Hunting for new Physics at the LHC

Run 2 and Future Prospects

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European School of High Energy Physics
Évora, 6th - 19th Sep. 2017

Outline

- How did we arrive to the LHC?
- Where do we {stand,go}?
- Experimental signatures and challenges in the hunt for new physics

Where do we {stand, go} ?

O(4%) of the pieces identified

O(96%) to be found

(c) Todd McLellan

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \rightarrow \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \rightarrow tt$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	$1\ e, \mu$	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \rightarrow WV \rightarrow qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \rightarrow tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e, μ	$\geq$1 b, $\geq$1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \rightarrow Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	1705.10751
	VLQ $TT \rightarrow Wb + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \rightarrow Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	1409.5500
	VLQ $BB \rightarrow Wt + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \rightarrow WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Should the new physics scale be at the LHC reach?

- K^0, D^0, B^0, B^0_s mass splittings yield tight constraints on new physics contributions

$$\delta\mathcal{L} = \frac{z_{qq'}}{\Lambda^2}\left(\bar{q}_L\gamma_\mu q'_L\right)^2 \Rightarrow \frac{\Delta m_h}{m_h} \sim \frac{|z_{qq'}|}{3}\left(\frac{f_h}{\Lambda}\right)^2$$

- If <u>flavour structure is trivial</u> (z~1)

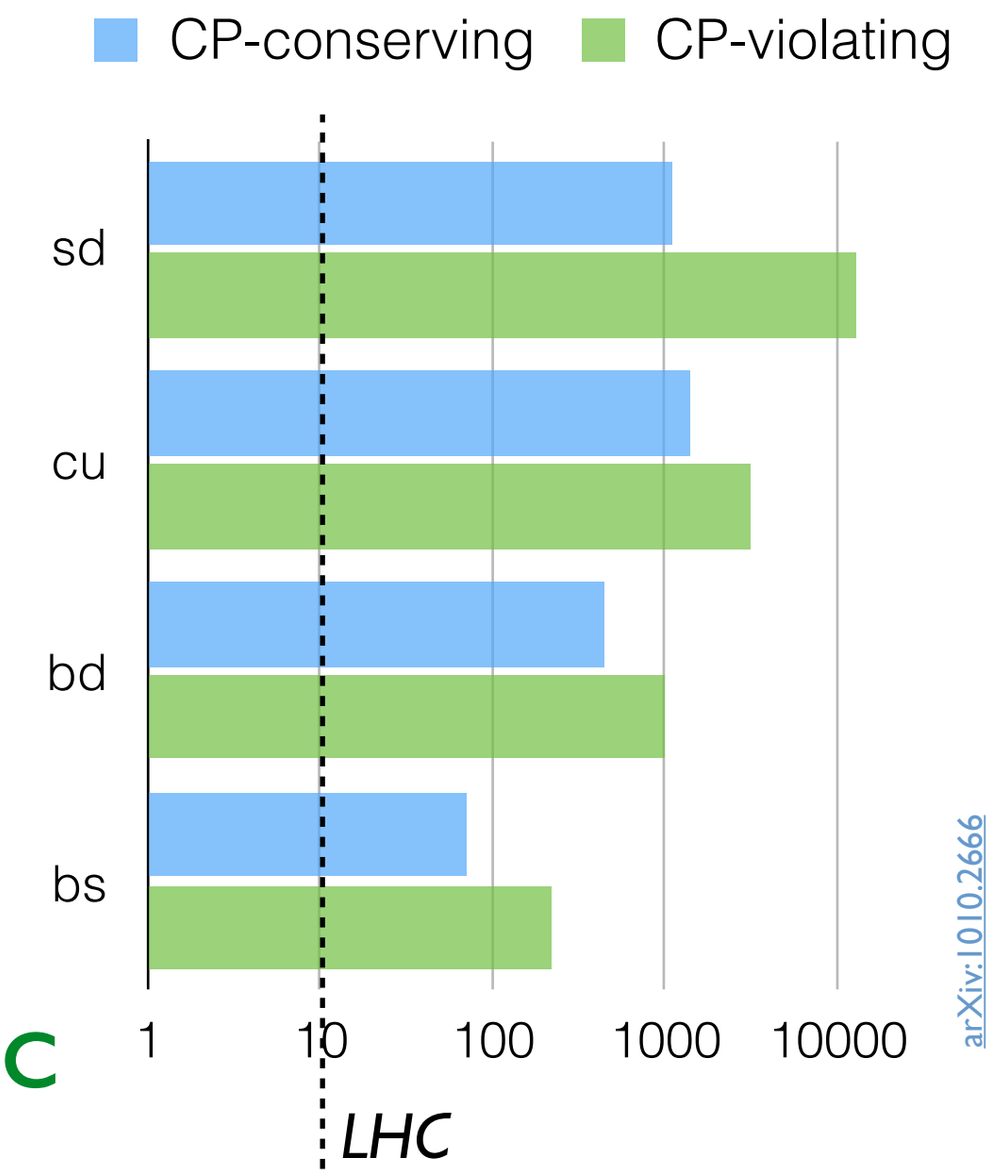
  $\Lambda \gtrsim$ O(100 TeV)

  ⇒ only glimpses of NP observed at the LHC?

- If <u>Λ ~ O(1 TeV)</u>

  NP flavour structure is far from trivial

  ⇒ flavour measurements are good probe of NP



Both cases ⇒ higher precision at the LHC

Searching for subtle NP effects in data

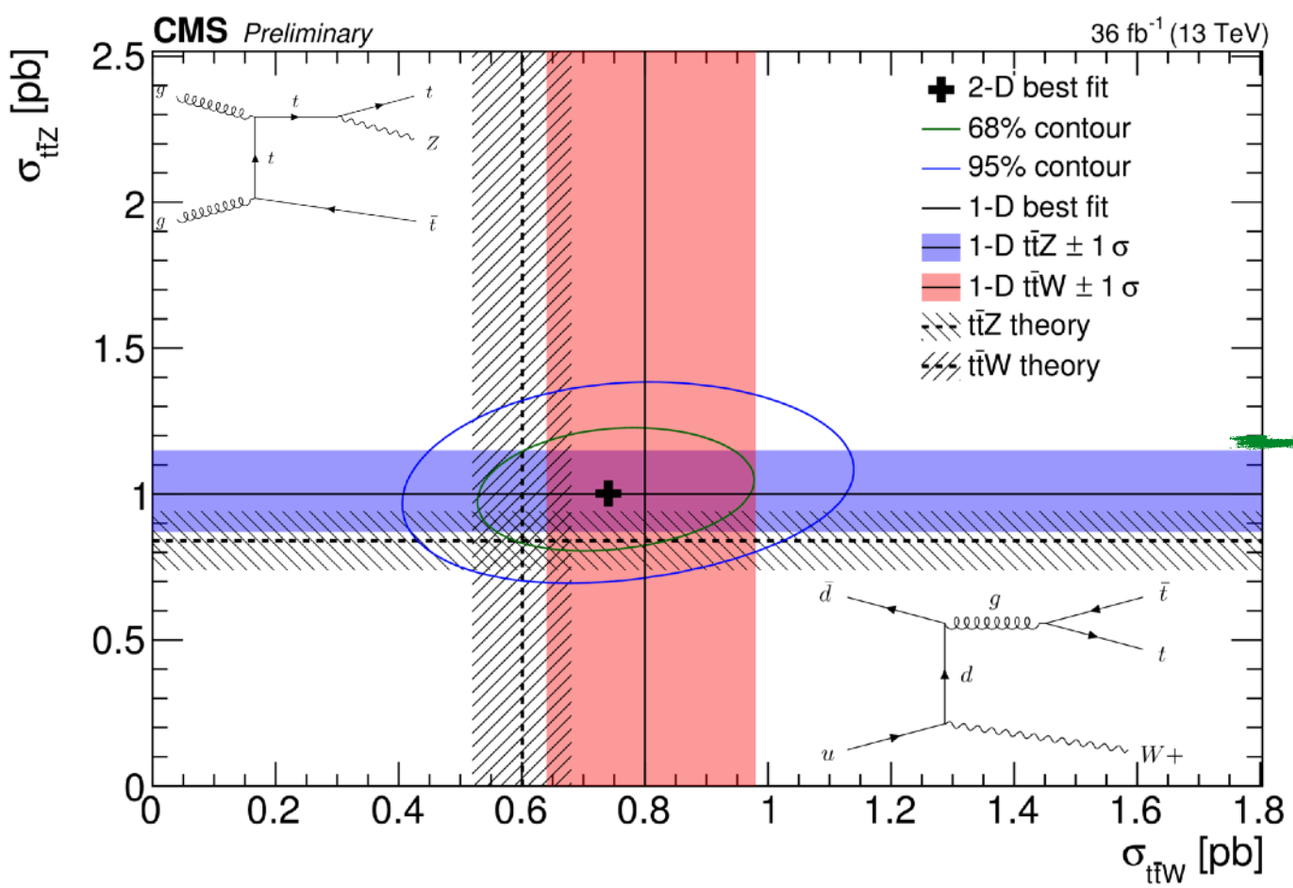
- **If the energy probed does not yet resolve the mass of the new particles**
  - look for deviations induced by Fermi-like interactions

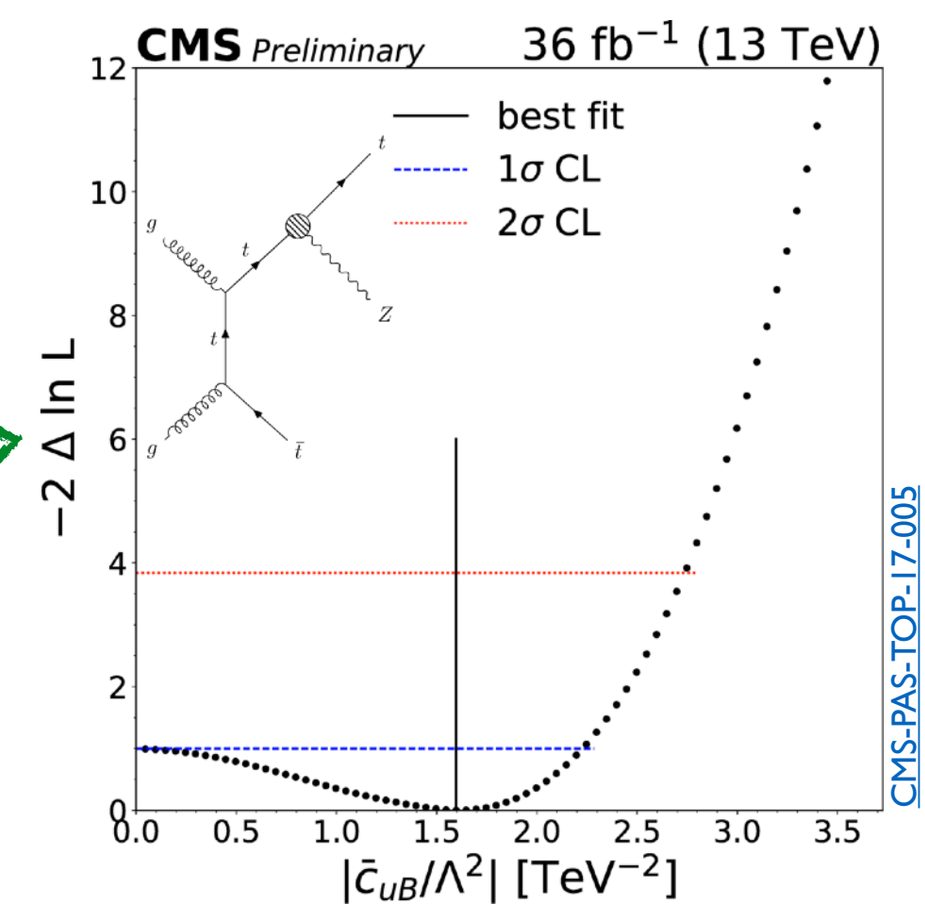
$$\delta\mathcal{L} = \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right) \longrightarrow \delta\sigma = \sum \frac{c_i^2}{\Lambda^2}\sigma_i + \sum \frac{c_i c_j}{\Lambda^4}\sigma_{ij} + \ldots$$

interference with the SM expectations

pure NP contribution although suppressed by $1/\Lambda^4$ may be non-negligible!

- **Several start moving in the direction of a a global scan of allowed NP contributions**

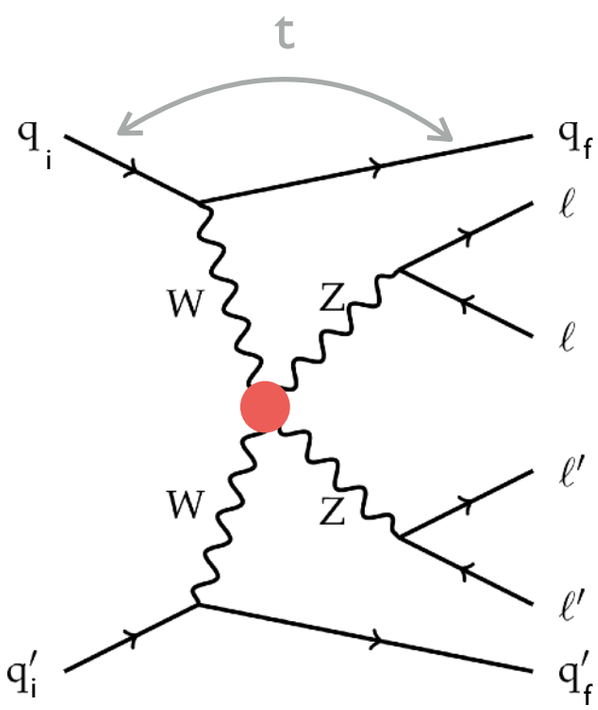




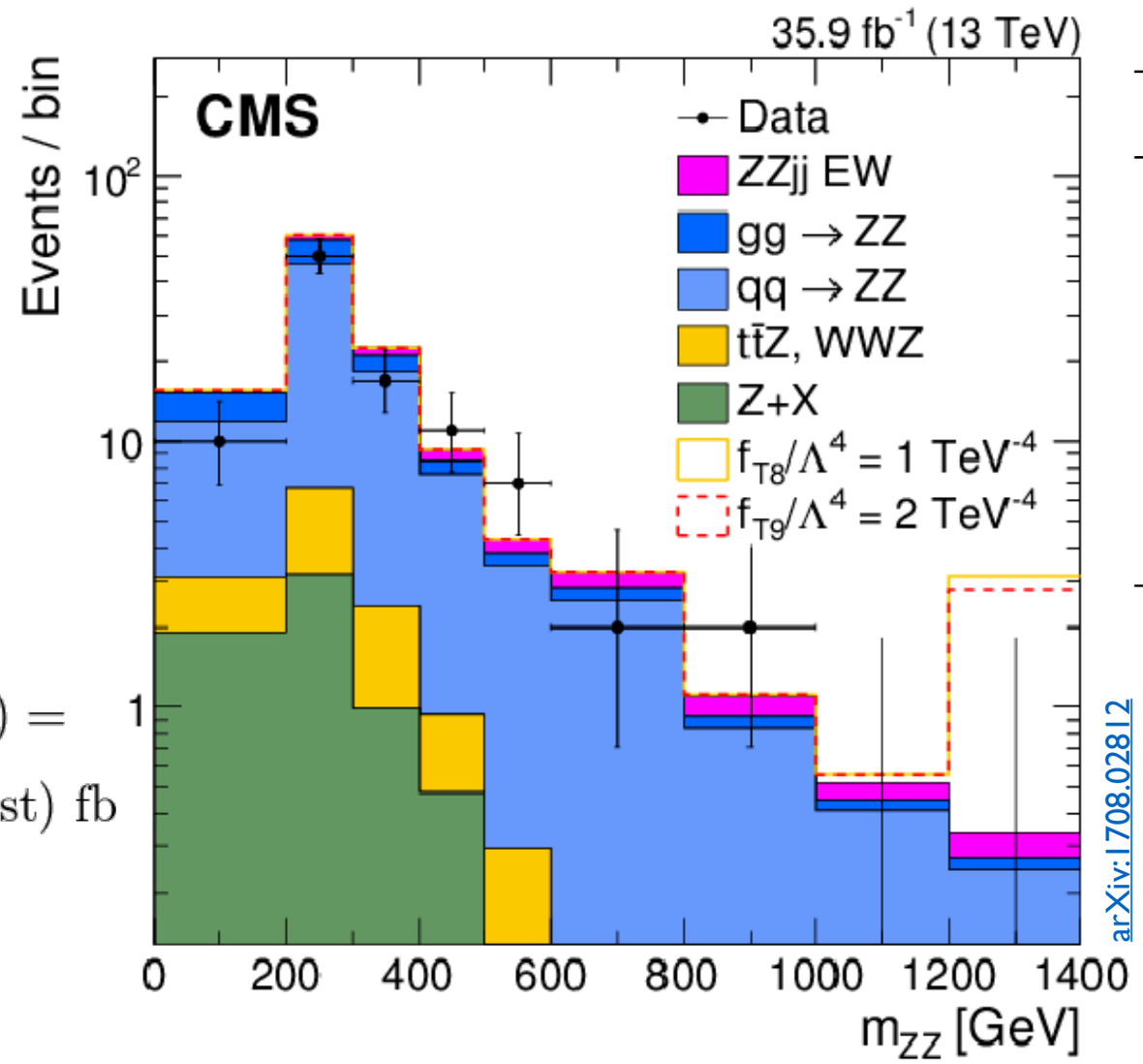
CMS-PAS-TOP-17-005

Boson scattering and anomalous couplings

- Boson scattering topologies start complementing the sensitivity to anomalous couplings
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: $t = (q_i - q_f)^2 = -2|\vec{q}_i||\vec{q}_f|\,(1-\cos\theta) \Rightarrow \Delta\eta \gg 1$



$$\sigma_{\rm EW}(pp \to ZZjj \to 4\ell jj) = 0.40^{+0.21}_{-0.16}({\rm stat})^{+0.13}_{-0.09}\ ({\rm syst})\ {\rm fb}$$



arXiv:1708.02812

Coupling	Exp.	Obs.
f_{T0}/Λ^4	[-0.53,0.51]	[-0.46,0.44]
f_{T1}/Λ^4	[-0.72,0.71]	[-0.61,0.61]
f_{T2}/Λ^4	[-1.4,1.4]	[-1.2,1.2]
f_{T8}/Λ^4	[-0.99,0.99]	[-0.84,0.84]
f_{T9}/Λ^4	[-2.1,2.1]	[-1.8,1.8]

find details on f_{Ti} in arXiv:hep-ph/0606118

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  - note: unitarity bounds are however strict on possible new physics contributions
  - decomposing the amplitude in partial waves (S, P, etc.)

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

$$\hat{\sigma} = \frac{16\pi}{\hat{s}} \sum_{l=0}^{\infty} (2l+1)|a_l|^2 \longleftrightarrow \hat{\sigma} = \frac{1}{\hat{s}} \mathrm{Im}\left[A(\theta=0)\right]$$

optical theorem

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- contributions to each wave are therefore limited to

$$|\mathrm{Re}(a_l)| < \frac{1}{2}$$

unitarity bounds ~2-3 TeV
(~10^{-4} smaller than current limits)

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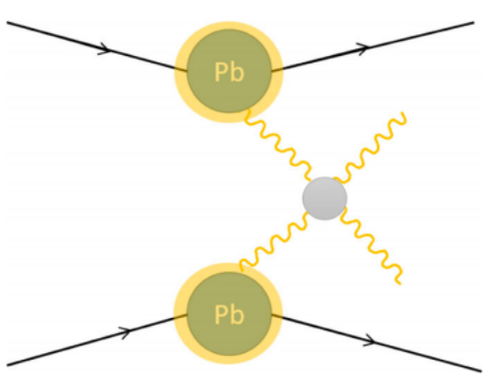
  - consider also central exclusive WW production, light-by-light scattering (PbPb)

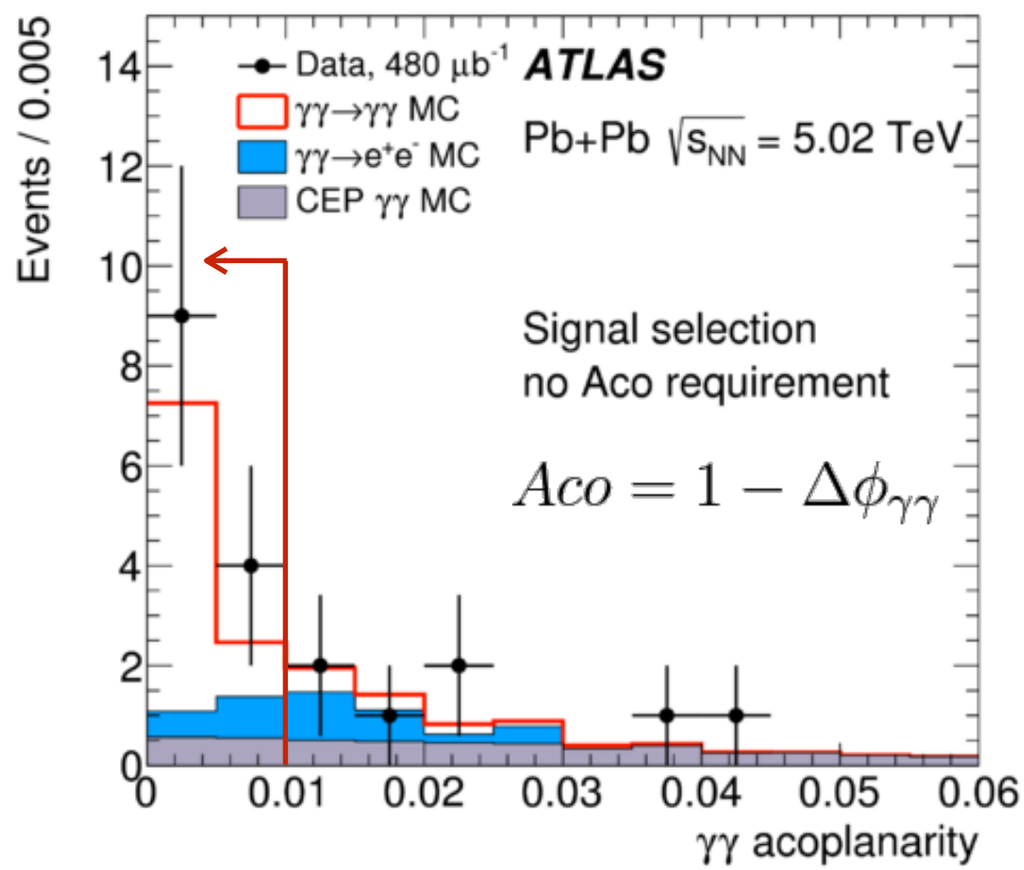
$$\sigma(PbPb(\gamma\gamma) \to Pb^* Pb^* \gamma\gamma) = 70 \pm 24_{\text{stat}} \pm 17_{\text{syst}} \text{ nb}$$

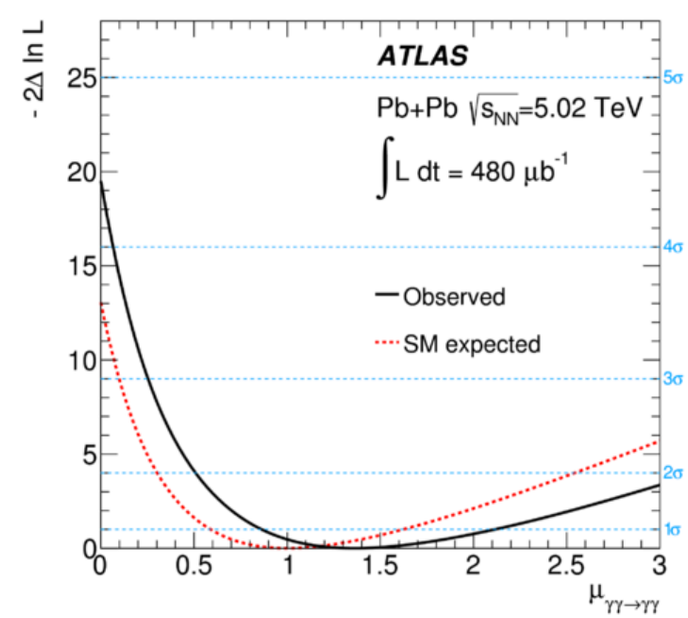
In classic electrodynamics

- Maxwell equations are linear
- fields can super-impose

Scattering driven by quantum loops







Nat Phys (2017)

Boson scattering and anomalous couplings

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  - consider also central exclusive WW production, light-by-light scattering (PbPb)

In classic electrodynamics

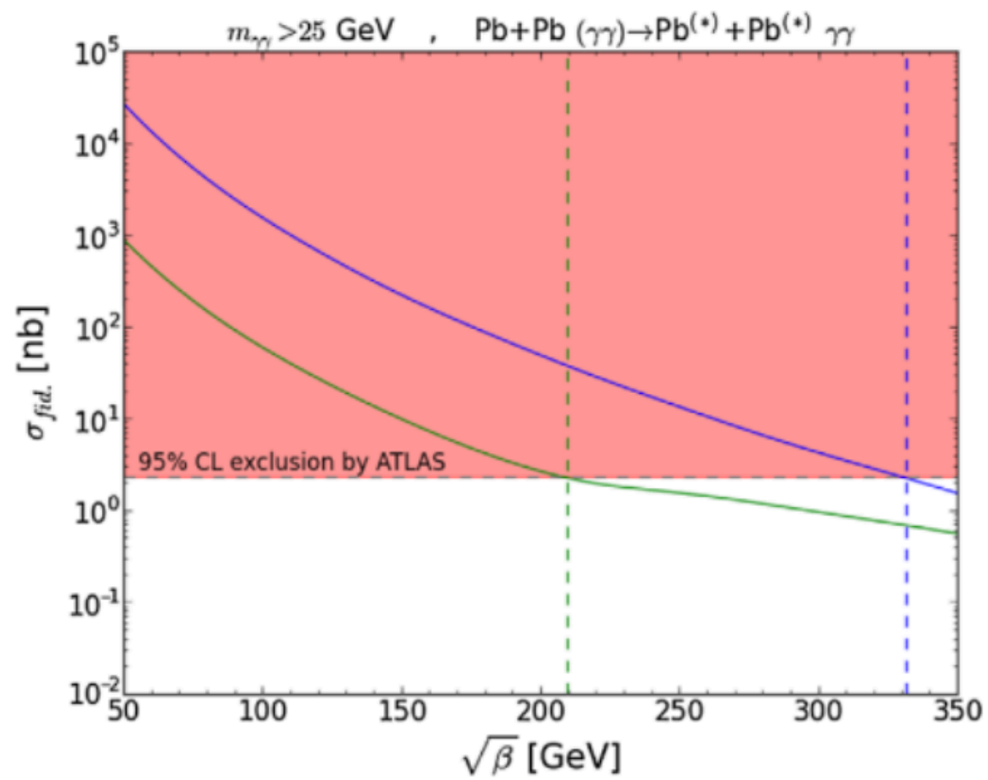
- Maxwell equations are linear
- fields can super-impose

