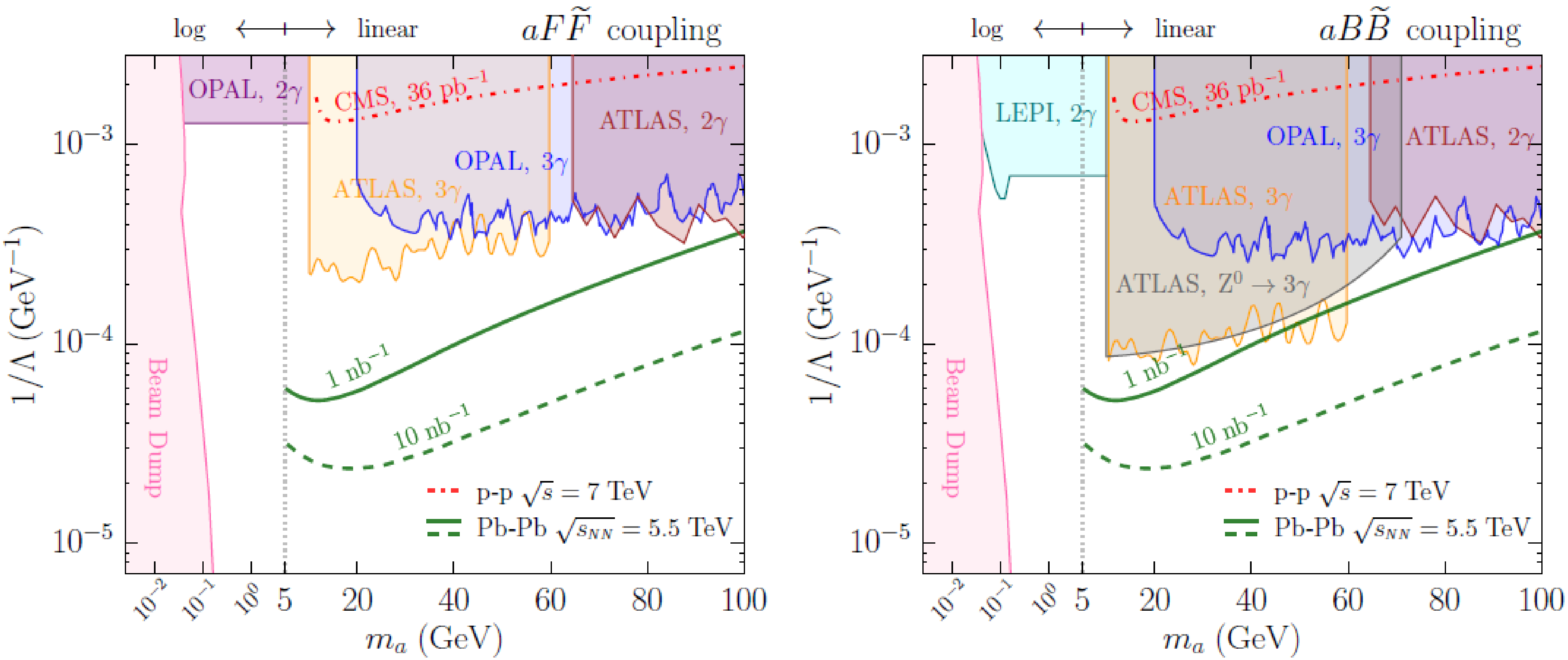
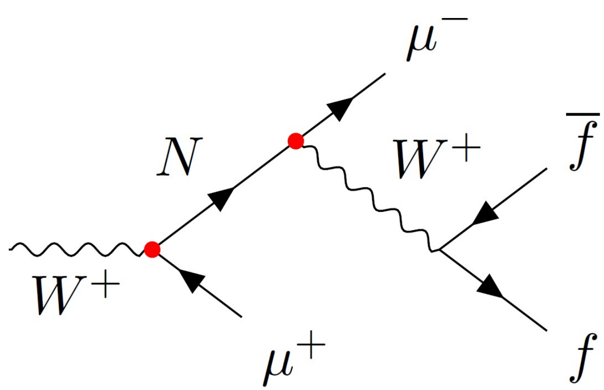


FIG. 4. *Left:* Expected sensitivity to the operator $\frac{1}{4}\frac{1}{\Lambda}aF\tilde{F}$ in heavy-ion UPCs at the LHC (green solid and dashed curves, for a Pb-Pb luminosity of 1 nb^{-1} and 10 nb^{-1}, respectively). Shown for comparison is the limit from 36 pb^{-1} of exclusive p-p collisions [25] (red dot-dash). New and updated exclusion limits from LEPII (OPAL 2γ, 3γ) [35] and from the LHC (ATLAS 2γ, 3γ) [36, 37] are indicated by the various shaded regions (see text). *Right*: The analogous results for the operator $\frac{1}{4\cos^2\theta_W}\frac{1}{\Lambda}aB\tilde{B}$. The LEPI, 2$\gamma$ (teal shaded) region is taken from [38].

Knapen, Lin, Lou, Melia, Phys.Rev.Lett. 118 (2017) 171801

Another N production mechanism



- Heavier N can be produced
- Much harder muon spectrum than B decay case → lower thresholds give little advantage
- We didn't consider the HI advantage in primary vertex assignment
- ArAr fares worse than pp, but „just“ by one order of magnitude; interesting cross check?

One month of LHC running:

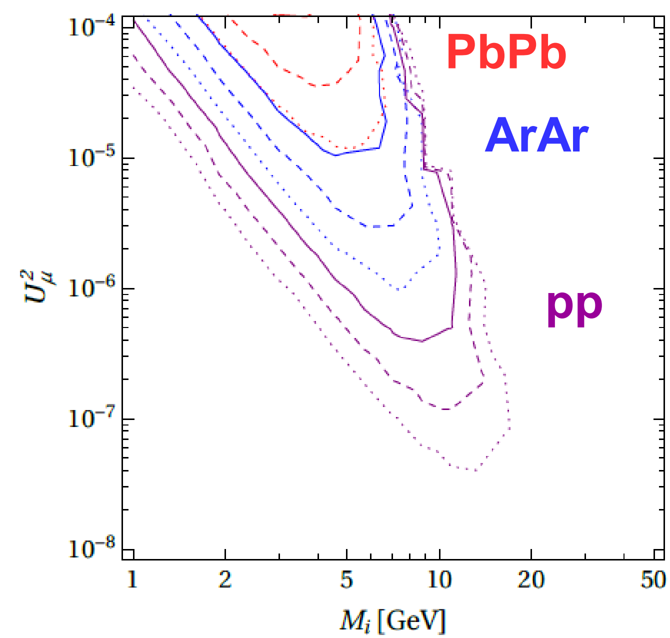


Figure 3: CMS reach for pp (purple), ArAr (blue), and PbPb (red) with equal running time corresponding to a luminosity of 5.4×10^4, 2.77 and $10^{-2}\,\mathrm{pb}^{-1}$, respectively. The solid, dashed and dotted curves correspond to 10, 30 and 100 signal events, respectively.

M. Drewes, A.G., J. Hajer, M. Lucente, O. Mattelaer, arXiv:1810.xxxx