Unless there is new physics

- e.g. massive-like contribution
- leads to different acoplanarity

Search for B-I monopoles at the LHC

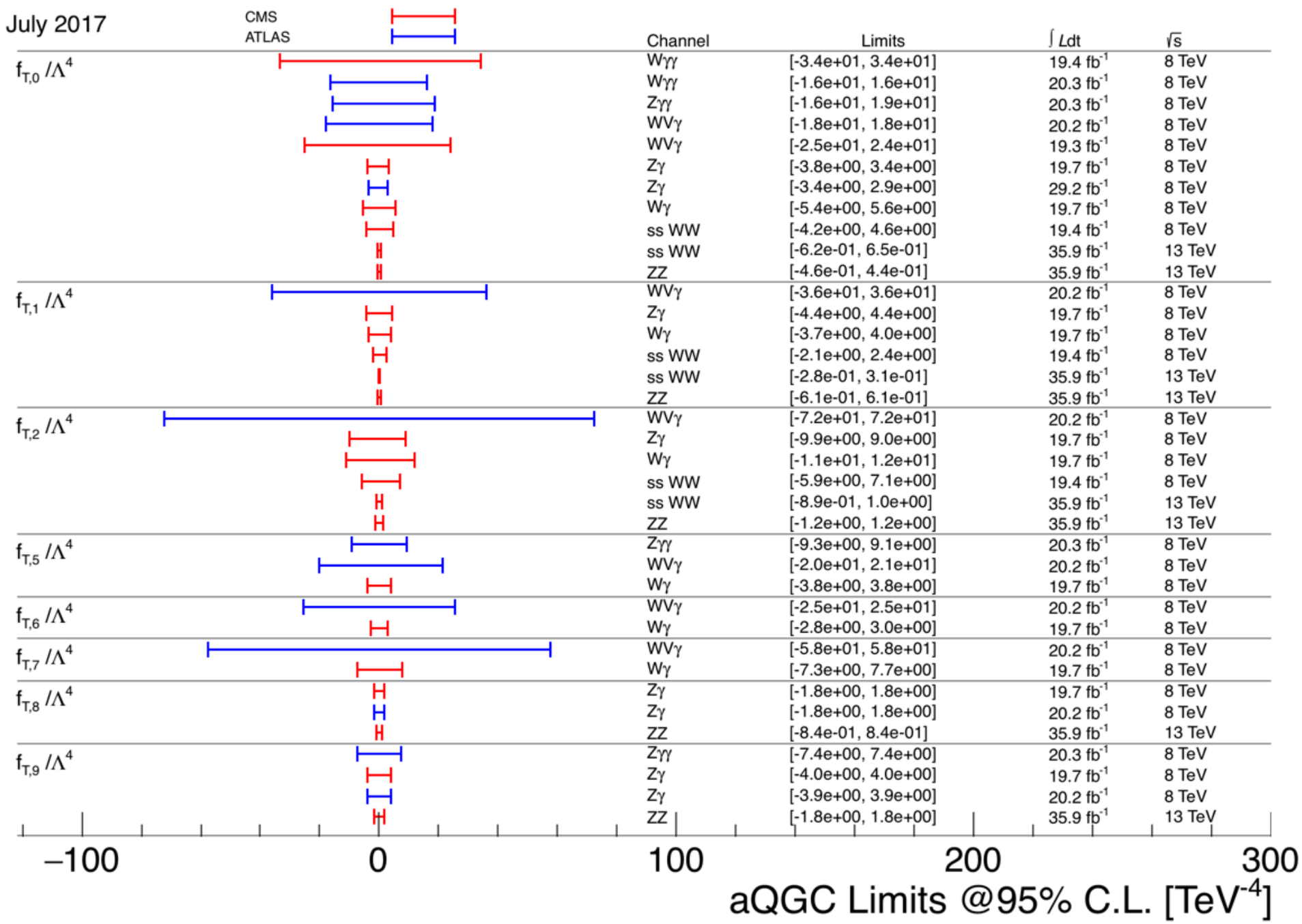
- $M_{\mathcal{M}}$>11 TeV



Phys. Rev. Lett. 118, 261802

$$\delta\mathcal{L}_{\text{Born-Infeld}} = \beta^2\left[1-\sqrt{1+\frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu}-\frac{1}{16\beta^4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2}\right]$$

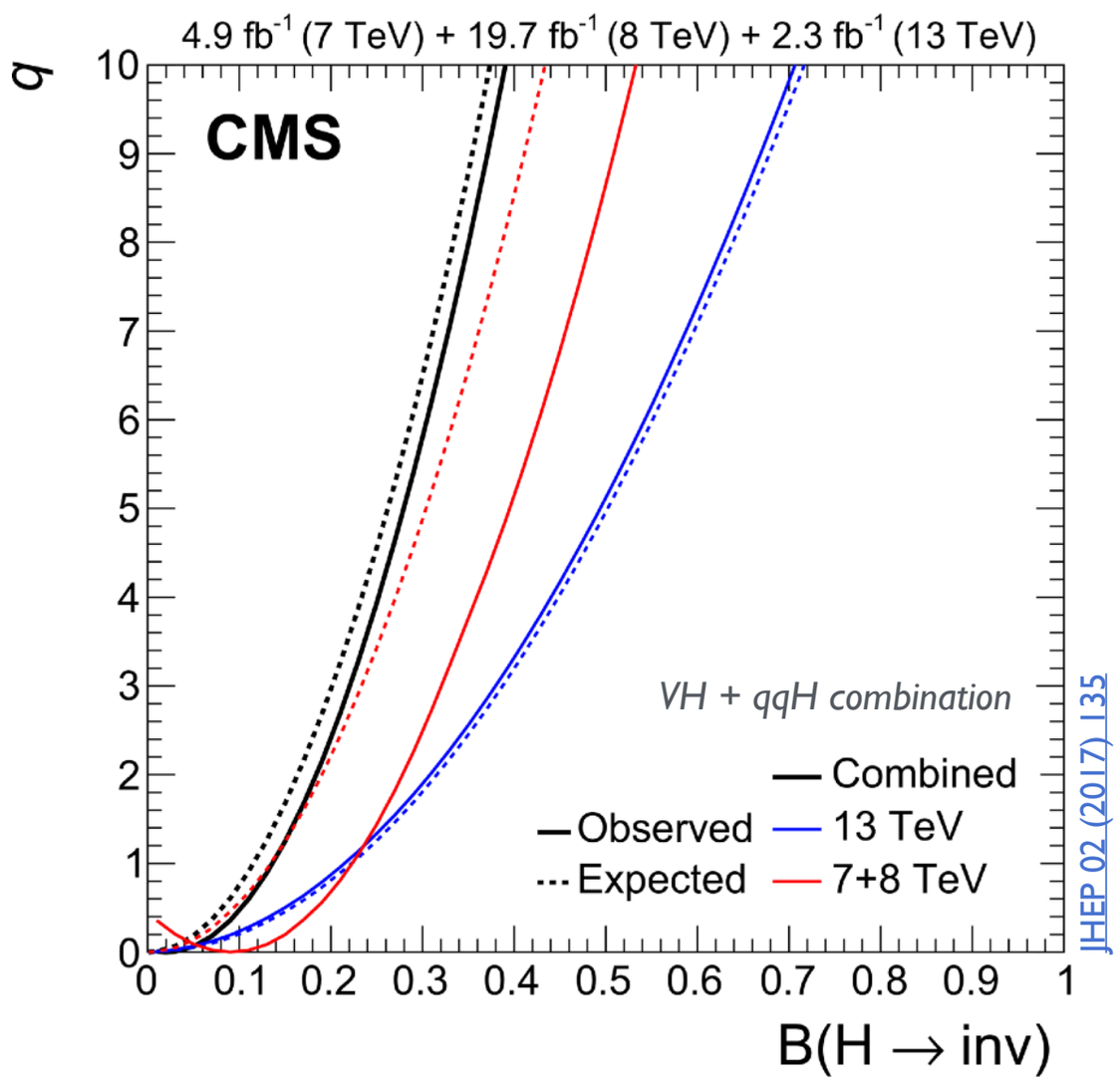
Limits on gauge couplings

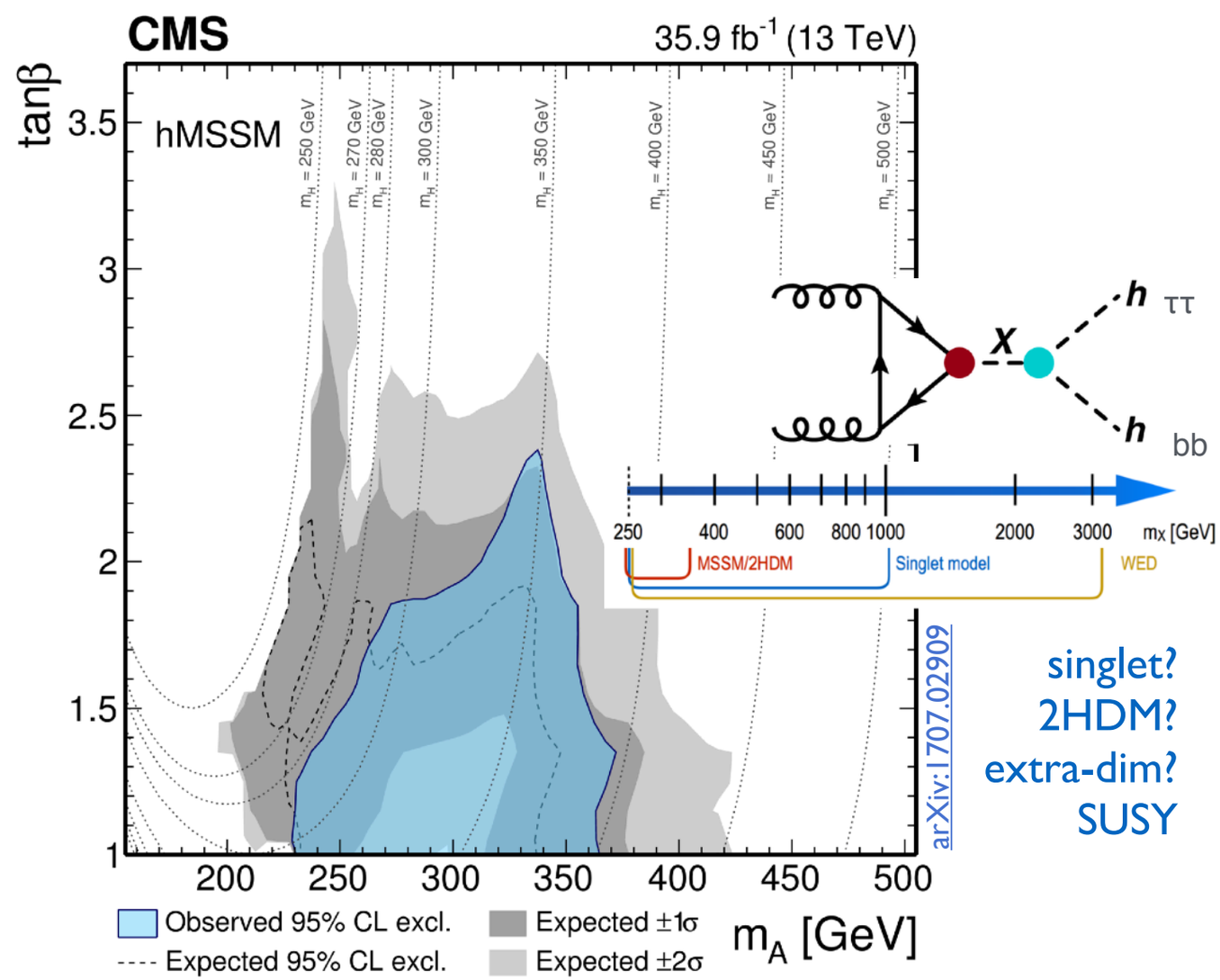


- Extensive summaries of triple, quartic gauge couplings available @ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Higgs as a portal

- **Still a (experimental) large room for invisible Higgs decays: BR<0.24 @ 95%CL**
  - significant changes in this BR could be due to new neutral particles : dark matter?
- **It may also be that the Higgs sector is more complex and accompanied by partners**
  - resonant associated (VH) and hh production, high-mass diboson resonances, ….





singlet?
2HDM?
extra-dim?
SUSY

Dark matter and Higgs

- **The limits on the invisible BR of the Higgs can be re-casted to limits dark matter production**

$$\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2},$$

$$\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}.$$

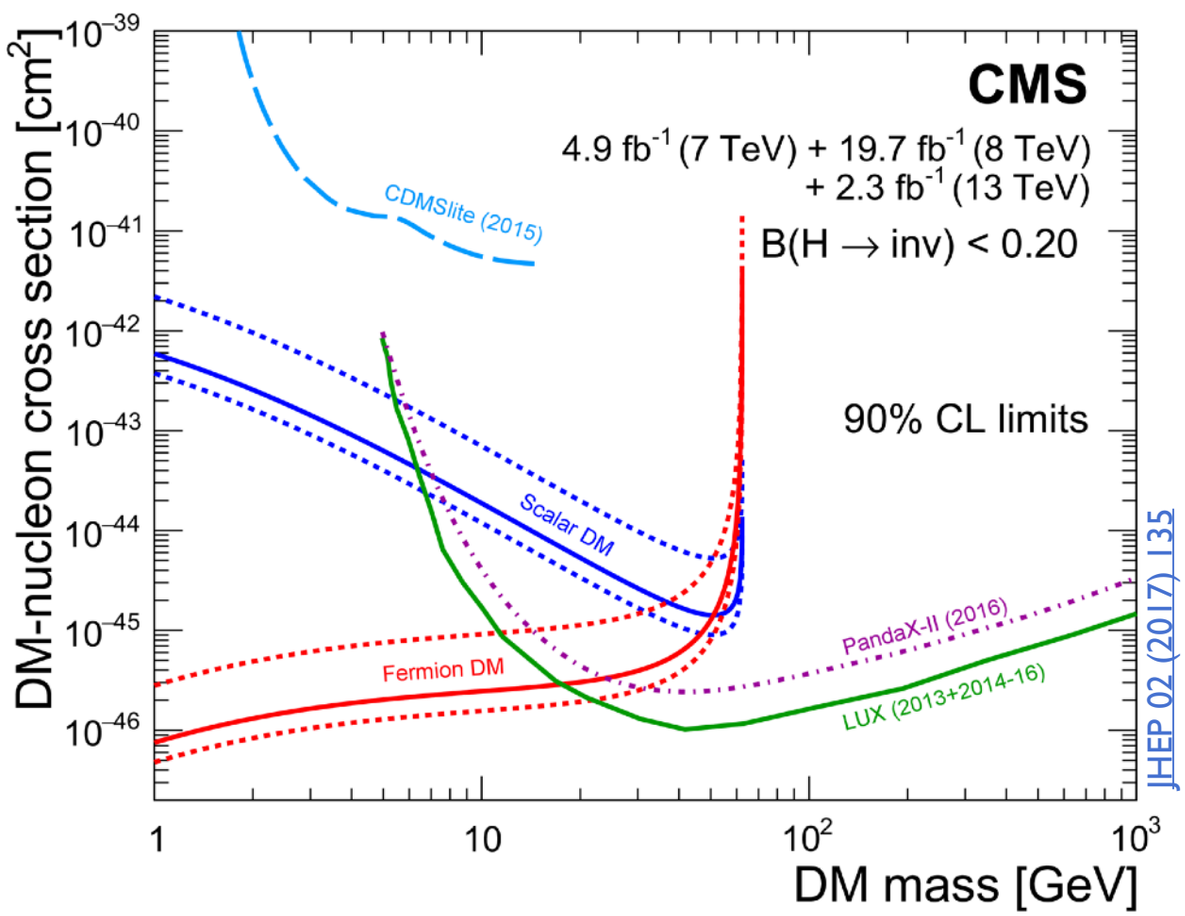
m_N - nucleon mass ~0.939 GeV
$v=246/\sqrt{2}$ GeV (vev)
f_N~0.326 central value for coupling (from lattice*)

$\beta = \sqrt{1 - 4M_\chi^2/m_H^2}.$

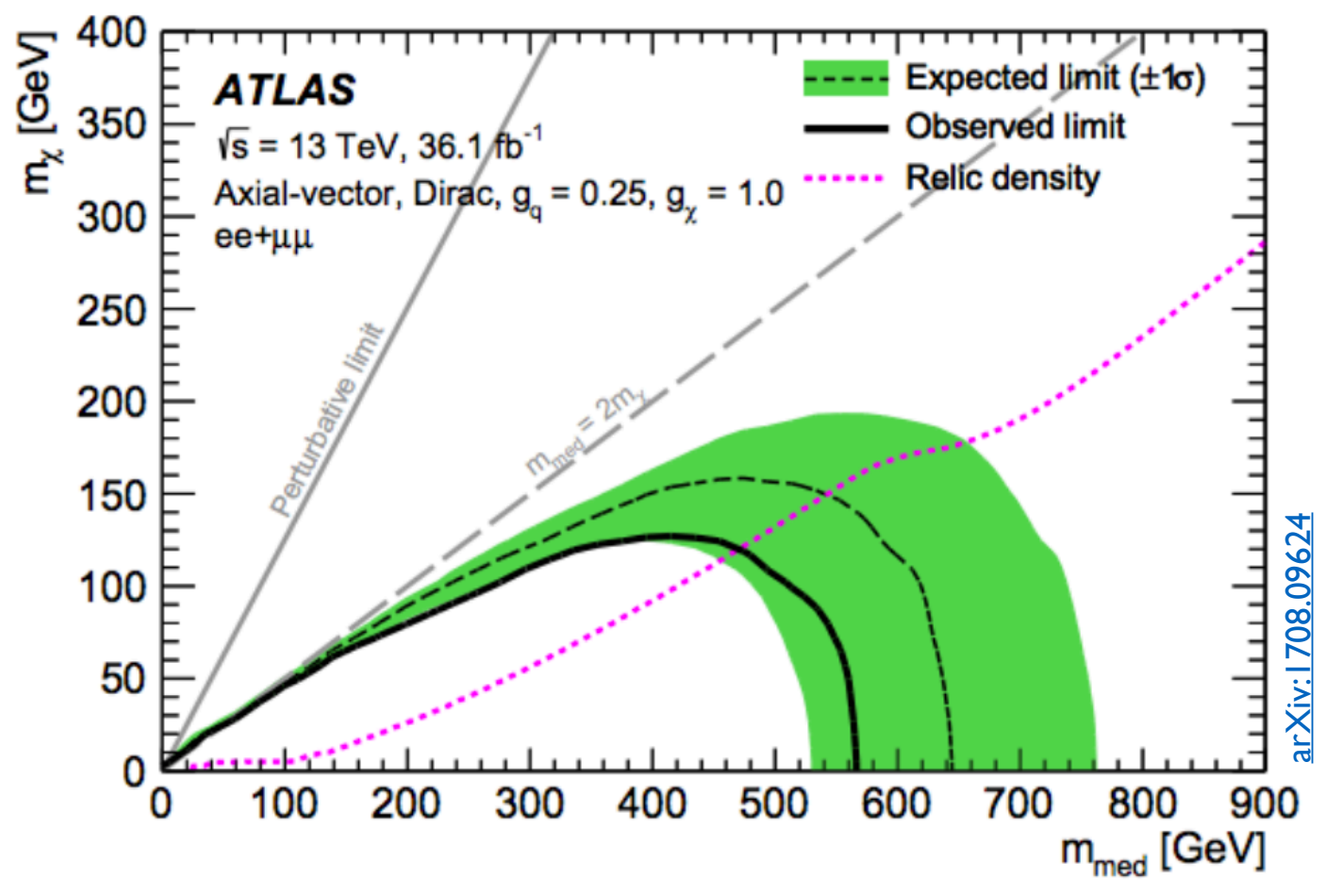
$\Gamma_{inv} = \Gamma_{SM}\, BR_{inv}/(1-BR_{inv})$

*PRD 81(2010) 014503, PRL 103(2009) 122002

- **Latest re-interpretations in terms of mediator-WIMP mass** (see CERN-LPCC-2016-001)

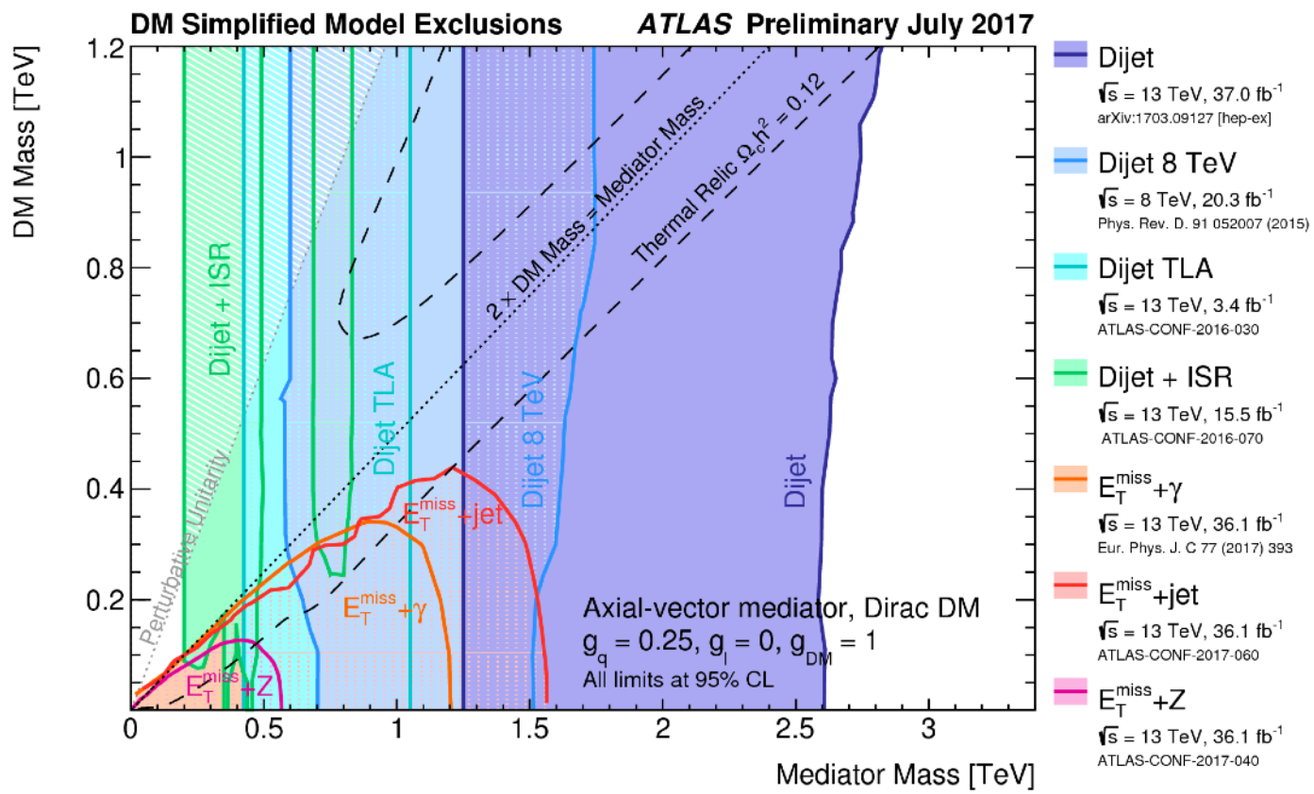


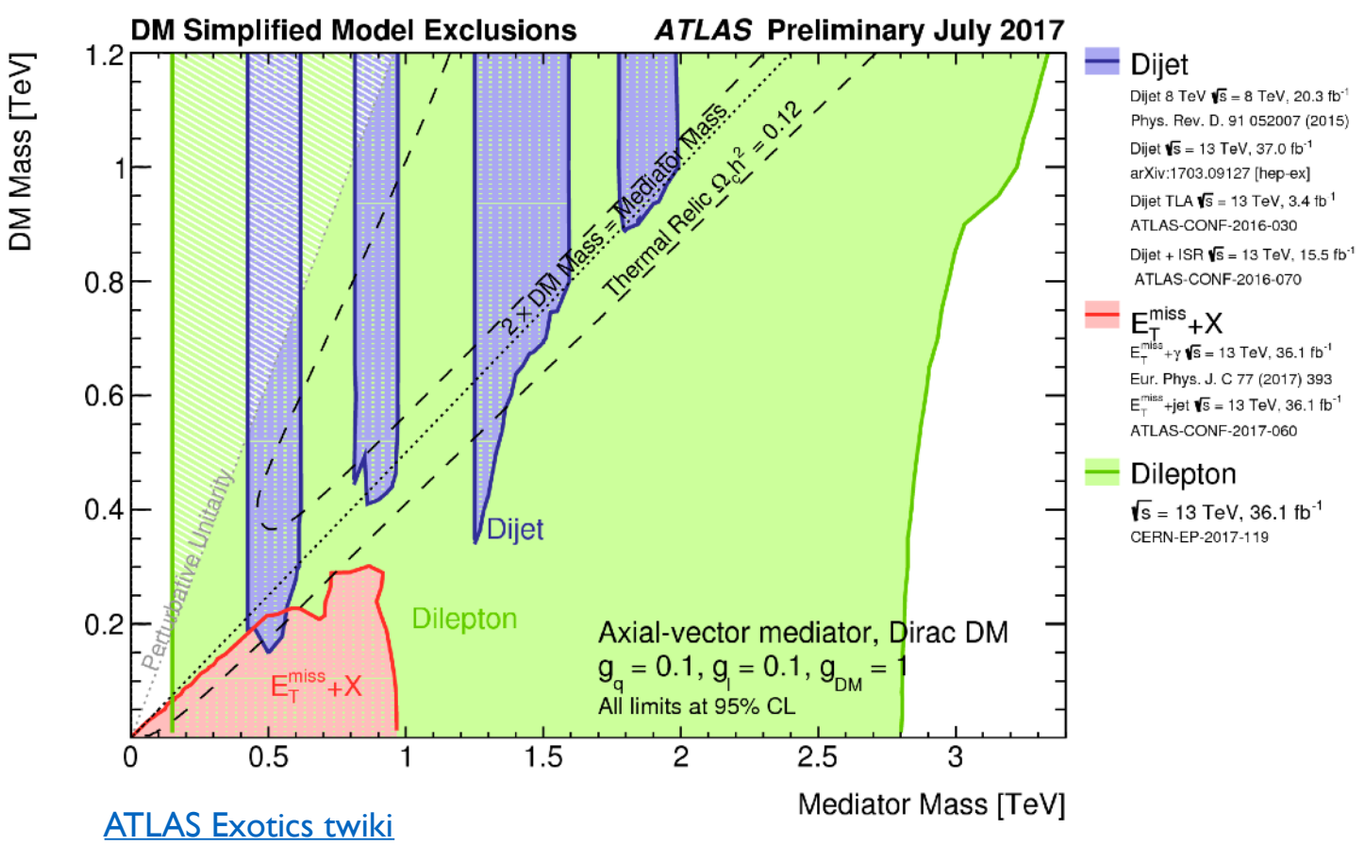
JHEP 02 (2017) 135



arXiv:1708.09624

Direct searchs for dark matter at the LHC

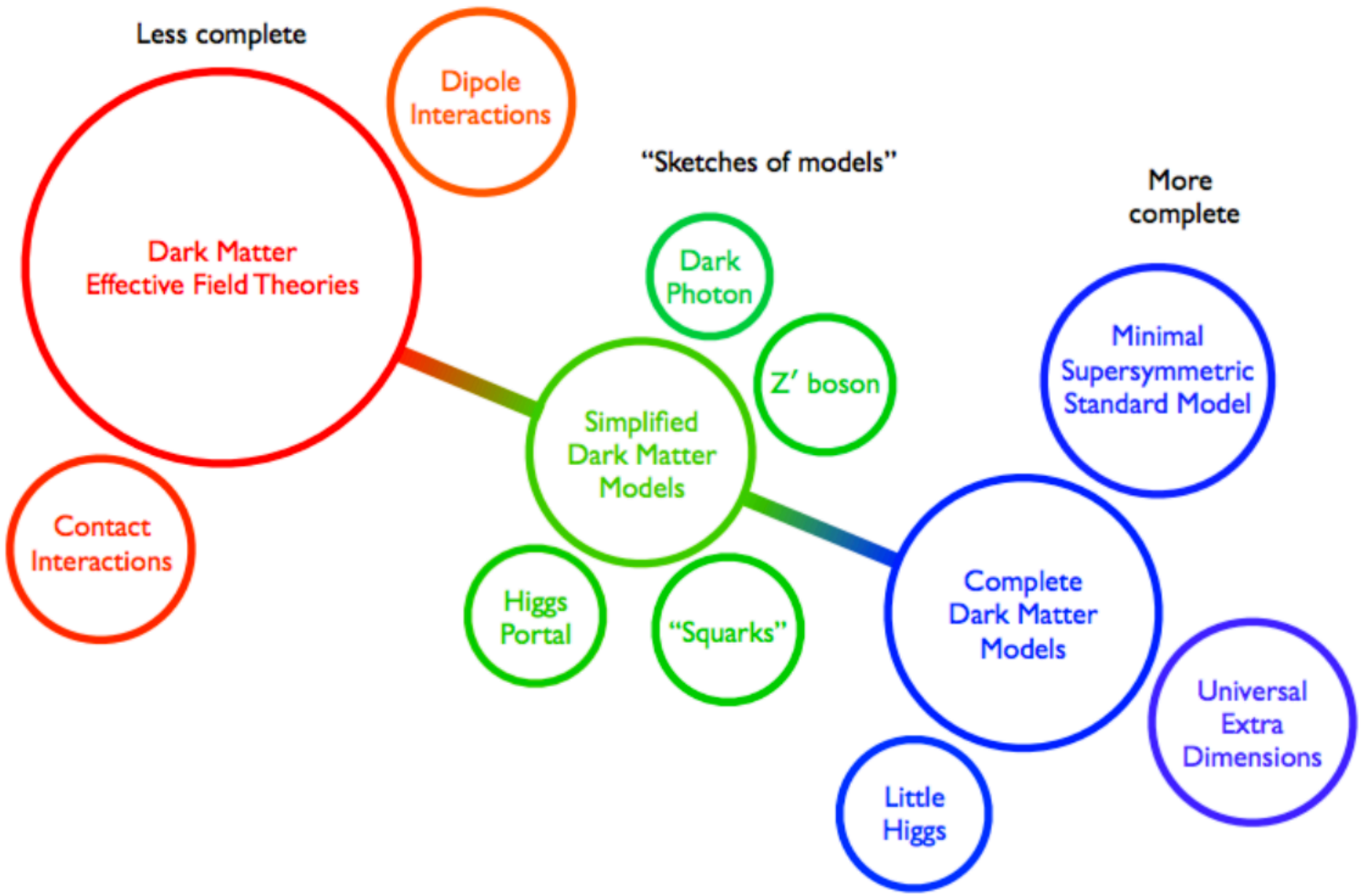




- **Wide range of searches for associated production of dark matter: mono-X, jet+ISR, top, H**
  - spin-dependent re-interpretation is unavoidable
  - nevertheless, nicely complements direct searches from dedicated experiments

ATLAS Exotics twiki

Data, models, what is the nature of BSM?



Phys. Dark Univ. 9-10 (2015) 8-23

- **Experimentalists rely on this type of model landscape to gauge their findings**
  - but the point is not so much what we plot/quote as limit
  - we want to fill in the puzzle by leaving no stone unturned

Outstanding questions

@ the dawn of the LHC

Electroweak symmetry breaking

- does the Higgs boson exist?

Dark matter

- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
- one type or more ?
- only gravitational or other interactions ?

Quarks and leptons

- why 3 families ?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Neutrinos

- ν masses, their origin - Higgs role?
- Majorana or Dirac ?
- CP violation
- additional species?
- sterile ν ?

Physics at the highest E-scales:

- how is gravity connected with the other forces ?
- do forces unify at high energy ?

Universe's accelerated expansion:

- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

adapted. from I. Shipsey @ ICHEP2016

Outstanding questions

@ middle of LHC Run 2

Electroweak symmetry breaking

- m_H natural or fine-tuned ?
- if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition

Dark matter

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- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

adapted. from I. Shipsey @ ICHEP2016

be happily unsettled and search for new physics

Experimental signatures and challenges

What do we effectively measure at the LHC?

Experimental signatures and challenges

Where theory meets experiment

What do we effectively measure at the LHC?

We count…

$$\sigma_{tot} = \frac{1}{A}\sigma_{fid} = \frac{1}{A} \cdot \frac{N_{signal}}{\mathcal{L} \cdot \varepsilon \cdot SF}$$

theory⊗experiment?

theory

acceptance $[N_{fid}/N_{tot}]_{gen}$

luminosity

efficiency $[N_{sel}/N_{gen}]_{fid}$

efficiency corrections

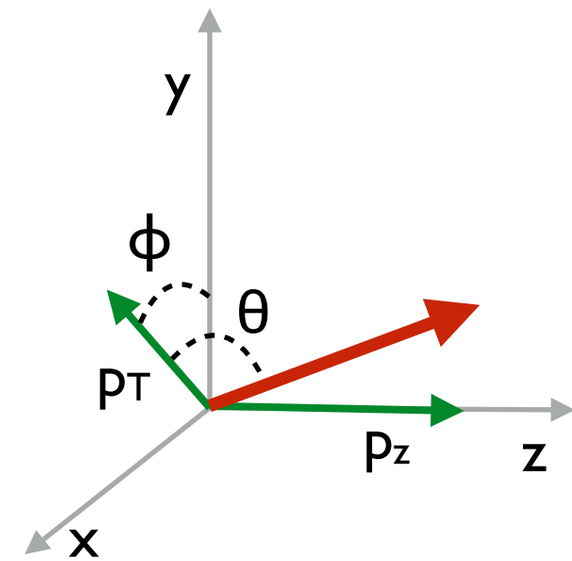
experiment

… that easy ?

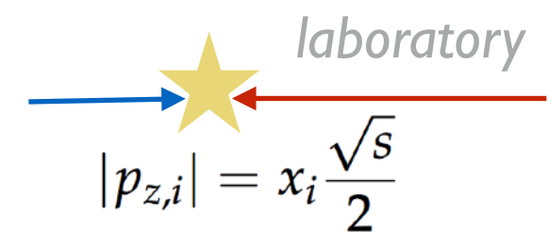
Kinematics at the LHC 101: a reminder

- **Initial longitudinal momentum of the constituents is unknown**
  - in addition many particles produced escape the acceptance of the detectors

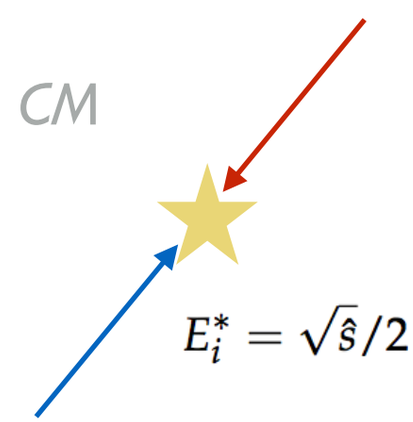
⇒ "visible" longitudinal momentum and energy are not conserved



- **Transverse quantities:** (p_T, ϕ)
  - fully reconstructed (modulo scale/resolution uncertainties)
  - it is Lorentz-invariant under transformations along z



- **Rapidity:** $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right) \overset{m<<p_T}{\rightarrow} \eta = -\ln\tan\frac{\theta}{2}$
  - it's an alternative measure of θ
  - it's additive under Lorentz transformations



$$y = y^* + y_{boost} = y^* + \frac{1}{2}\ln\left(\frac{1-\beta}{1+\beta}\right)$$

i.e rapidity distances are Lorentz-invariant

Kinematics at the LHC 101: a reminder (cont.)

- **Angular distances must therefore be expressed as function of y (or η) and ϕ**

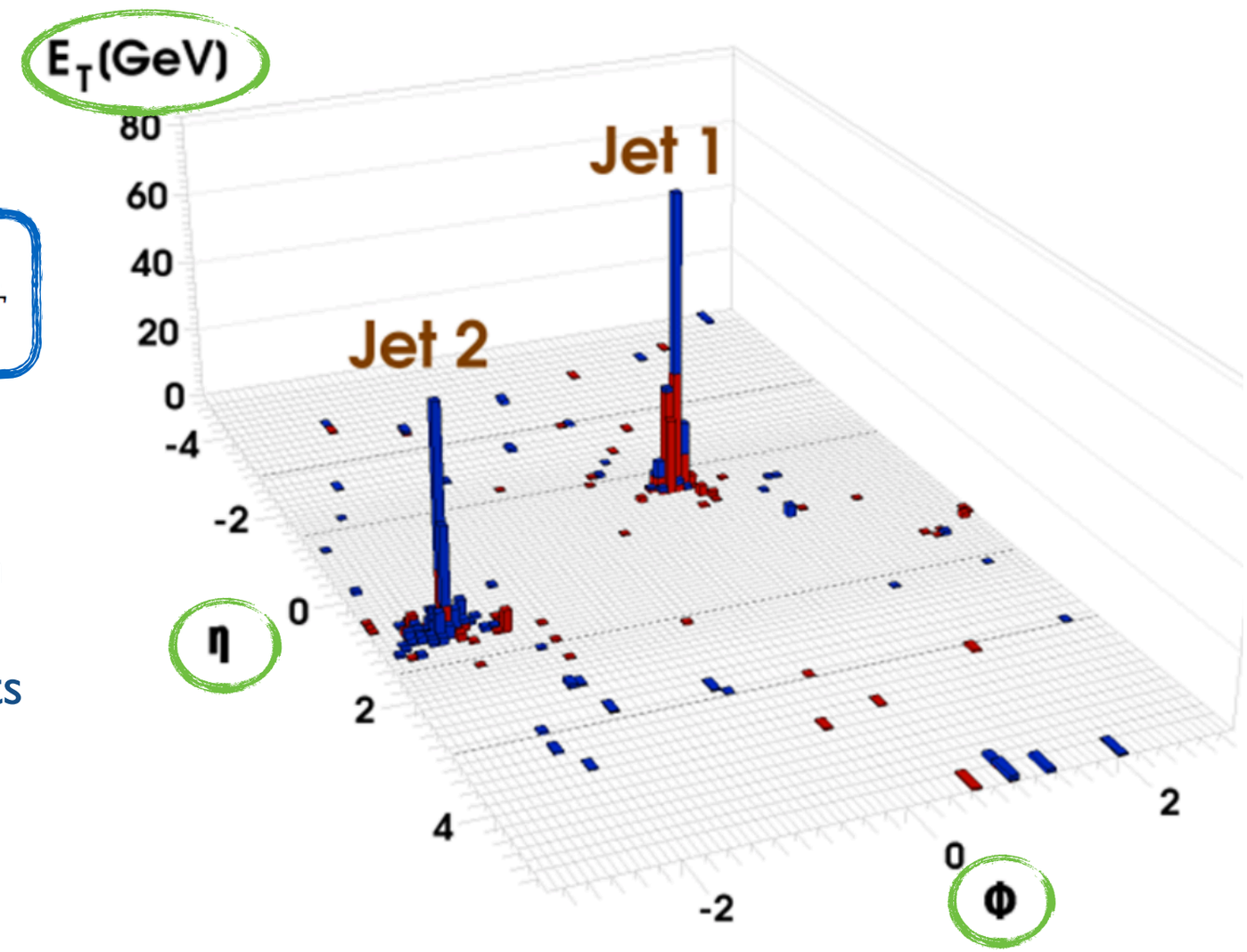
- **Four-momenta are expressed as** $(E,\ p_x,\ p_y,\ p_z) = (m_T \cosh y,\ p_T \cos\phi,\ p_T \sin\phi,\ m_T \sinh y)$
  - where the transverse mass is $m_T = \sqrt{m^2 + p_T^2}$

- **Element in kinematics phase space:**

$$\frac{d^3p}{E} = p_T dp_T\, dy\, d\phi = \pi\, dy\, dp_T^2$$

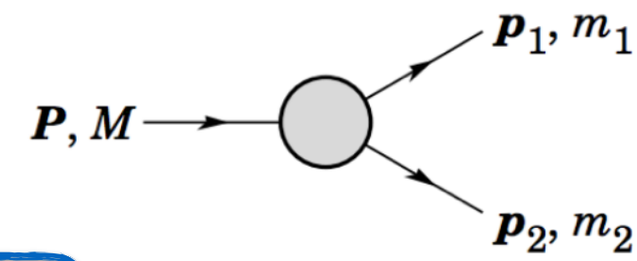
This is the basis for the representation

of the detectors and our measurements



Curious Lorentz-invariants at the LHC

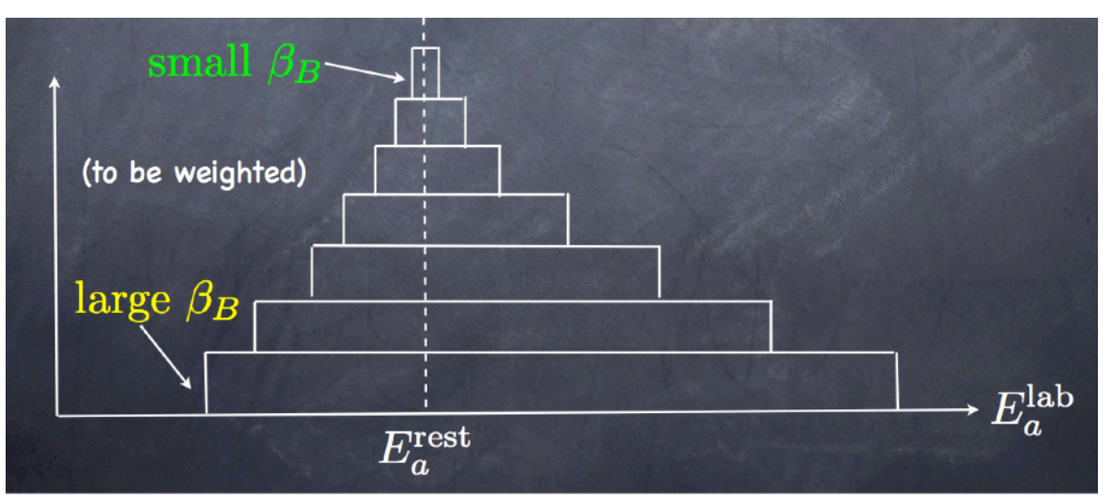
- **Although energy is not Lorentz-invariant the peak of its distribution may be**
  - consider an unpolarized two-body decay: $\pi^0 \to \gamma\gamma$, $t \to Wb$
  - expect uniform angle distribution in the rest-frame (S-wave emission)



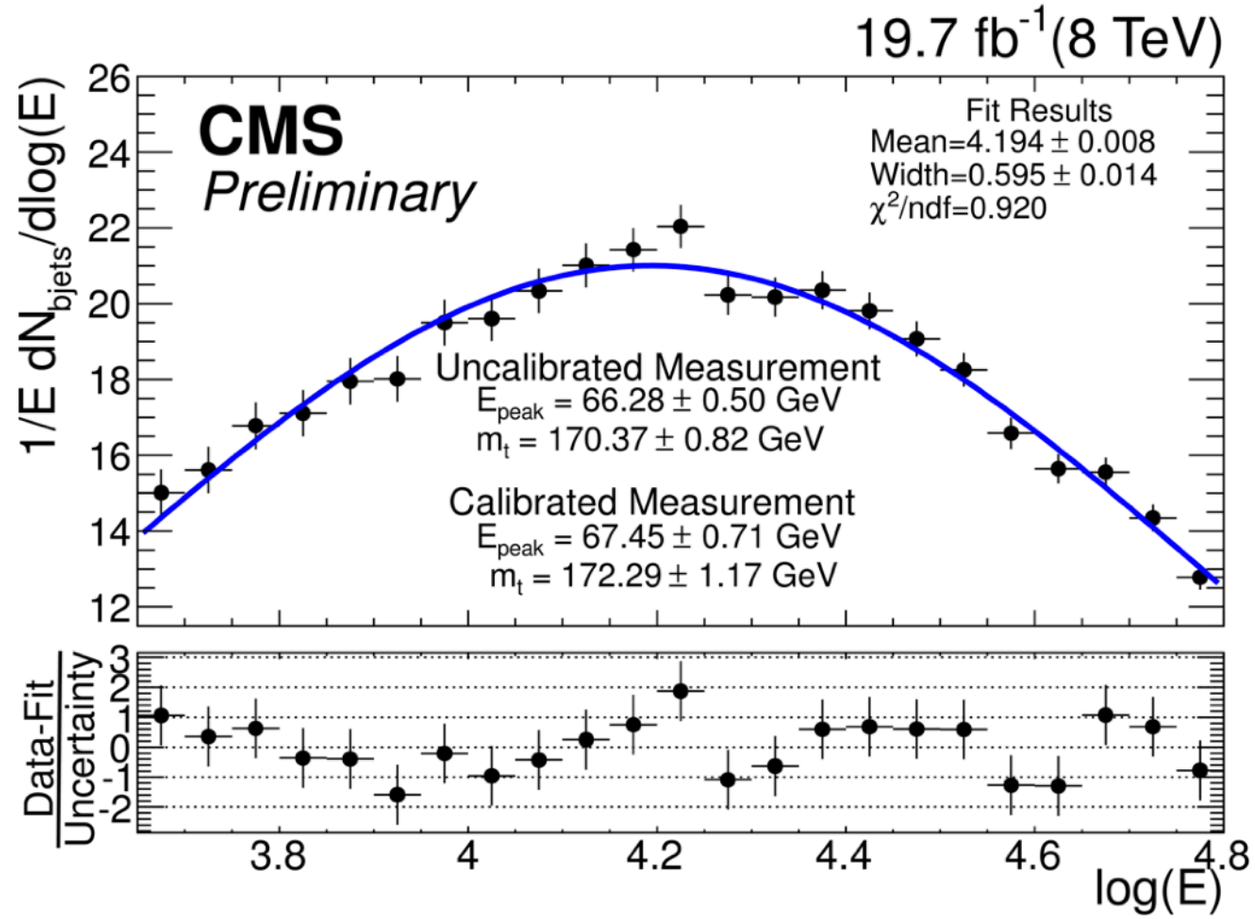
$$E_b = \frac{m_t^2 - m_W^2}{2m_t} \Rightarrow m_t = E_b \left[1 + \sqrt{1 + \left(\frac{M_W}{2E_b}\right)^2}\right]$$

  - energy peak in the lab preserves rest-frame mono-chromatic emission

(largest contribution at each boost)



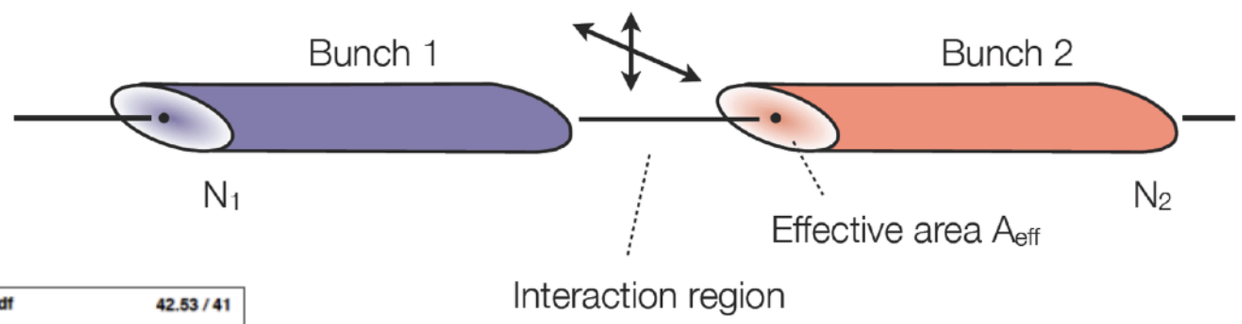
Phys.Rev. D88 (2013) 057701

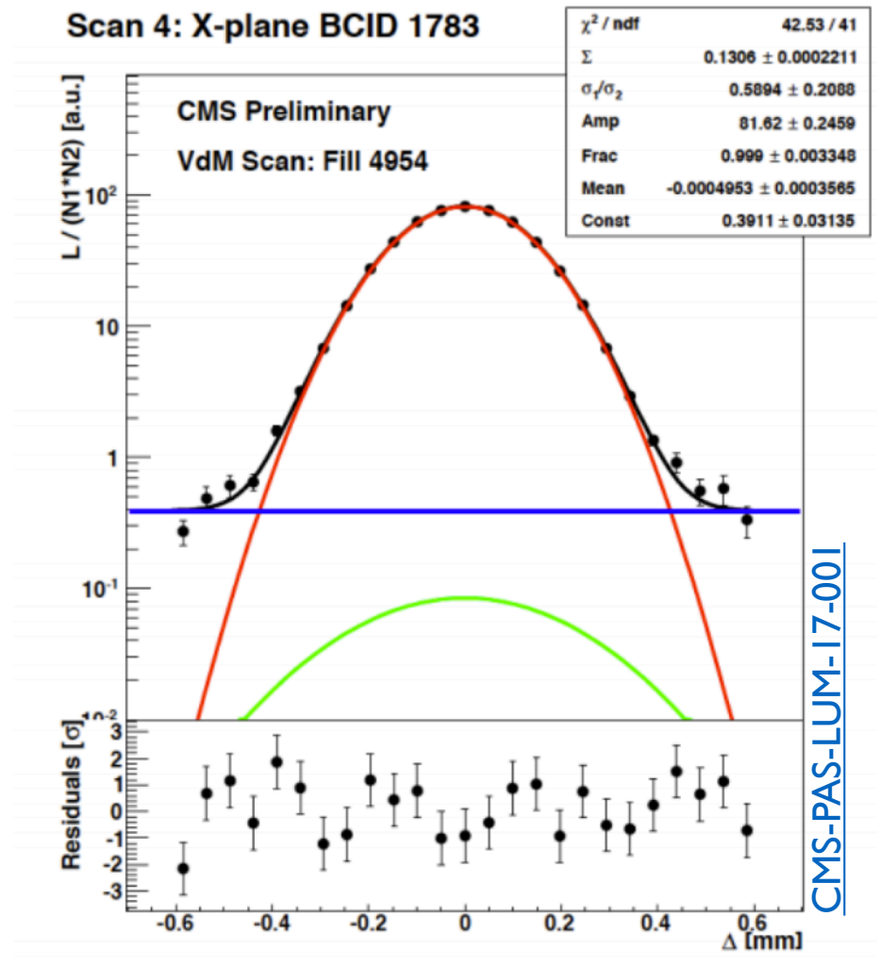


CMS-PAS-TOP-15-002

First things first: luminosity determination

- **Usually determined from dedicated Van-der-Meer scans** (CERN-ISR-PO-68-31)
  - beams are scanned and the shape and size of the luminous region is measured
  - measure relative interaction rate as function of the separation of the beam $\mathcal{L} = \frac{\dot{N}}{\sigma}$





CMS-PAS-LUM-17-001

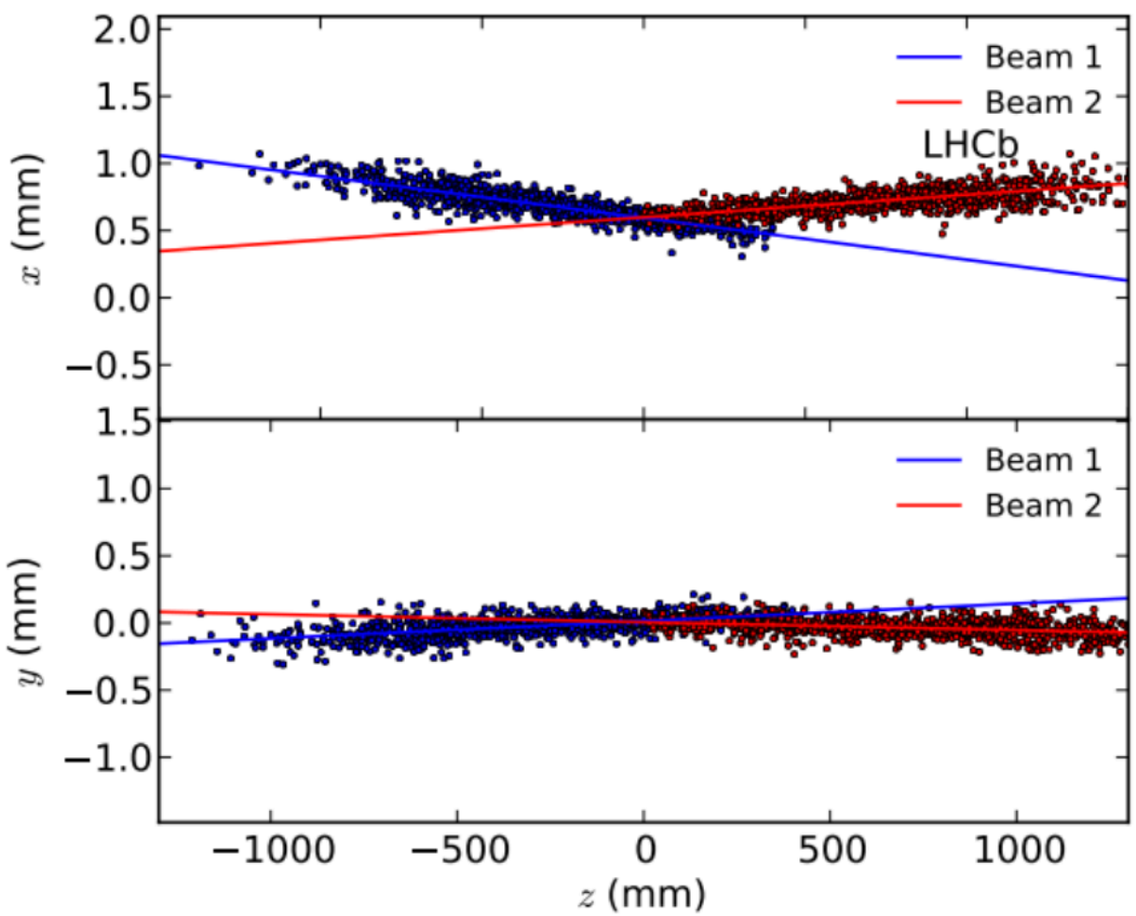
- **Counting hits establishes a "visible min. bias cross section"**
  - width of the beam determined from scan
  - hits counted in the detector (e.g. pixel clusters)
- **Largest uncertainties from**
  - x-y dependencies, length scale calibration
  - sub-detector checks

$$\frac{\delta\sigma}{\sigma}\Big|_{\text{Run 2}} \approx 3.2\% \text{ ATLAS } (2.5\% \text{ CMS})$$

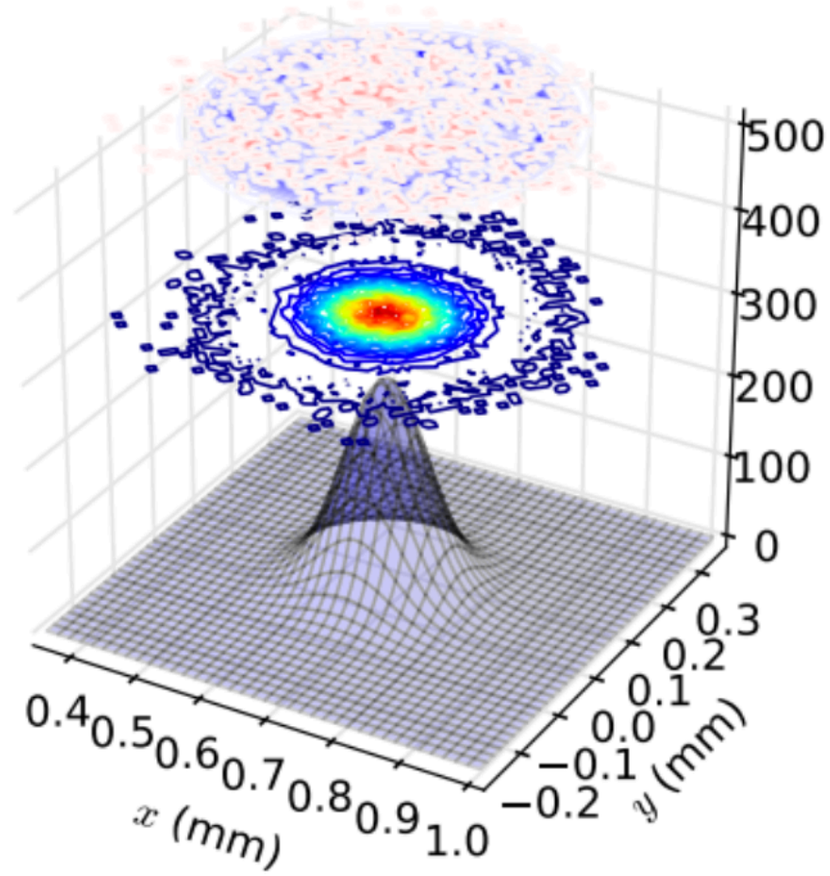
Reducing x-y dependencies in the luminosity calibration

$$\mathcal{L} = (f N_b N_p) N_{p'} \Omega$$

- **LHCb tracking system is able to measure the beams overlap integral very accurately**
  - direct measurement of the beam profile without need for displacement - complements VdM scan
  - x-y dependency is measured in situ, minimizing potential bias in the VdM scan
  - after combination $\frac{\delta\sigma}{\sigma}|_{\text{LHCb 8 TeV}} = 1.2\%$



Beam-beam

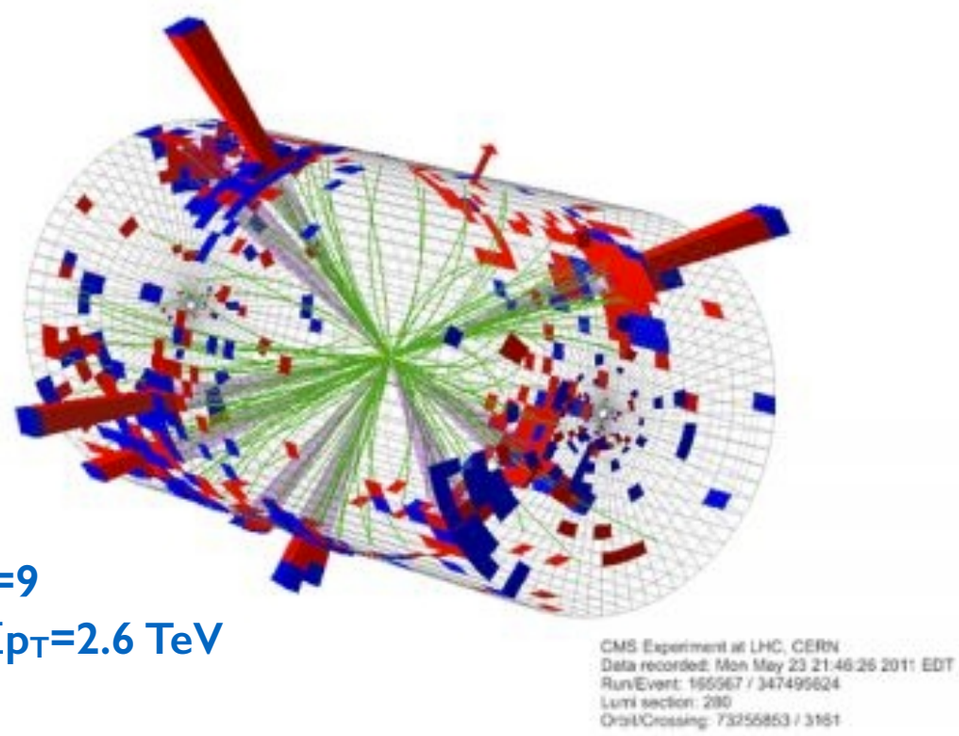


2014 JINST 9 P12005

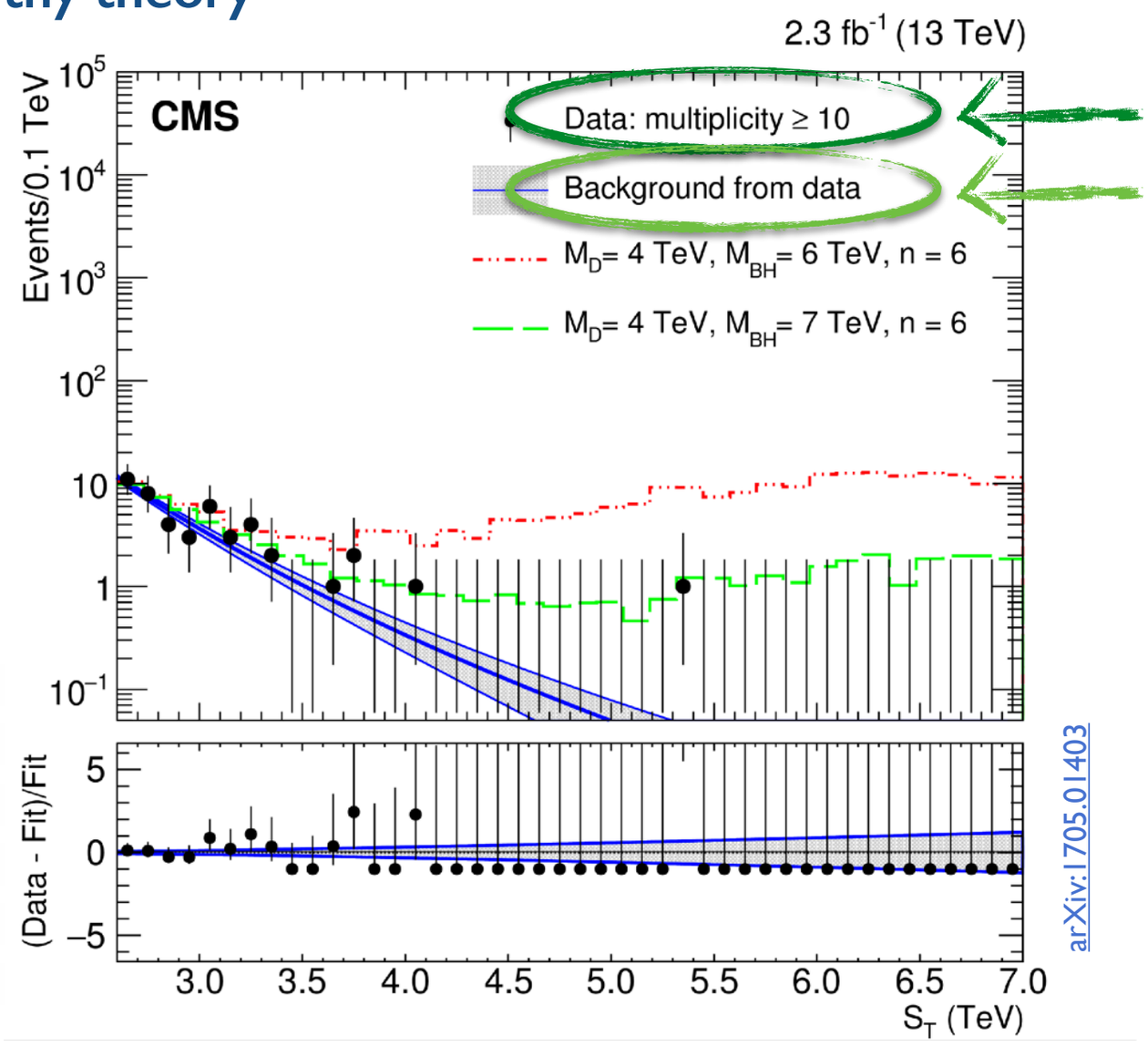
Understand the signature

- **Leptons, photons, jets, missing transverse energy, …**
  - …but also displaced objects, disappearing tracks, out-of-time decays,…
- **Signal: theory predictions forecast signature but <u>how does it look in the detector?</u>**
- **Backgrounds: sometimes no trustworthy theory**

…and so the fun begins!

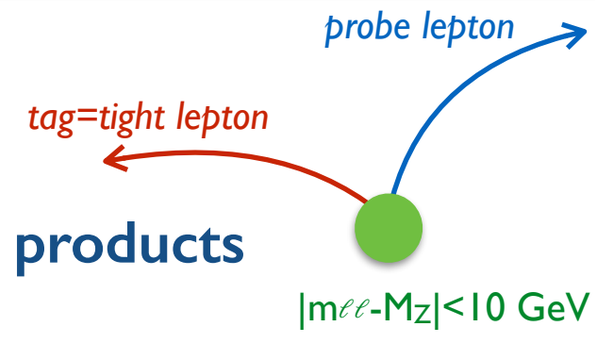


N_{jets}=9
$S_T=\Sigma p_T$=2.6 TeV

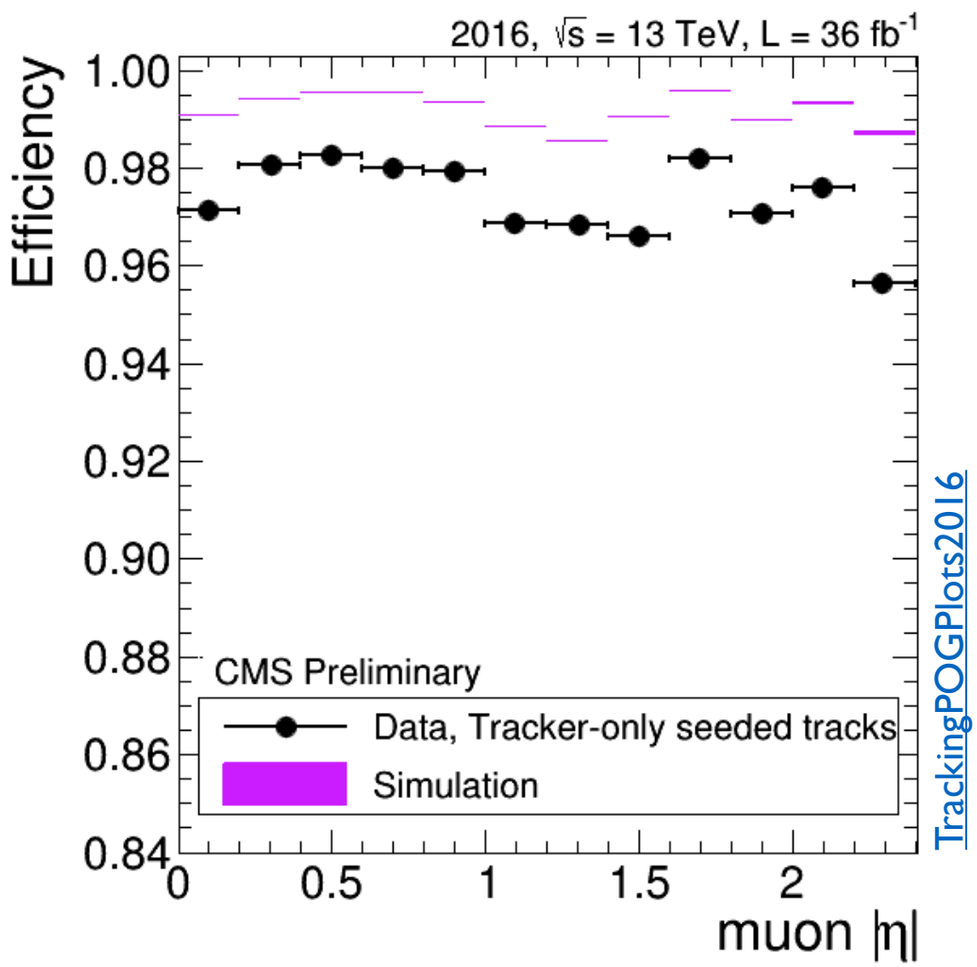


arXiv:1705.01403

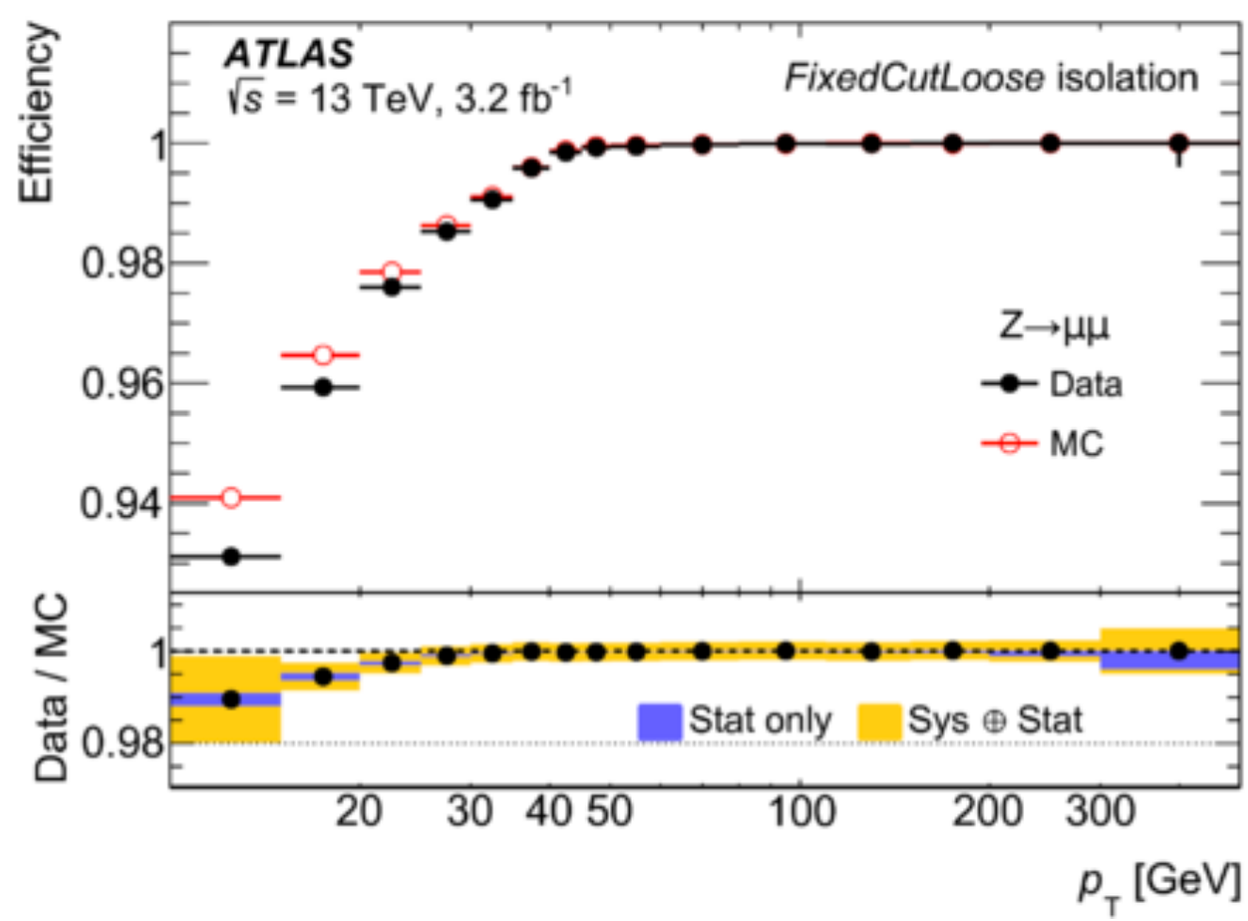
Know thy (in)efficiencies



- **Use data as much as possible to check the expected efficiencies**
- **E.g. $D^* \to K + n\pi$, J/ψ or $Z \to \ell\ell$: "easy" to trigger, yield resonant decay products**
  - count events which pass and fail selection requirements: trigger, tracking, id, isolation,…
  - events in each category are related by the efficiency of the requirement $\begin{cases} N_{pass} = \varepsilon N \\ N_{fail} = (1-\varepsilon) N \end{cases}$
- **Difference between data and simulation can be used as correction factor**



TrackingPOGPlots2016



Eur. Phys. J. C (2016) 76:292

Energy scale calibration (ATLAS LAr example)

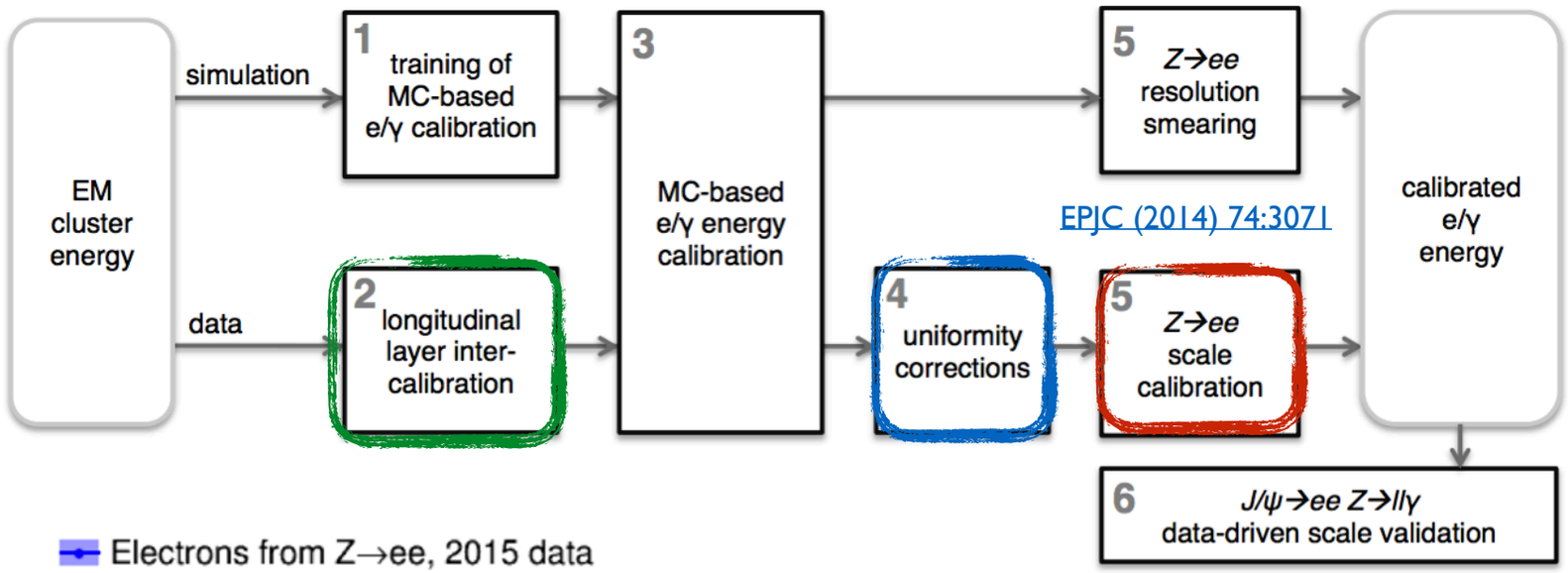
- **Several steps correcting as much as possible from the data the initial MC-based energy regression**
  - *inter-calibration* (longitudinal sections): use MIP deposits from Z→μμ
  - *upstream material corrections*: ratio of super cluster energies in different longitudinal sections (e, $\gamma_{unc.}$)
  - *residual differences in response and resolution* are probed using shift and width of the Z→ee peak

$$E^{\text{data}} = [1 + \alpha(\eta)]E^{MC}$$

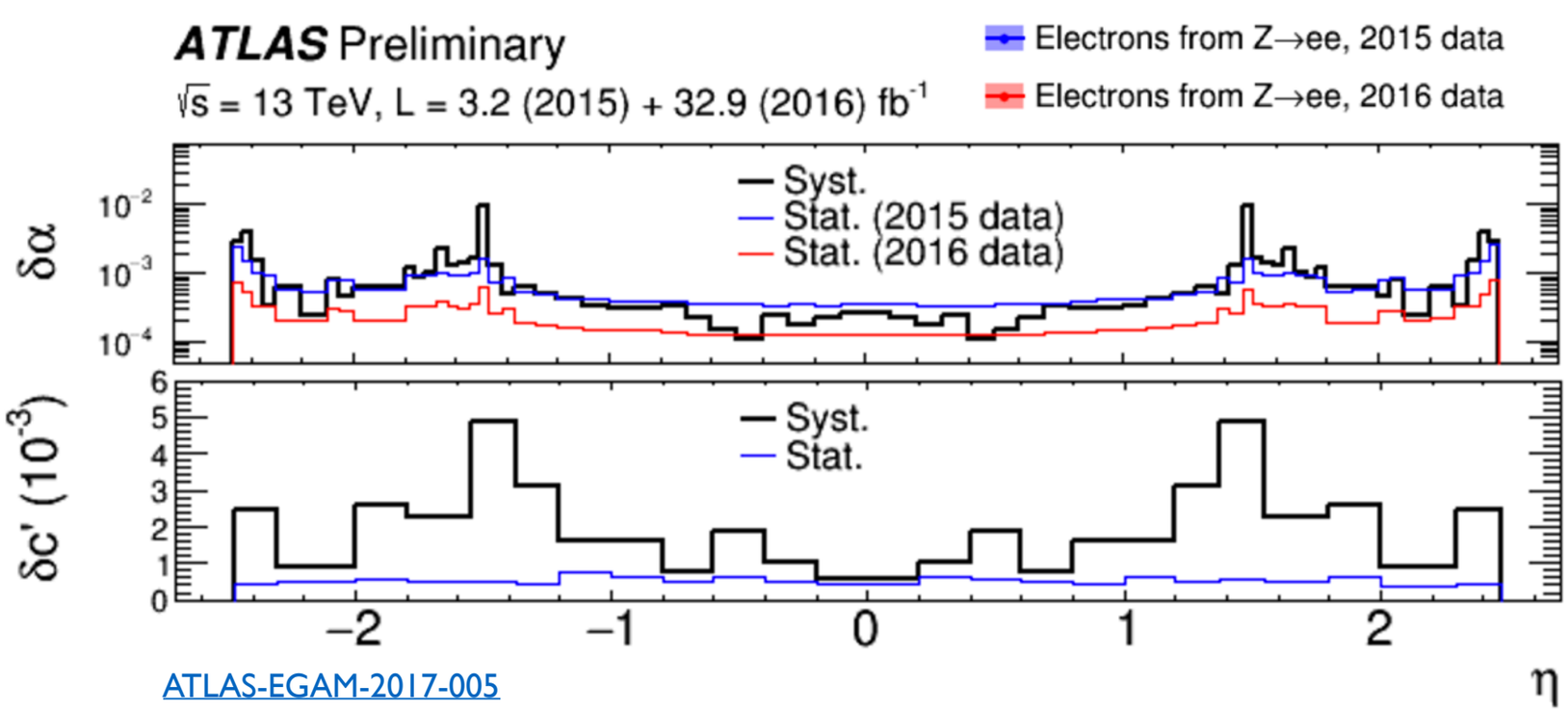
$$\frac{\delta E}{E}|_{\text{data}} = \frac{\delta E}{E}|_{\text{MC}} \oplus c(\eta)$$

$$m_{ee}^{\text{data}} = m_{ee}^{MC}\left[1 + \frac{\alpha(\eta_1) + \alpha(\eta_2)}{2}\right]$$

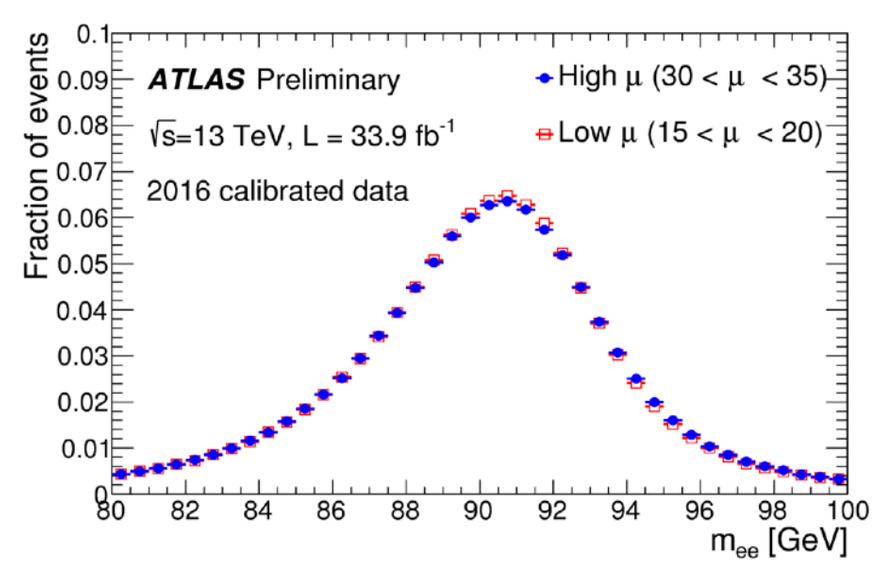
$$\frac{\delta m}{m}|_{\text{data}} = \frac{\delta m}{m}|_{\text{MC}} \oplus \left[\frac{c(\eta_1) \oplus c(\eta_2)}{2}\right]$$



EPJC (2014) 74:3071

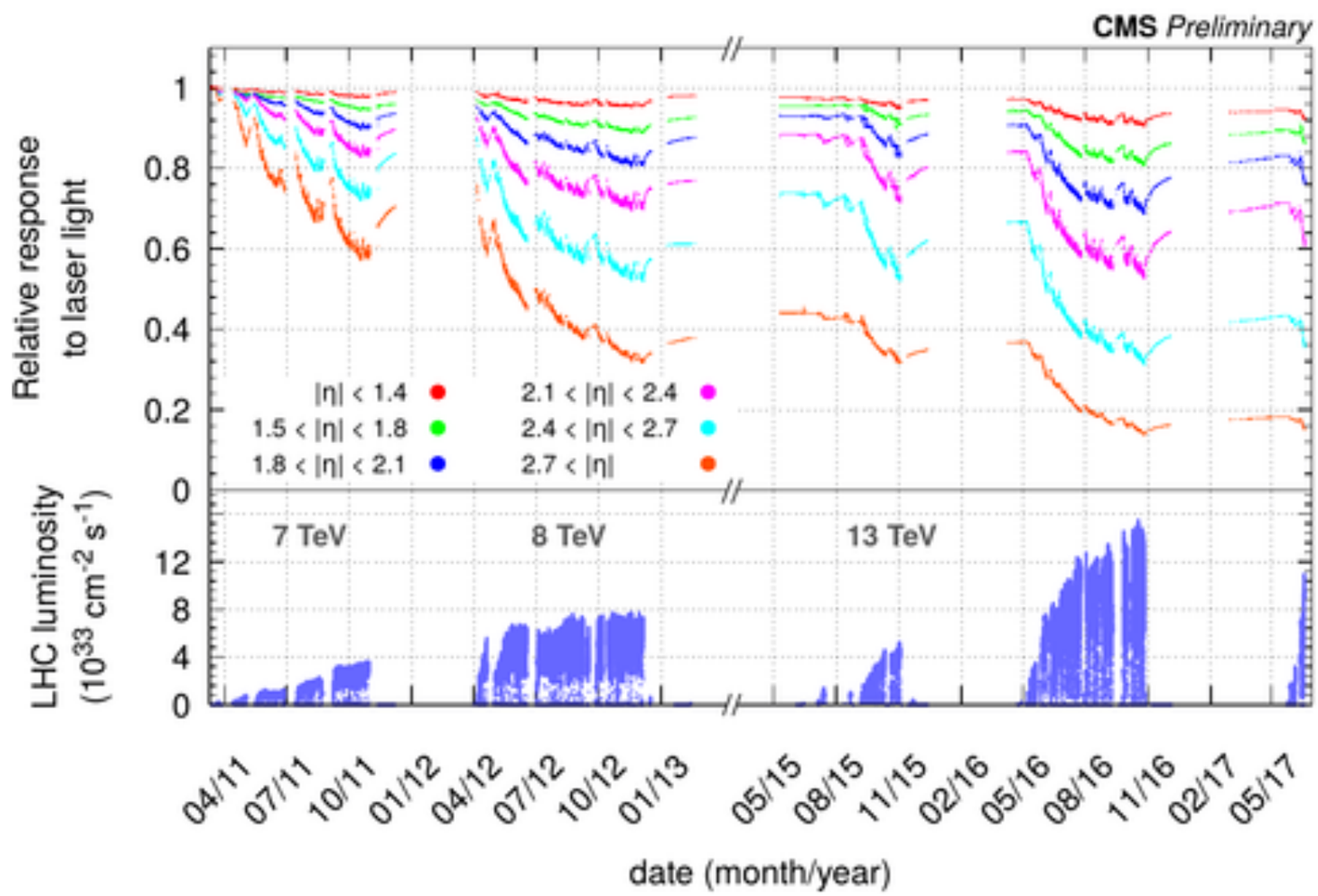


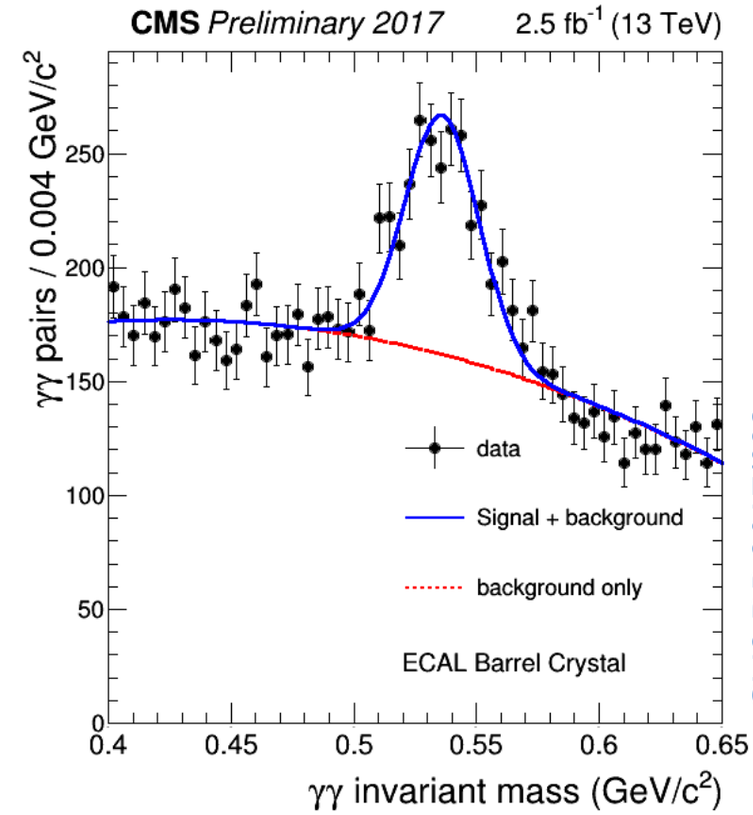
ATLAS-EGAM-2017-005



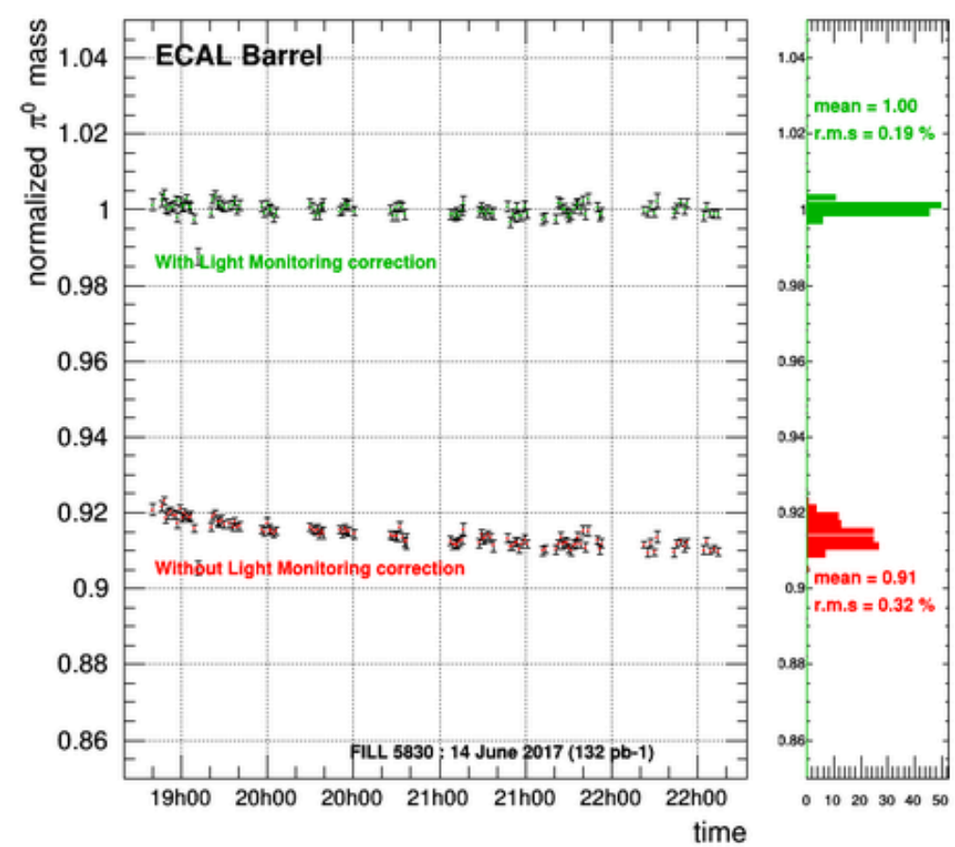
ATLAS-EGAM-2016-006

Monitoring the response throughout the run (CMS ECAL example)





CMS-DP-2017/023



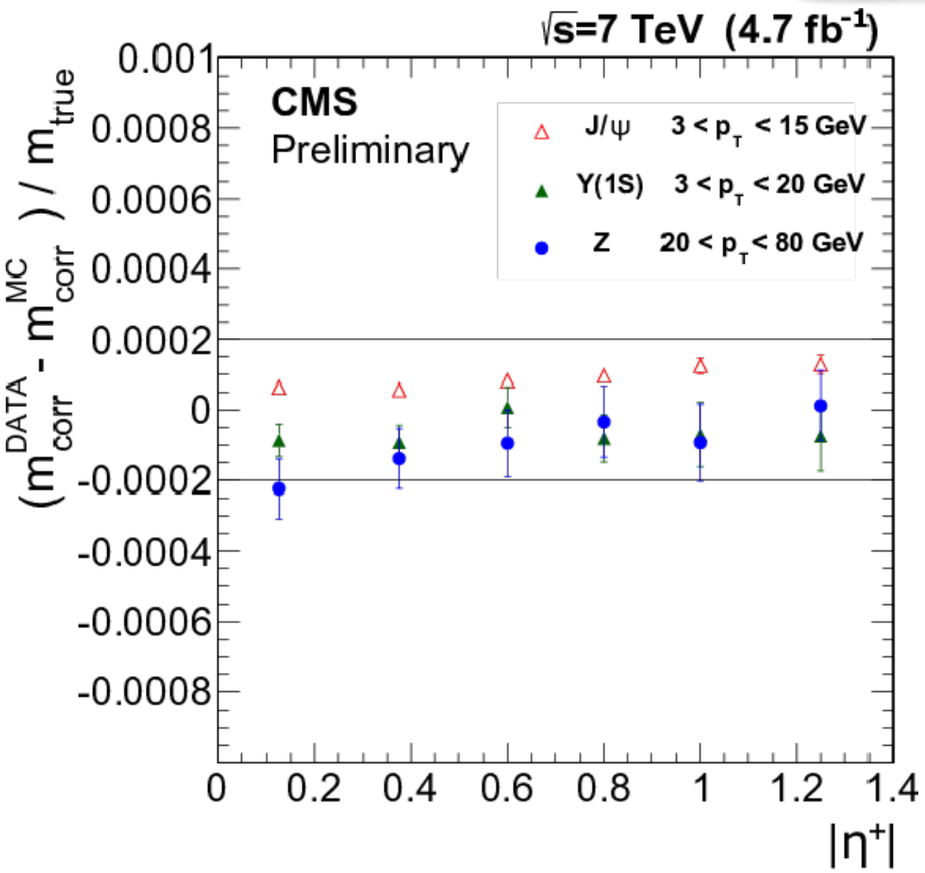
- **Continuous monitoring of the detector is needed**
  - radiation induces coloured centres in crystals
  - significant loss of response at high luminosity
- **Laser used for transparency corrections in CMS ECAL**
  - $\pi^0 \rightarrow \gamma\gamma$ can be used to check response and dispersion

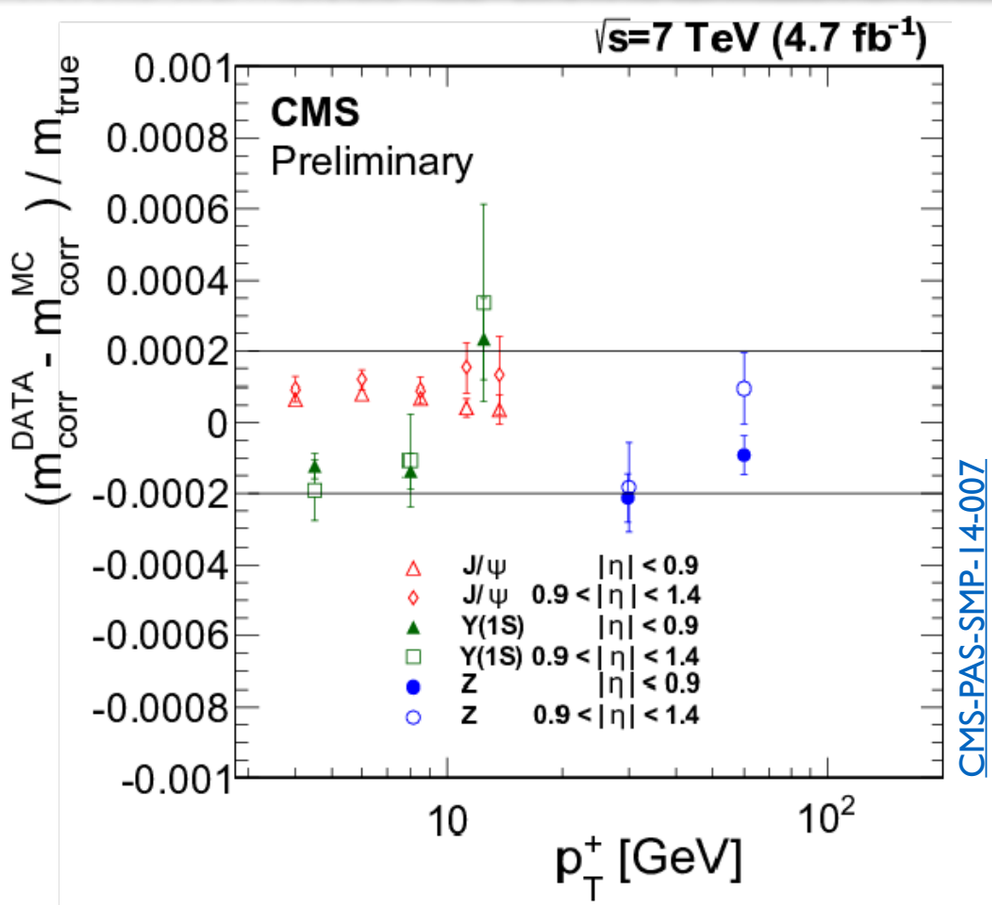
Further refinements at analysis level (CMS muons example)

- **Improve over the standard muon reconstruction by taking into account**
  - local modifications of the magnetic field ((A-1)~0.0005) = multiplicative factor
  - residual misalignment effects (M~10^{-4}/GeV) = additive factor, charge dependent
  - imperfect material modelling effects (ε~4MeV) = depends on sinθ

estimated with a Kalman filter technique

$$k^c = \frac{1}{p_T^c} = (A-1)k + qM + \frac{k}{1 + k\varepsilon \sin\theta}$$



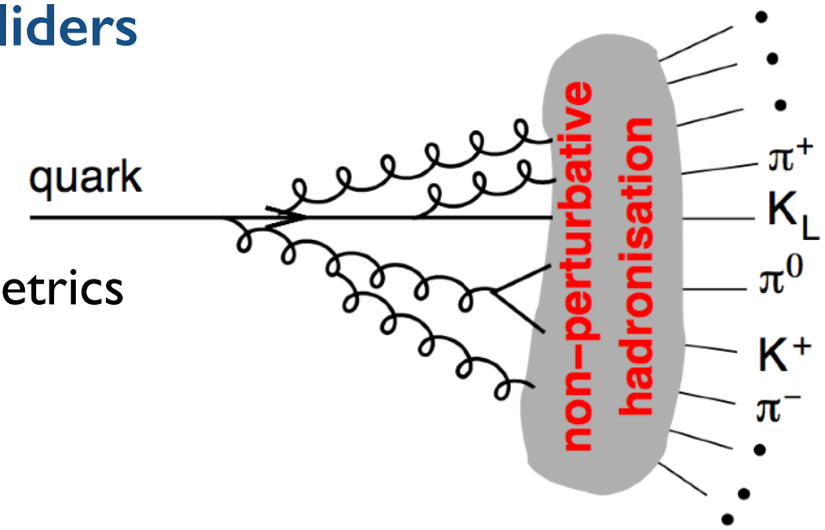


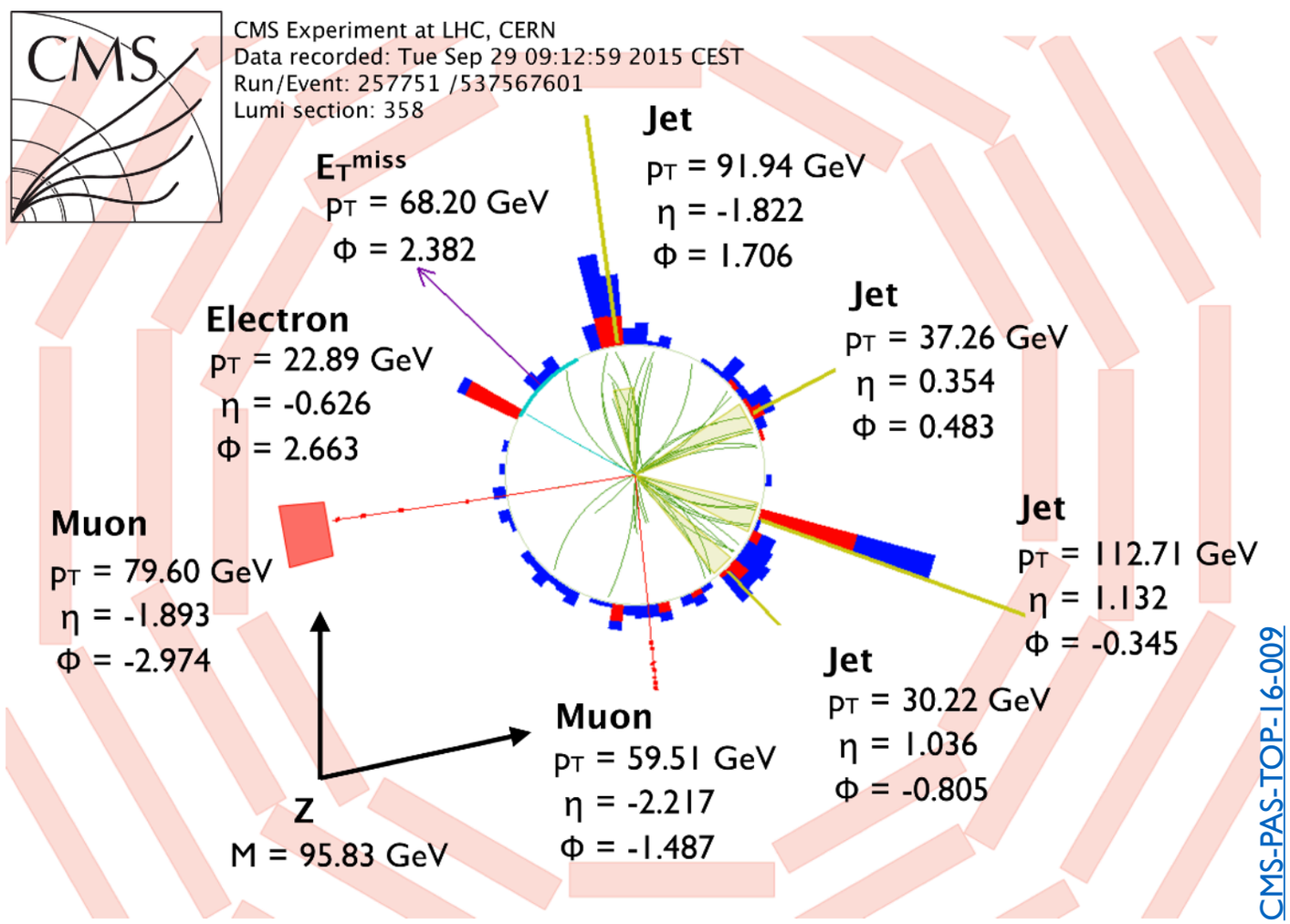
CMS-PAS-SMP-14-007

translates to ~14 MeV uncertainty on M_W using only p_T information

Jets

- **Jet clustering algorithms are extensively used in hadron colliders**
  - collect the final state products after the hadronisation
  - $d_{ab} = \min\{p_{T,a}^{2n}, p_{T,b}^{2n}\}\frac{\Delta R_{ab}^2}{R^2}$ $\quad d_{aB} = p_{T,a}^{2n}$ define the metrics
  - at each step find smallest: if d_{ab} recombine, if d_{aB} a jet is found
  - (anti-)k_T algorithm uses n= 1 (-1), Cambridge-Aachen uses n=0





← *ttZ event with anti-k_T with R=0.4*

The particle flow algorithm yields a close to generator level reconstruction of the jet constituents

Jets

- **Jet clustering algorithms are extensively used in hadron colliders**
  - collect the final state products after the hadronisation
  - $d_{ab} = \min\{p_{T,a}^{2n}, p_{T,b}^{2n}\}\frac{\Delta R_{ab}^2}{R^2}$ $\quad d_{aB} = p_{T,a}^{2n}$ define the metrics
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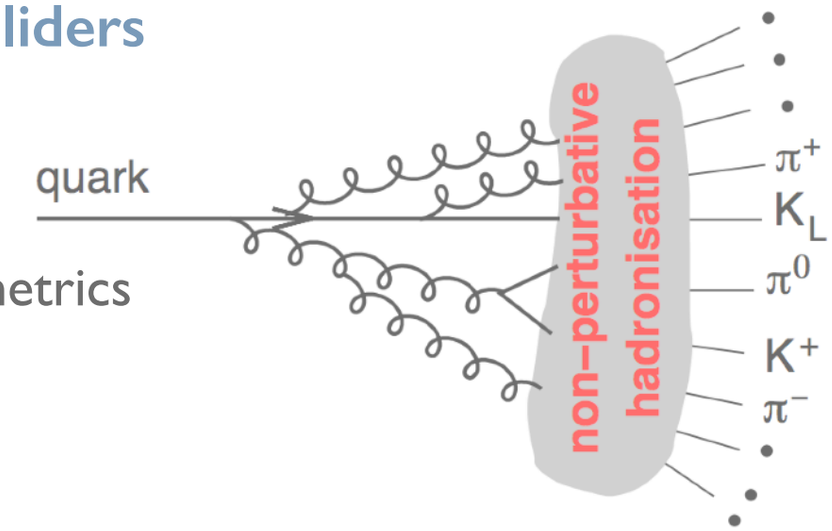
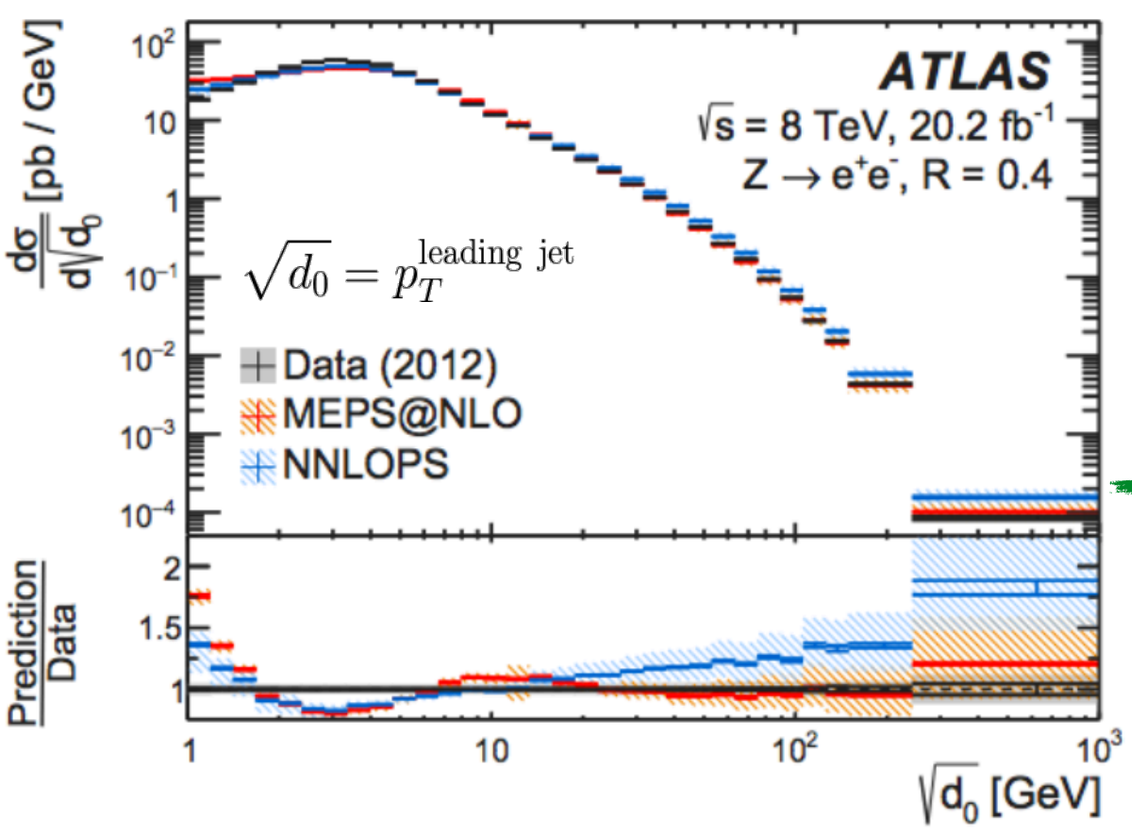
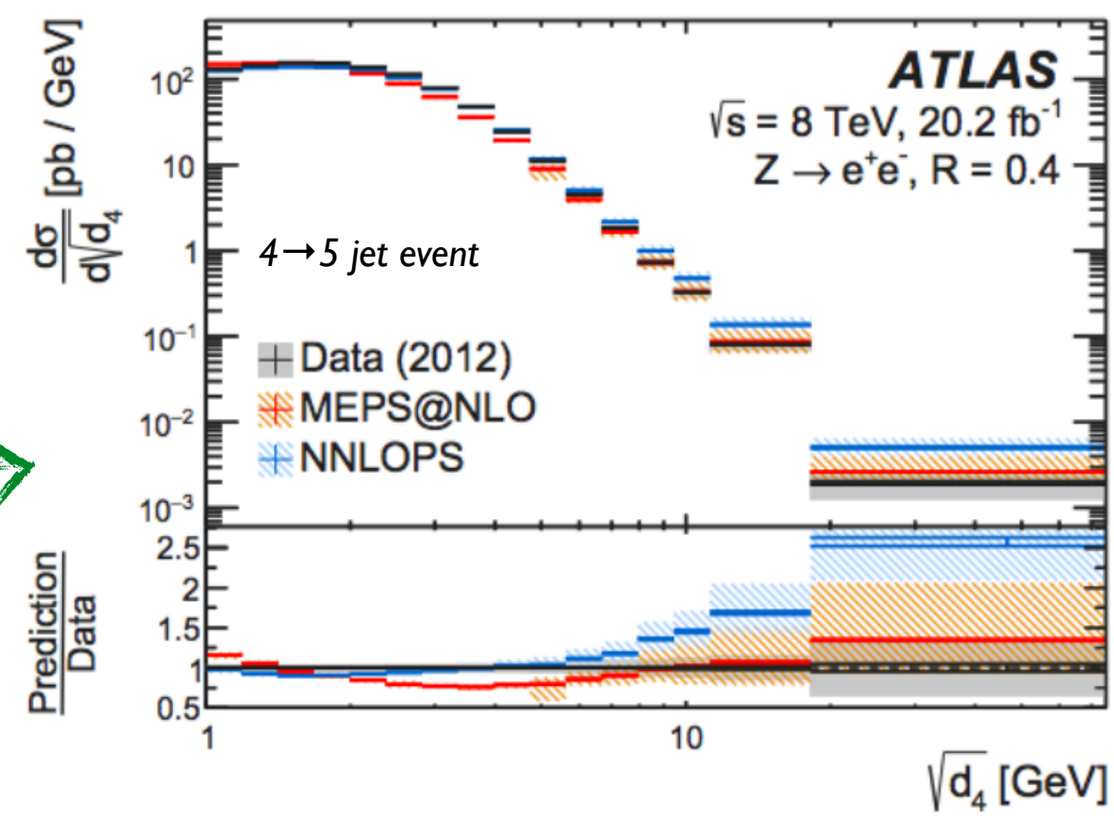


- **The event minimum $\{d_{ab}, d_{aB}\}$ tells us at which point a N jet event is resolved to N+1**

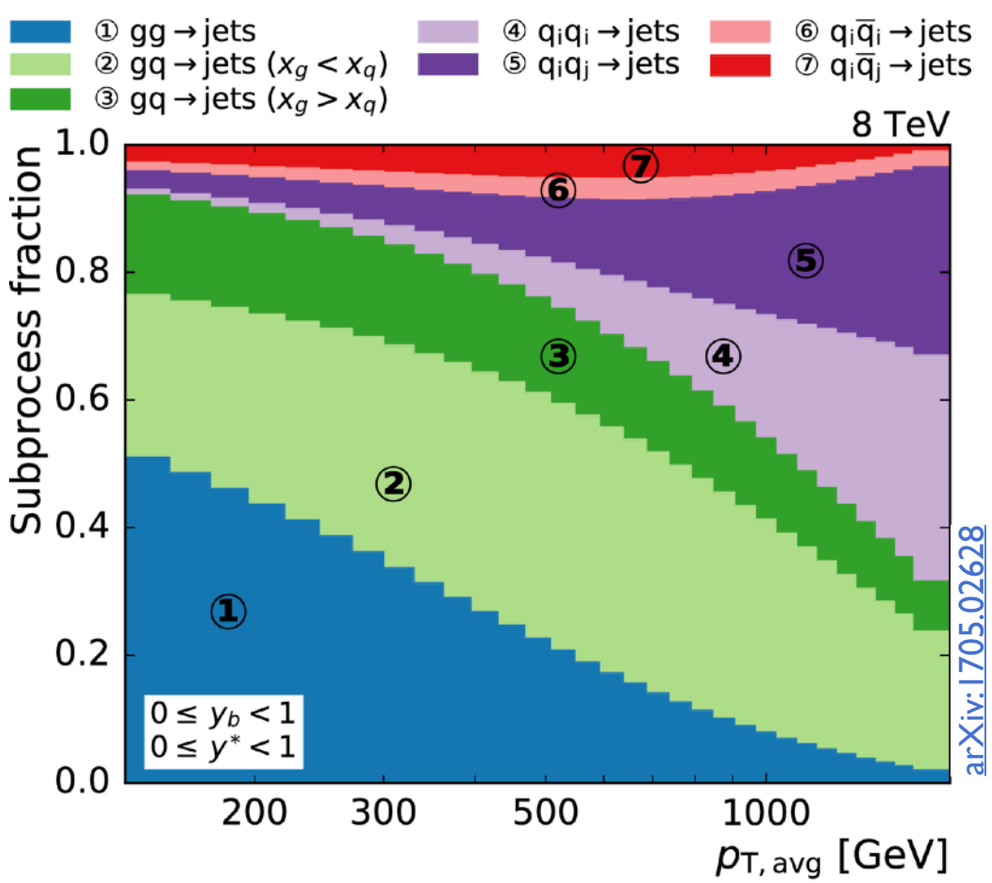


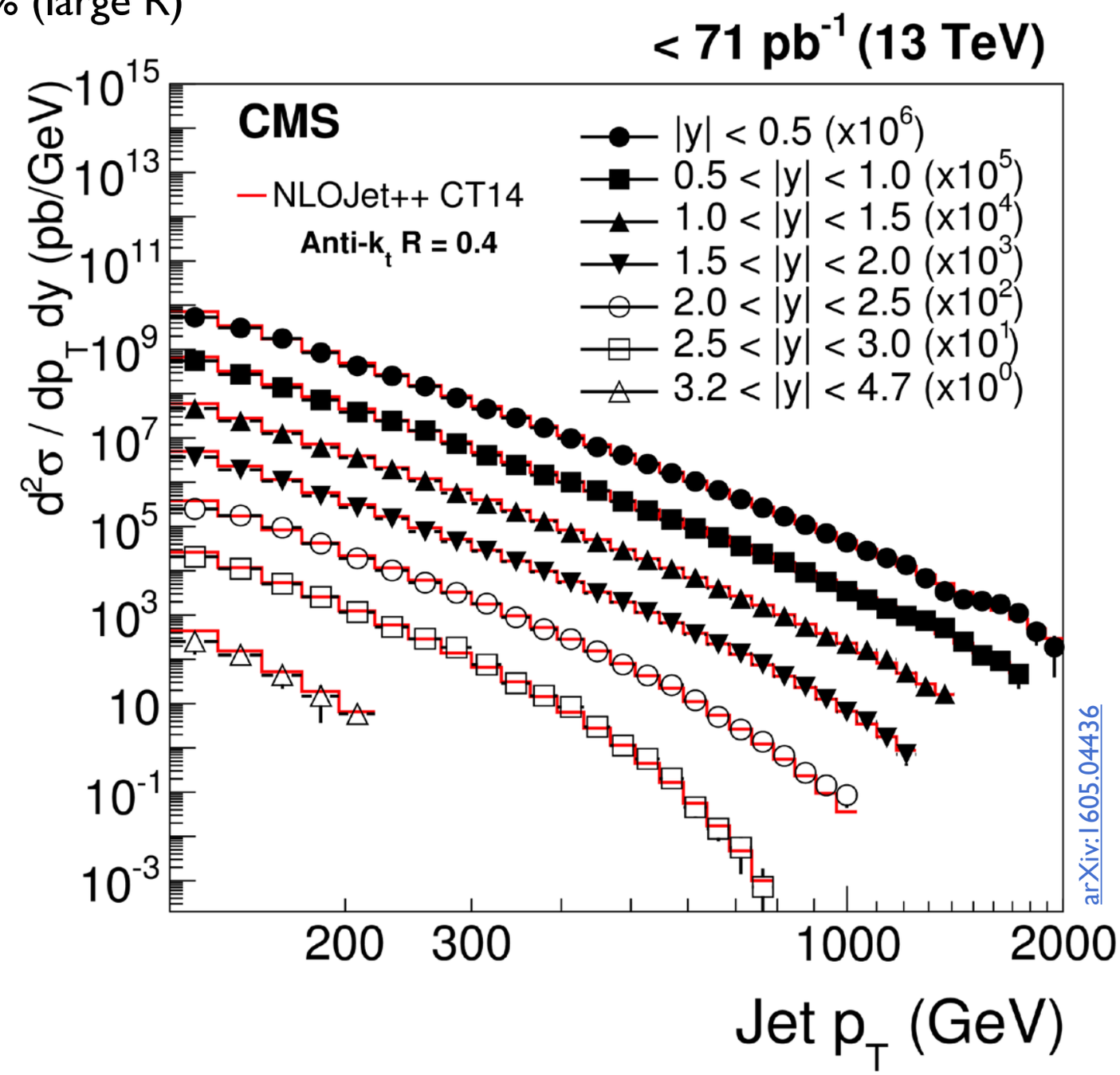


JHEP08 (2017) 026

Hadronic event shapes

- **Jet cross section @ TeV scale with early data**
  - sensitive to PDFs, α_S
- **Compare to NLO QCD prediction (NLOJet++)**
  - <u>non-perturbative corrections</u> can be ~15% (large R)
  - EWK corrections up to 5% (at high p_T)

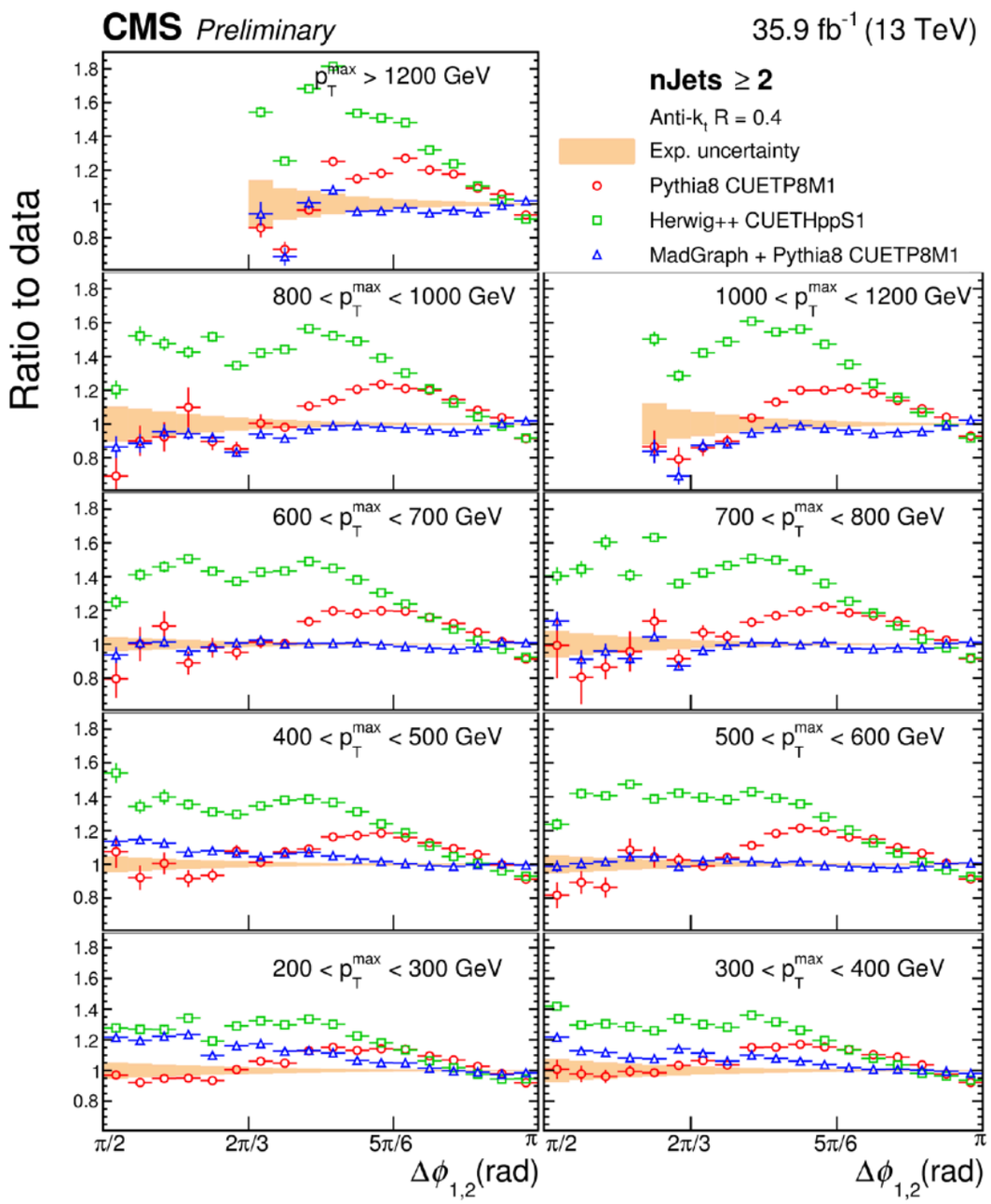


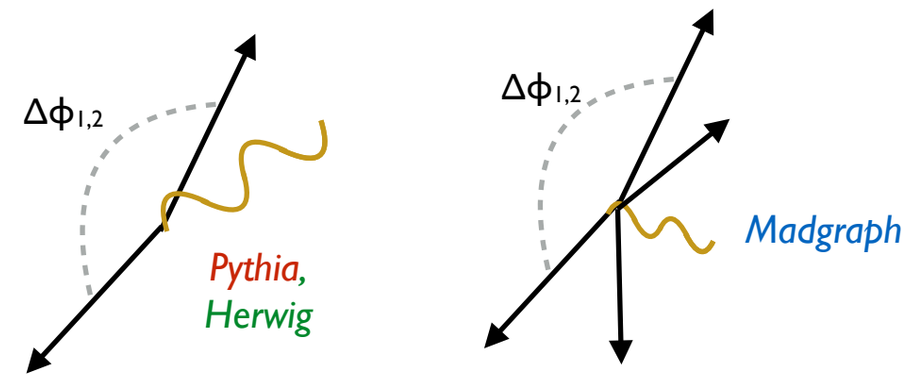


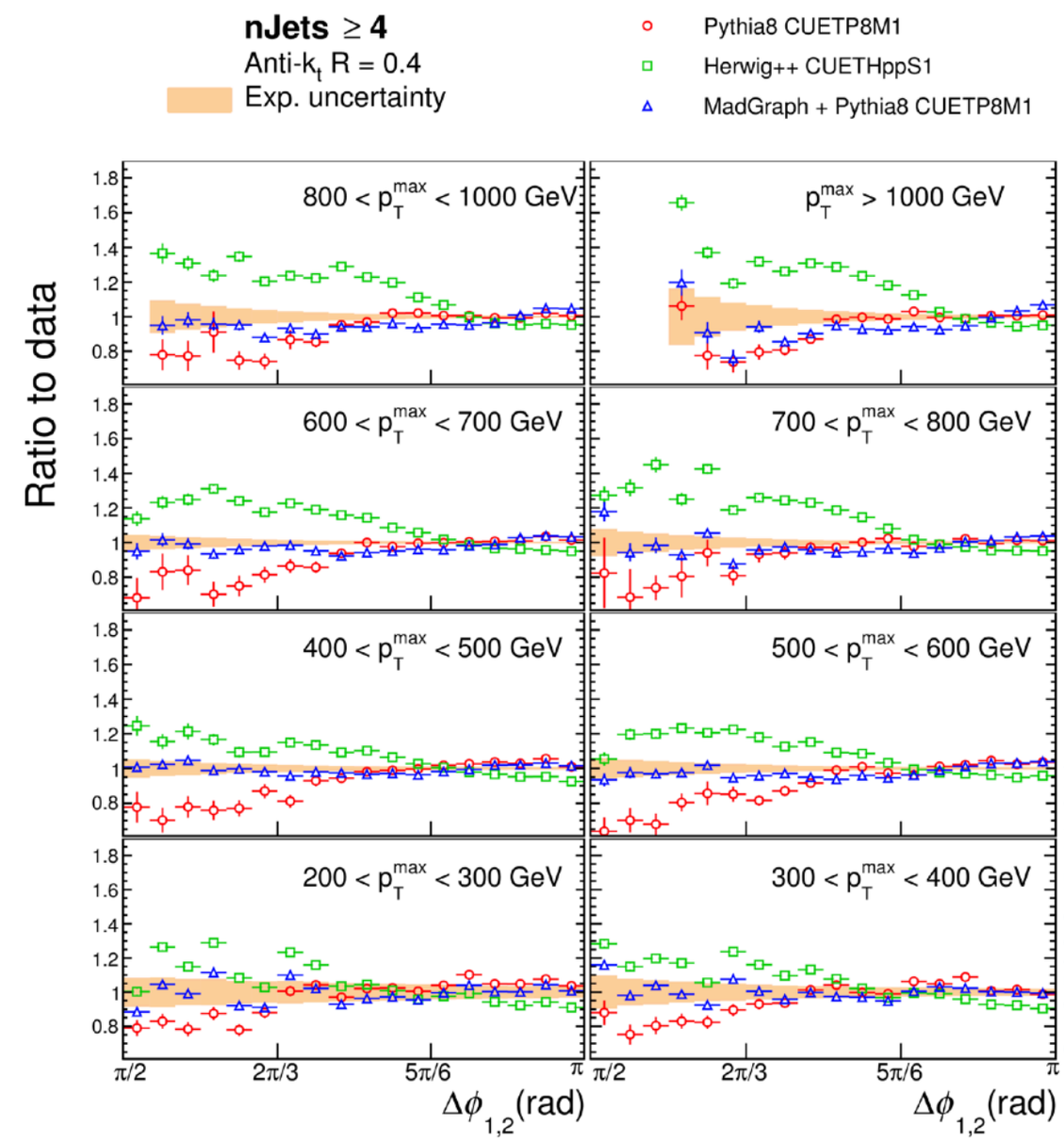
Splittings and azimuthal decorrelations

- **Azimuthal angles in N-jets**
  - how well is QCD splitting predicted?

    soft / collinear / hard regimes probed

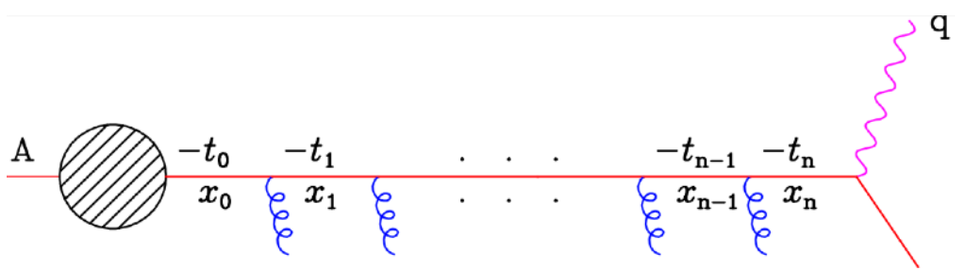






CMS-PAS-SMP-16-014

Jet mass an interesting probe of the jet nature I



- **Jet splitting from pQCD evolution**
  - have soft singularities in z = $E_{emmited}/E_{parent}$

    (except g→qq - asymmetric in z)
  - mass drop at each split moderated by Sudakov factor

    form factor rapidly vanishing $\Delta_q(t) \sim \left[\frac{\alpha_S(t)}{\alpha_S(t_0)}\right]^{p \ln t}$

    ⇒ soft mass drops expected in splittings

Quarks, gluons, acquire a "visible" mass through the process of QCD shower

First emission yields the dominant contribution to the observed jet mass

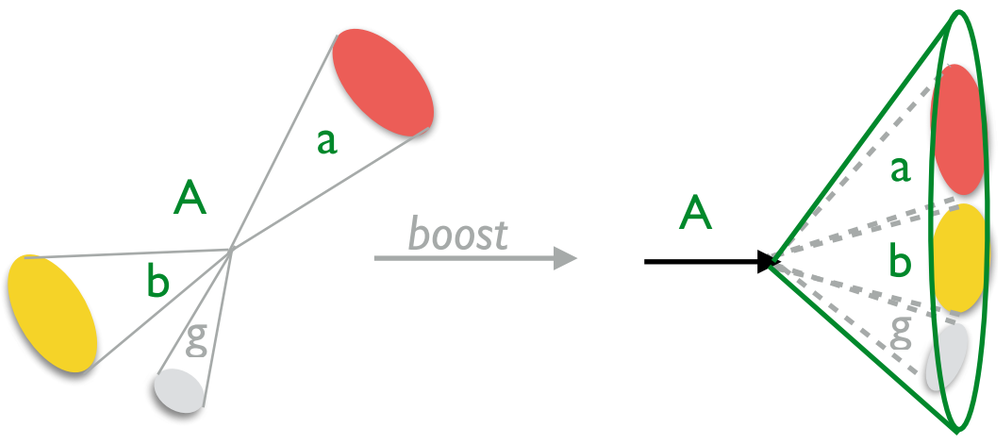
$$< m^2 > \approx p_T^2 \int_0^{R^2} \frac{d\theta^2}{\theta^2} \int dz\ z(1-z)\theta^2 \frac{\alpha_S}{2\pi} \mathcal{P}(z) \approx \frac{\alpha_S}{\pi}\ \frac{3}{8} C_F\ p_T^2 R^2$$

QCD suppression factor

colour factor ($C_A/20$ for gluons)

linear growth in (p_T,R)

Jet mass an interesting probe of the jet nature II

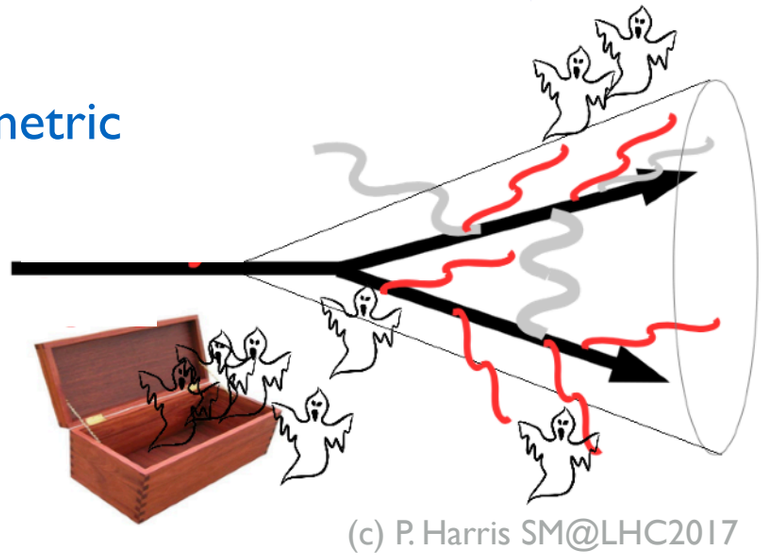


- **Jet splitting from a decay occurs**
  - in one step : A → ab
  - at a hard scale $m^2 \approx 2\,\vec{p}_{T,a}\cdot\vec{p}_{T,b} \Rightarrow \Delta R^2_{a,b} \approx z(1-z)\left(\frac{p_{T,A}}{m}\right)^2$
  - uniform distribution in z = $p_{T,a}/p_{T,A}$
  - expect however "pollution" from further emissions

- **"<u>splitting</u>" algorithm:** clean up the soft, collinear radiation, identify hard splitting
  - start by clustering the jet (usually a large jet cone is used)
  - unwind the process one step at a time checking if it's hard and symmetric

$$\max(m_a, m_b) < \mu m_A \qquad y_{ij} > y_{\rm cut}$$

  - if not discard the softest of (a,b)
  - stop if condition is met or you ran out of splittings to unwind



Mass drop and filtering yield a pileup robust result

- **"filtering step"**: due to underlying event, pileup the mass drop scale may be distorted

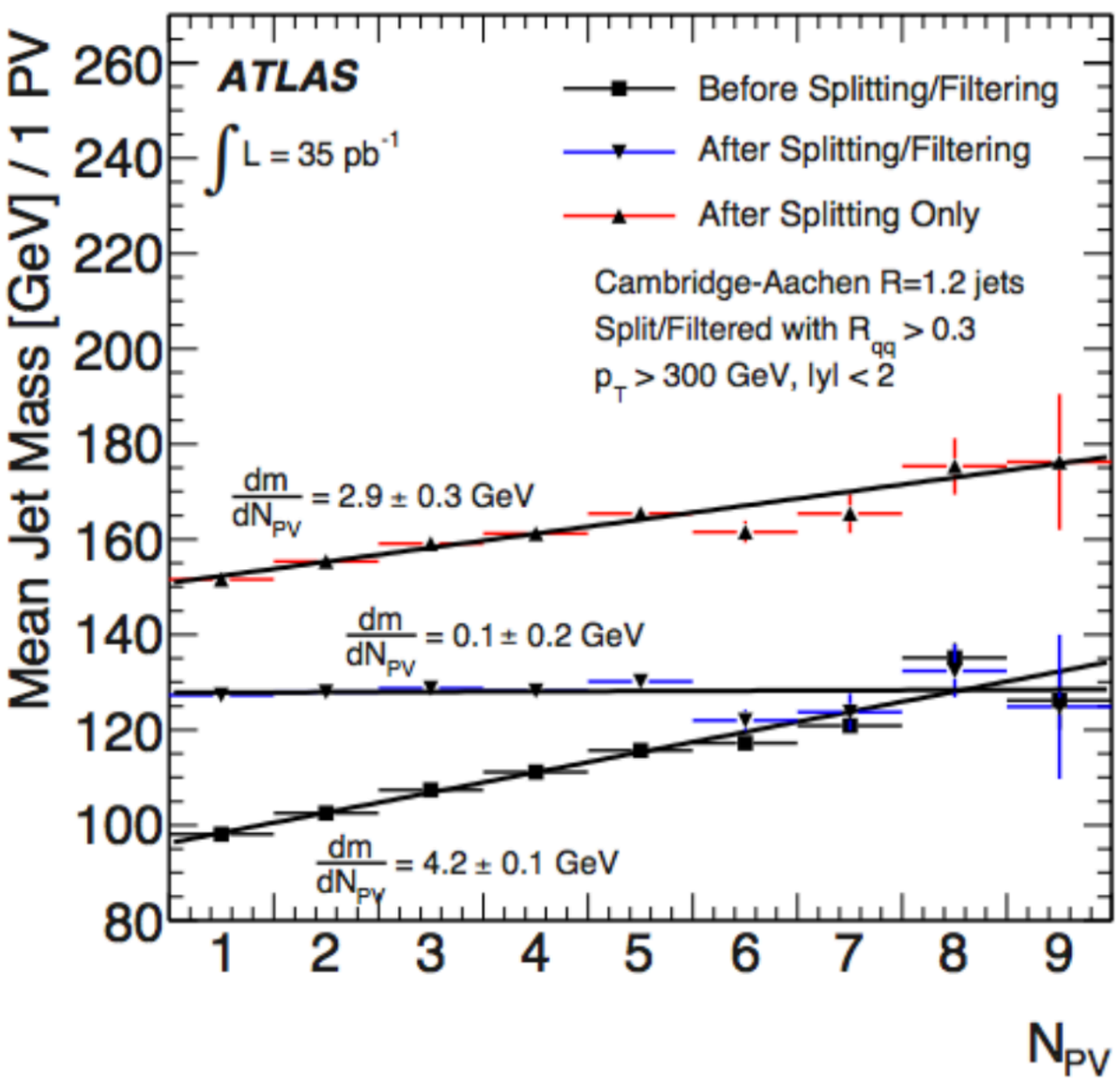
$$\frac{d < m^2 >}{dR} \approx \Lambda_{\rm soft} \; (p_T R) \; R^2$$

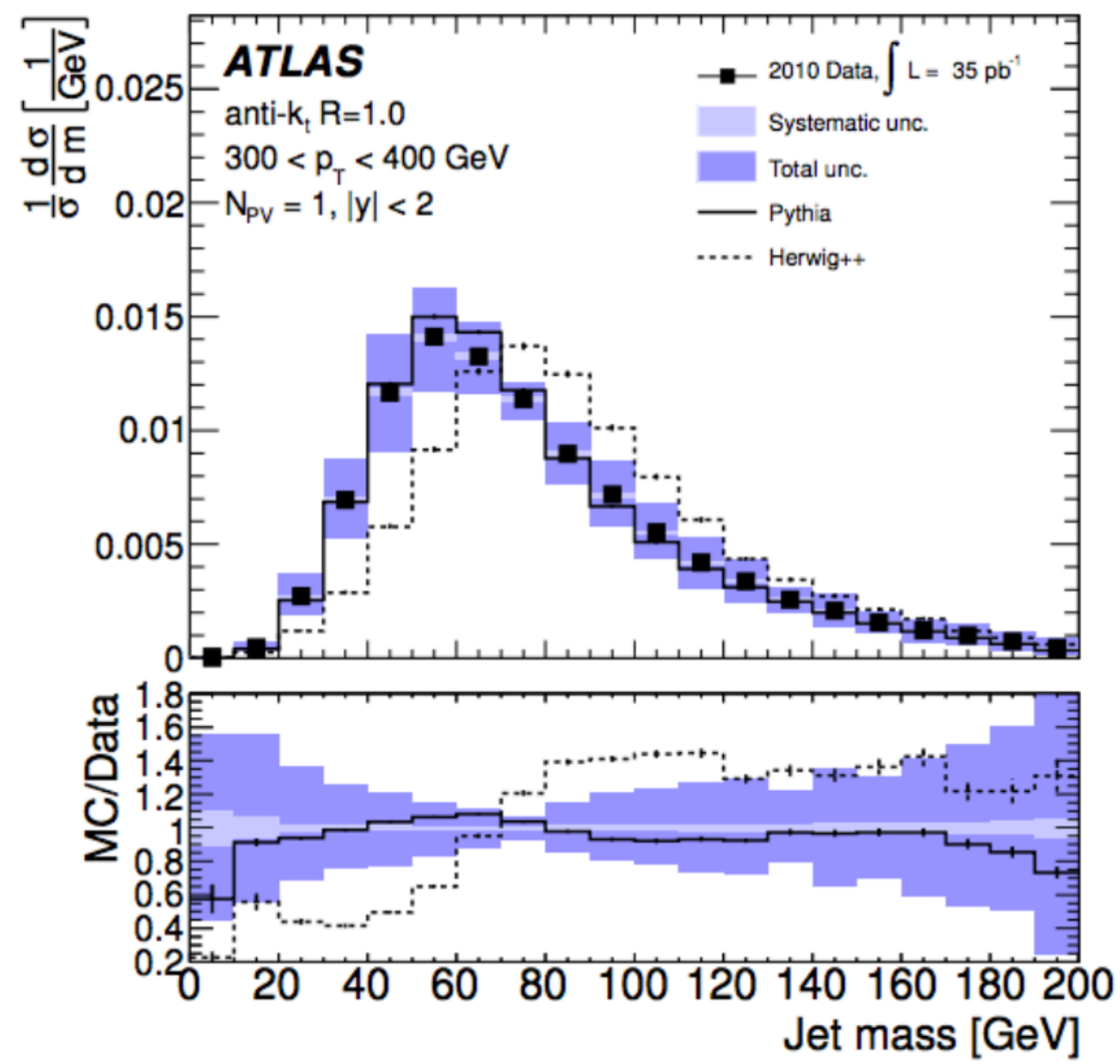
constant per rapidity unit

soft particles away from jet core

jet area

re-cluster the jet found with $R_{\rm filt} = \min(\Delta R_{ab}/2, 0.3)$





JHEP 1205 (2012) 128

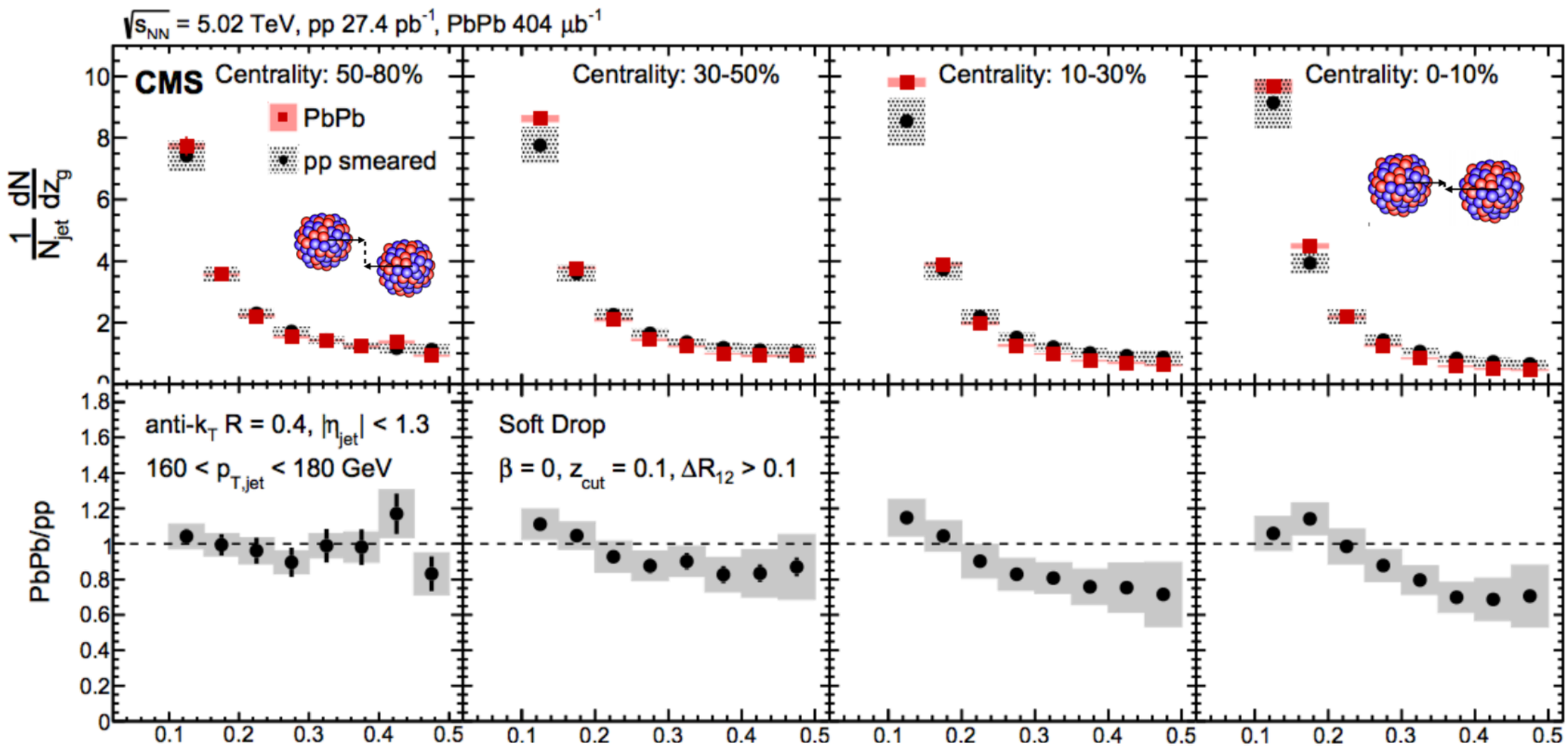
Soft drop condition as a probe of the medium

- **Soft drop works as the "splitting" step** (see s36)
  - discard softer of the jets until condition is met

$$\frac{p_{T,2}}{p_{T,1}+p_{T,2}} < z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

soft-drop: JHEP 1405 (2014) 146

- **Splitting scale can be probed from max. "declustering" scale found**
  - useful observable to probe the medium

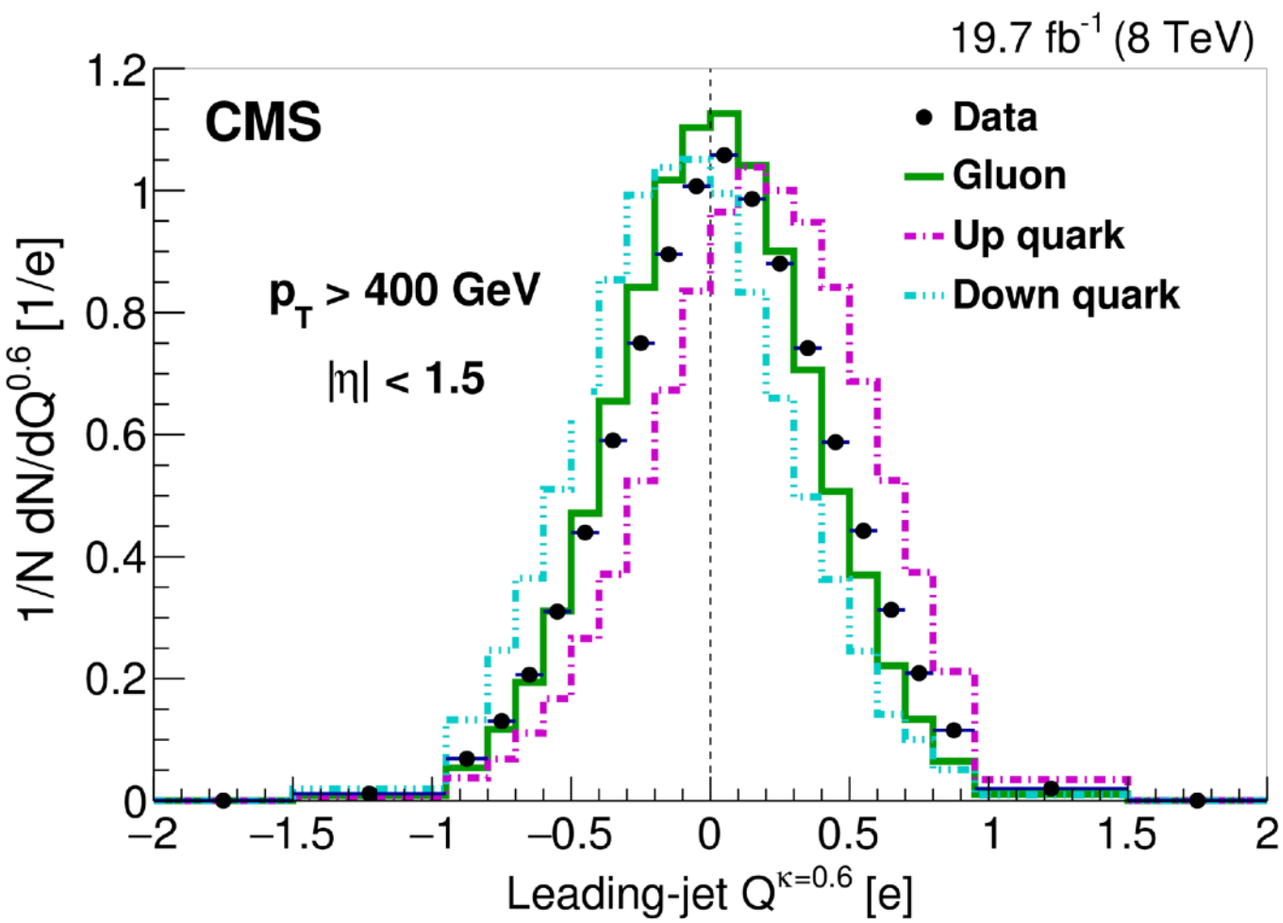


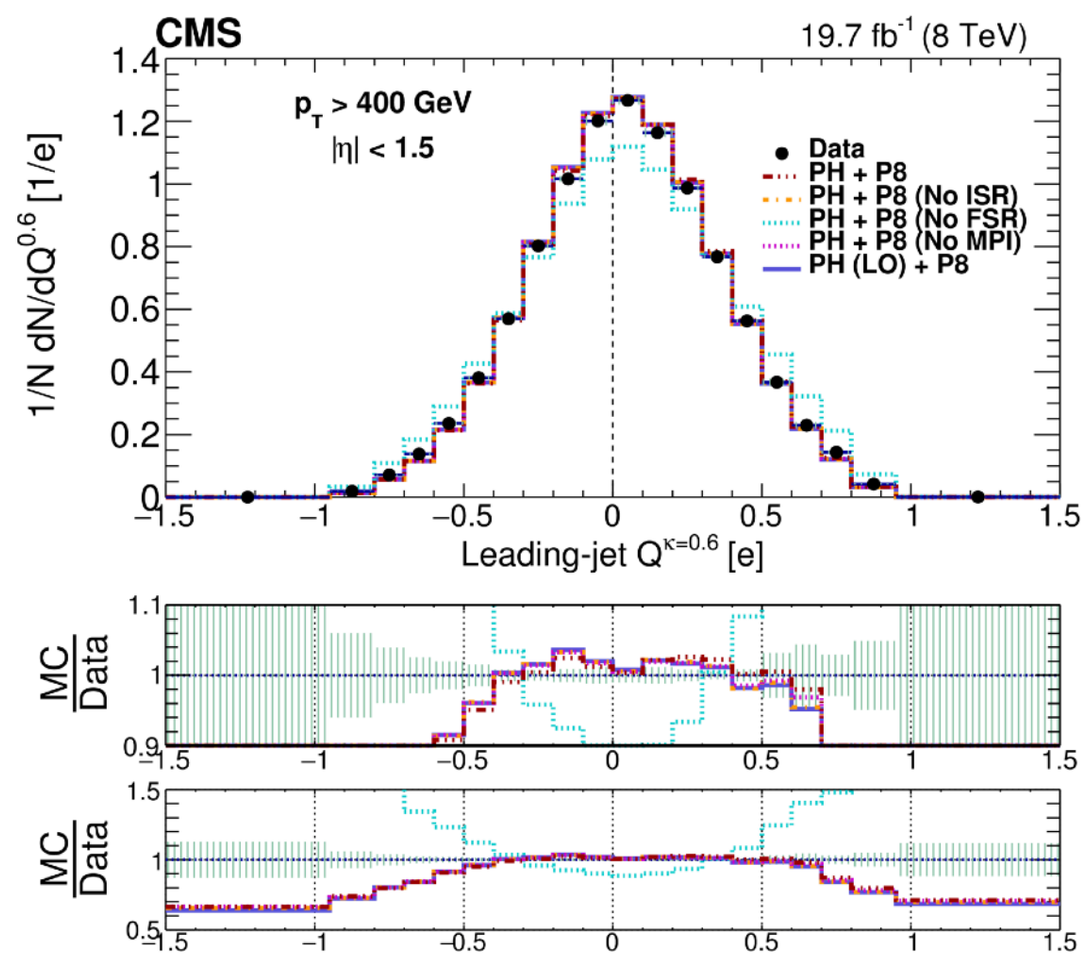
$$z_g = \frac{p_{T,2}}{p_{T,1}+p_{T,2}}$$

arXiv:1708.09429

Jets and fragmentation

- **Hardest hadrons preserve residual sensitivity to partonic charge**
  - sensitivity can be used as probe for fragmentation
  - simple / effective p_T-weighted average $Q^\kappa = \frac{1}{(p_T^{jet})^\kappa} \sum_i Q_i (p_T^i)^\kappa$ Nucl.Phys. B136 (1978) 1

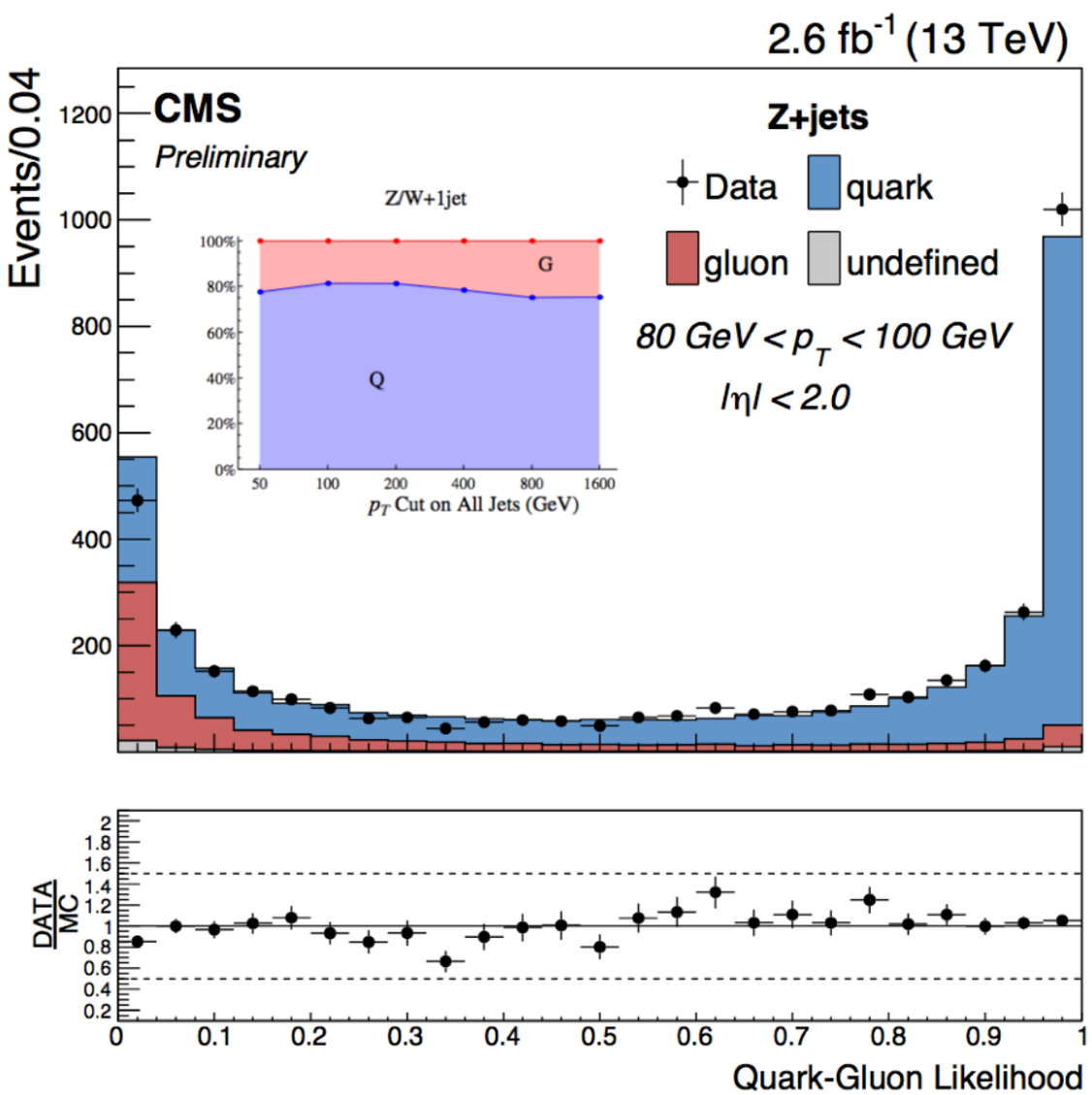


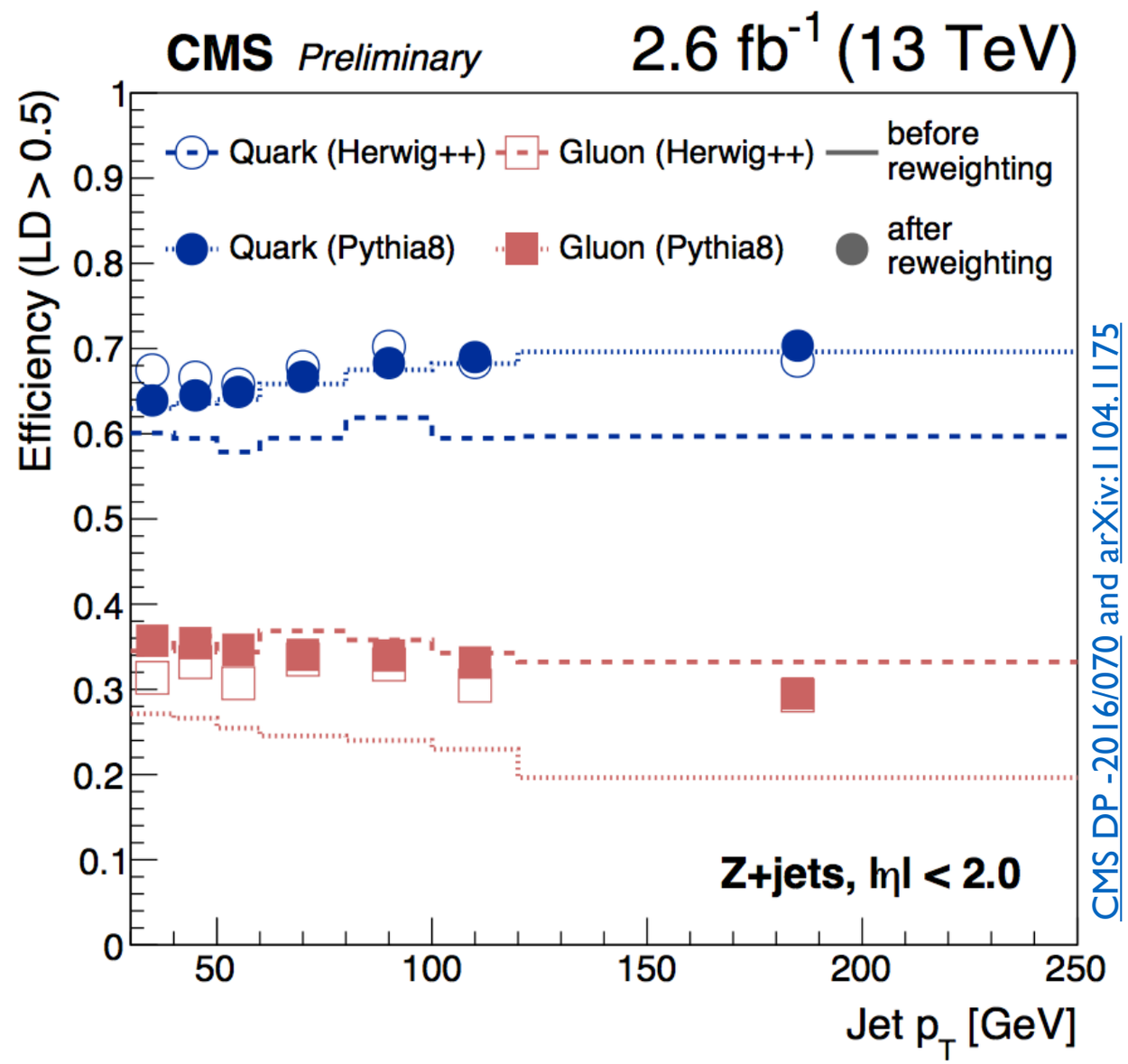


arXiv:1706.05868

Using fragmentation properties to discriminate q/g

- **Simple variables can be joined to build up multivariate discriminator**
  - gluon jets: diffuse, softer fragmentation, higher multiplicity
  - a scan of O(103) variables @ http://jets.physics.harvard.edu/qvg/
  - validation needed: use q-enriched (Z) / g-enriched (dijets) to correct expectations





Heavy flavour jets and fragmentation

- **Heavy quark fragmentation tuned from Z→bb @ LEP**
  - mass leads to most of the energy being carried by single hadron
  - charm and bottom mesons are long-lived hadrons

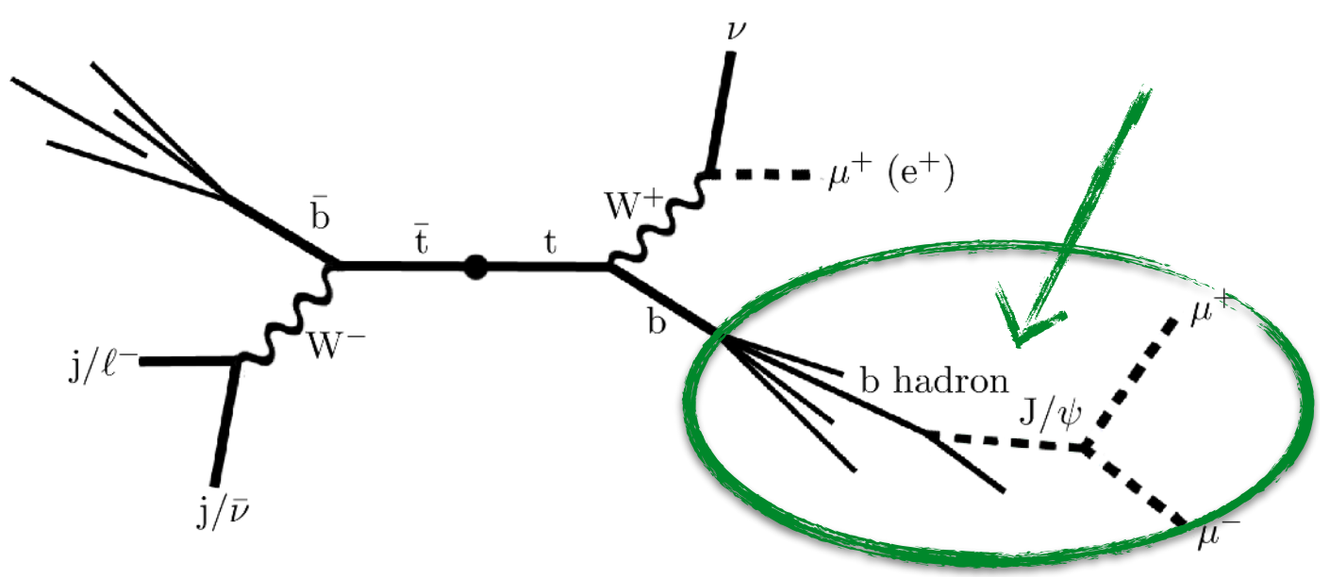
    ⇒ displaced vertices which can be reconstructed in the tracker

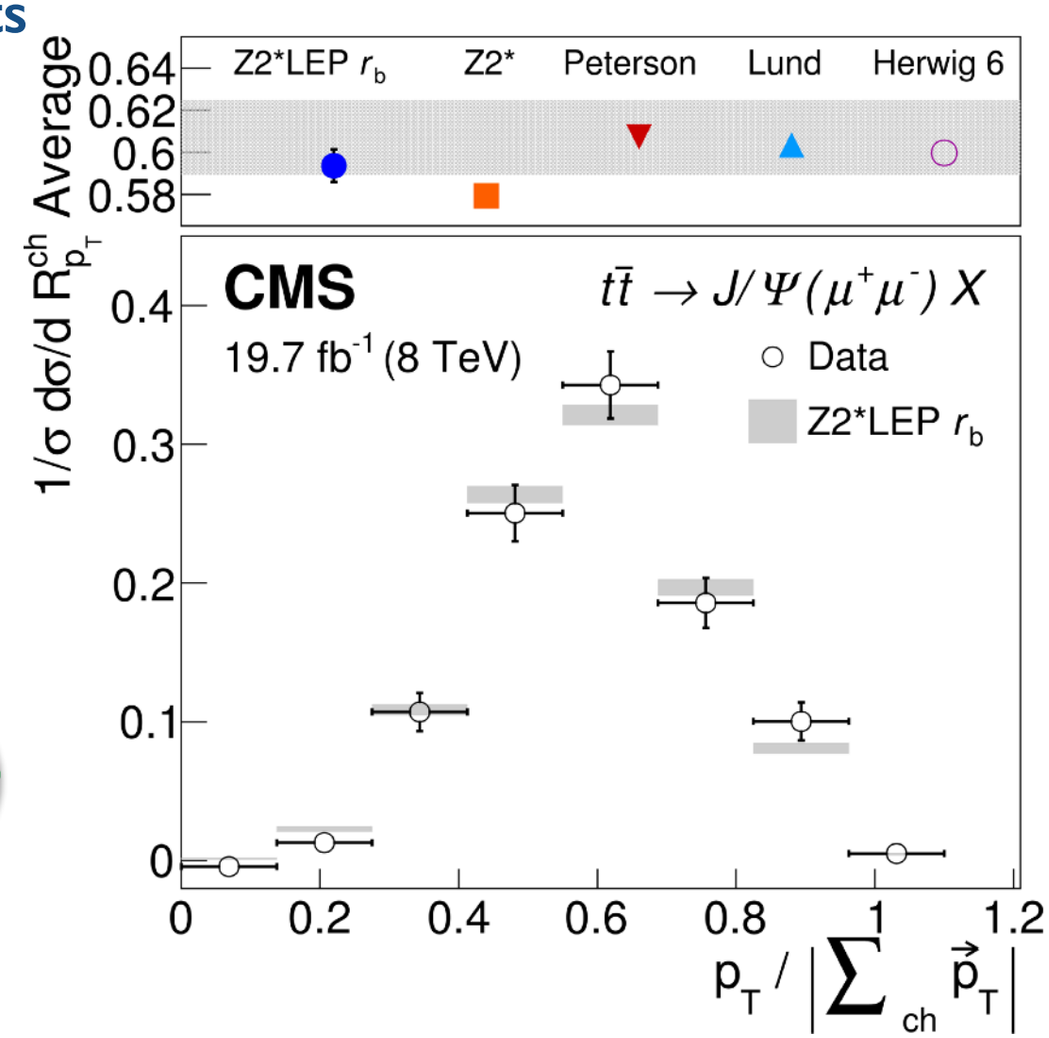
$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$

m

$$f(z) \propto \frac{1}{z^{1+r\cdot bm_\perp^2}}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$

- **Explicit reconstruction of charmed mesons in b jets**
  - probe fragmentation properties of heavy quarks

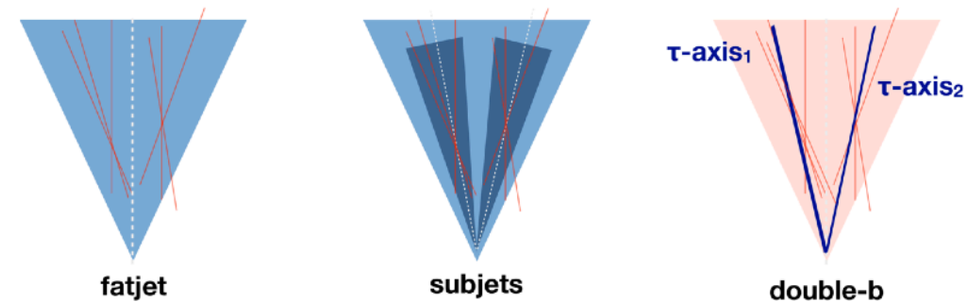


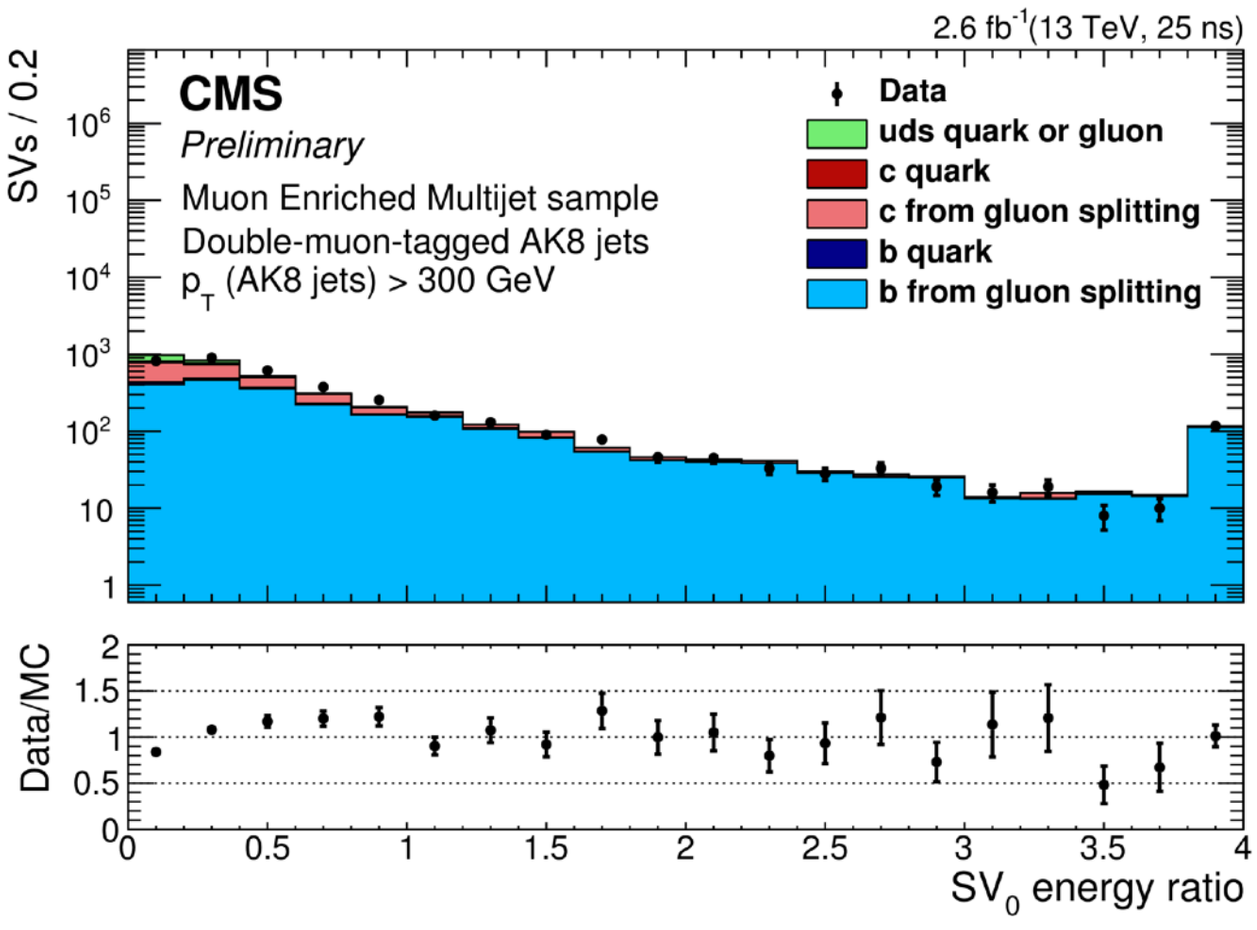


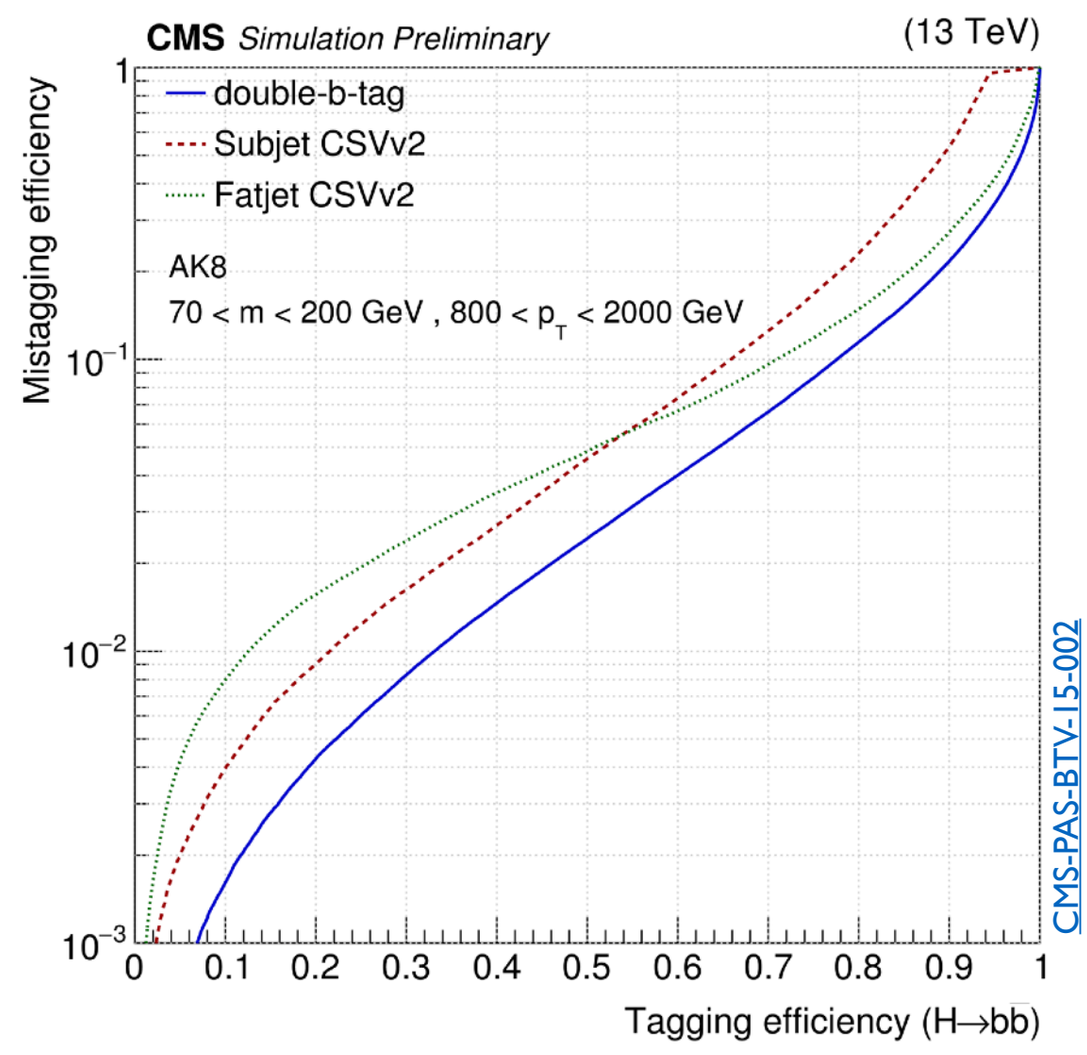
PRD 93 (2016) 092006

Using b/c fragmentation properties to discriminate from udsg

- **Secondary vertex : most discriminating variables**
  - but also track impact parameters, soft leptons etc.
  - efficiency/mistag rate must be validated in data
- **Gain from exploring further the sub-structure**
  - use the sub-jettiness axis to guide the regions of interest







CMS-PAS-BTV-15-002

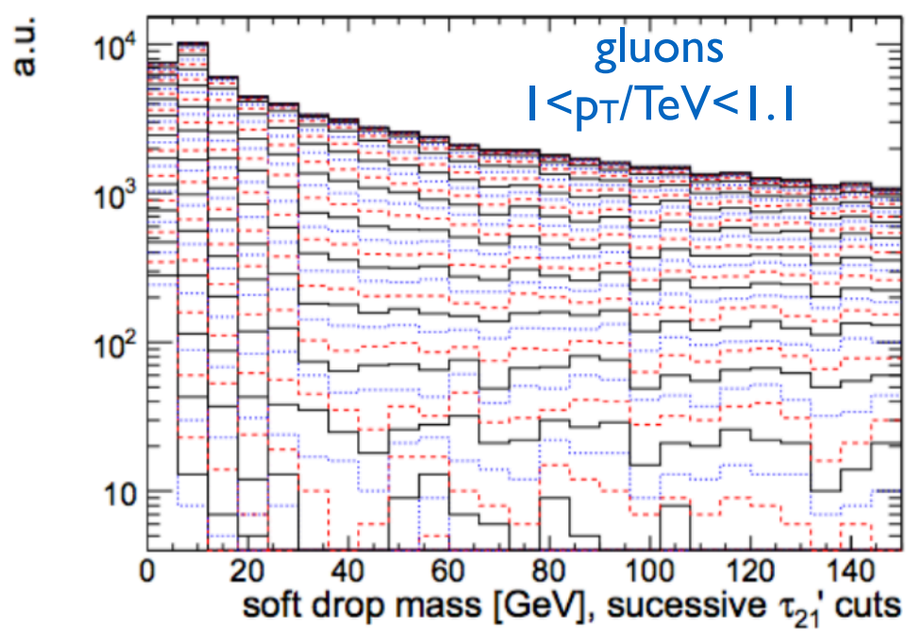
Ingredients to measure efficiency in-situ

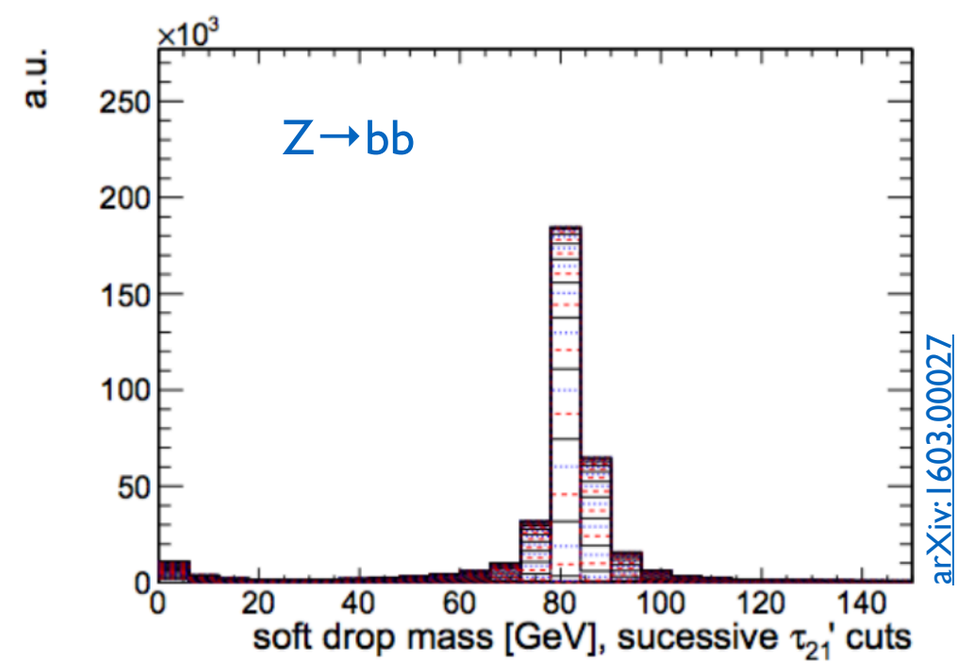
- **Mass dependency on p_T shapes backgrounds when hard cuts are applied**
  - make background look as uniform as possible independently of the jet p_T : $m \rightarrow \log(m^2/p_T^2)$
  - transform selection variables such that they preserve background shape

    e.g. cuts on N-subjettiness usually shape the backgrounds due to p_T

    linear transformation based on average behavior tends to flatten the background

$$\tau'_{21} = \tau_2/\tau_1 - \alpha\rho - \log p_T/\mu$$

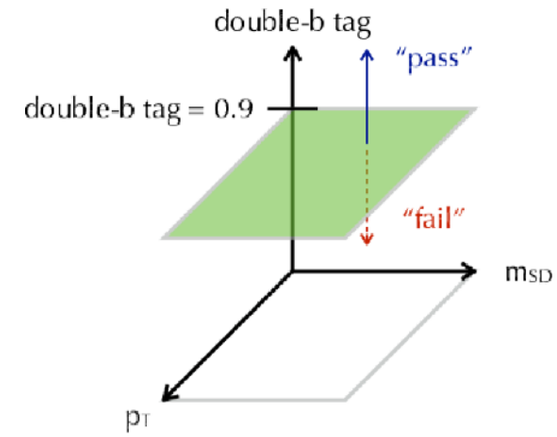


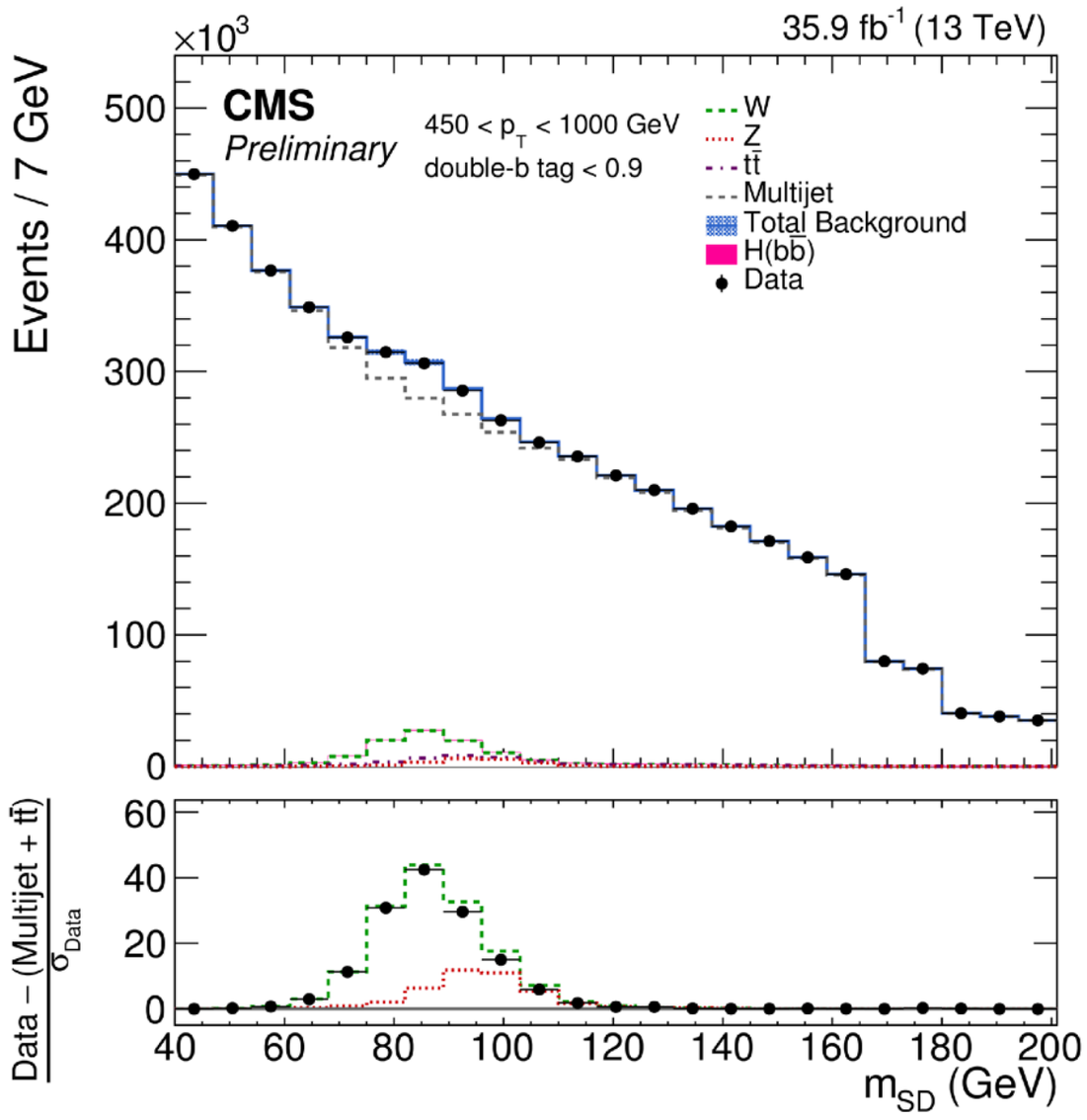


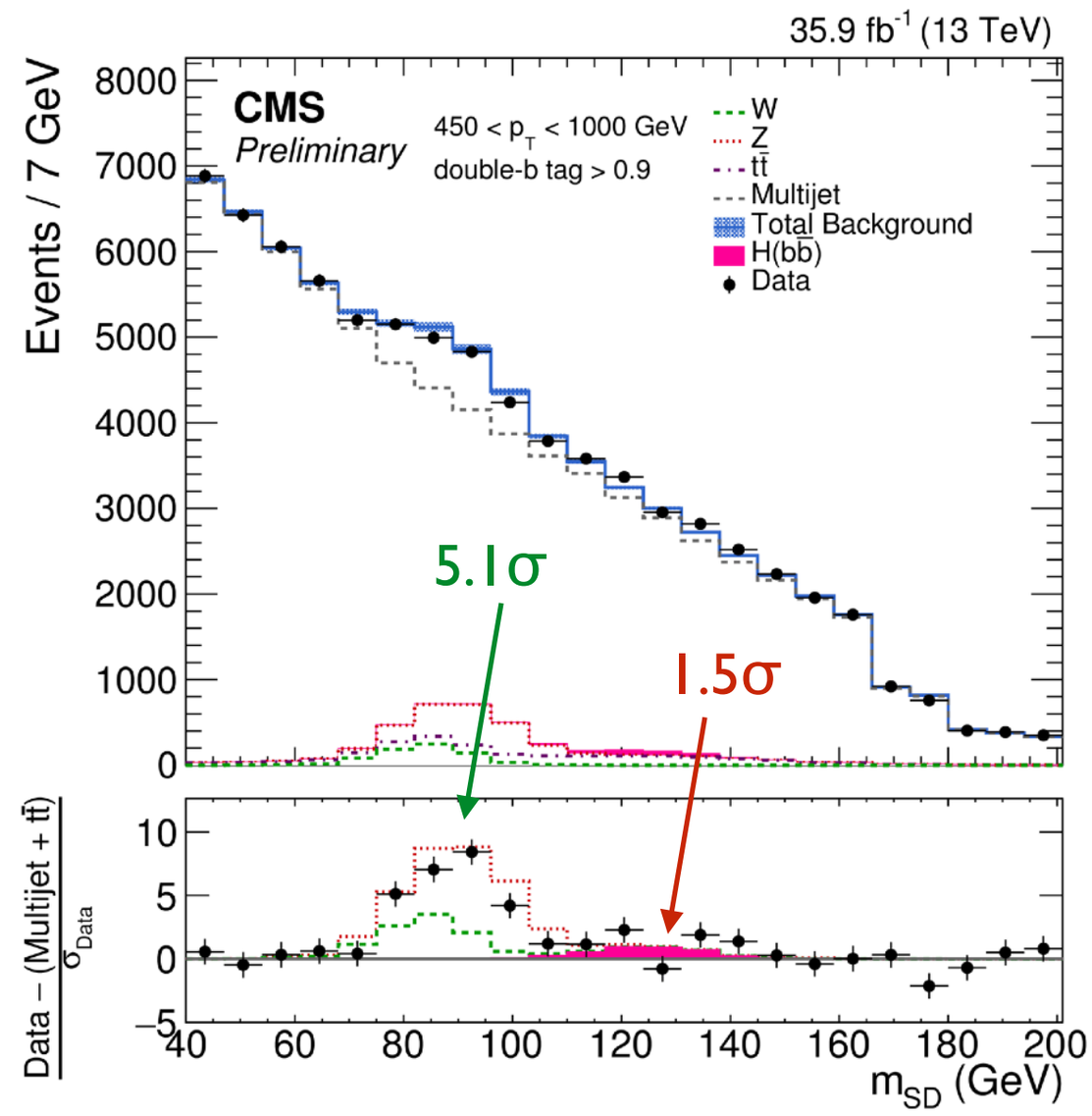
crucial to make the analysis scale with statistics: simultaneous fit pass and fail regions

Ingredients to observe H→bb

- Fail category: Z,W peaks allow further calibration of the signal
- Pass category: bias on signal efficiency kept to a minimum







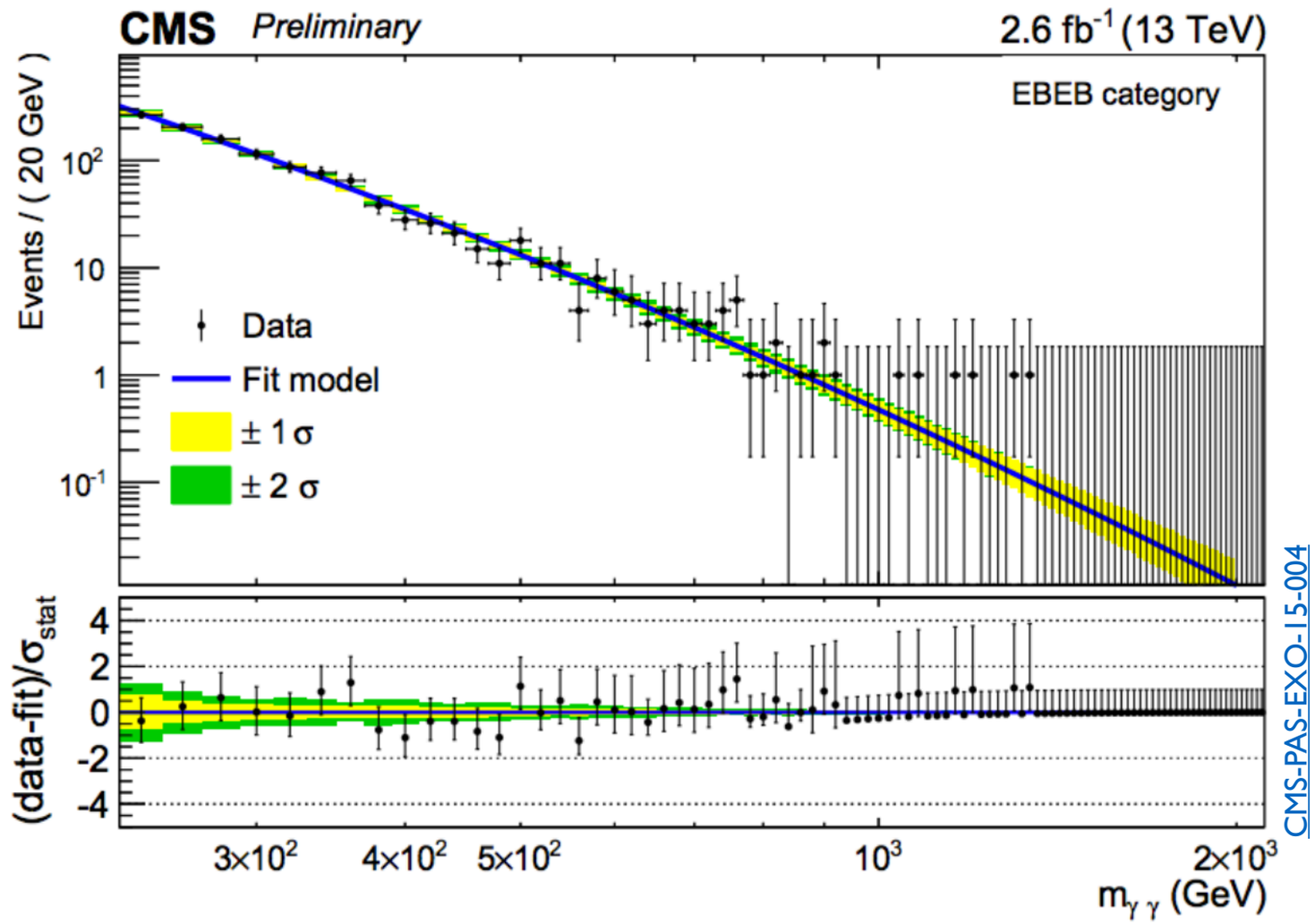
Modelling backgrounds and statistical flukes

Modelling backgrounds and statistical flukes

Modelling backgrounds and statistical flukes

(c) Geotripper blog

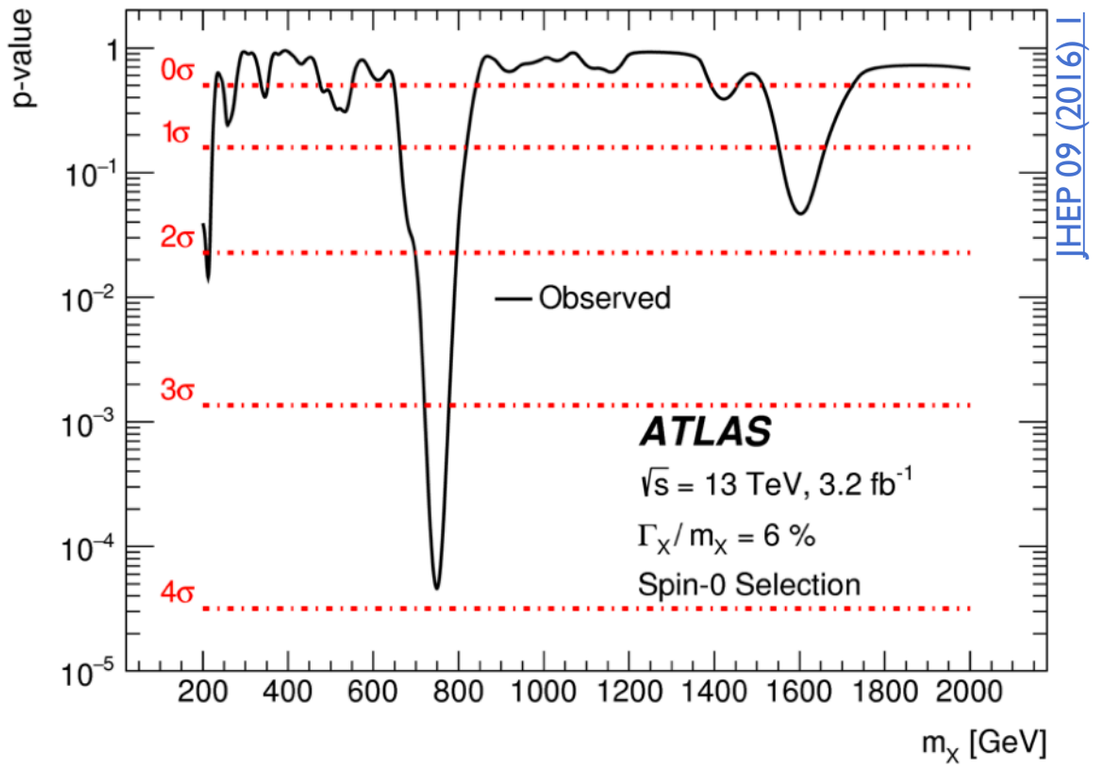
Modelling backgrounds and statistical flukes



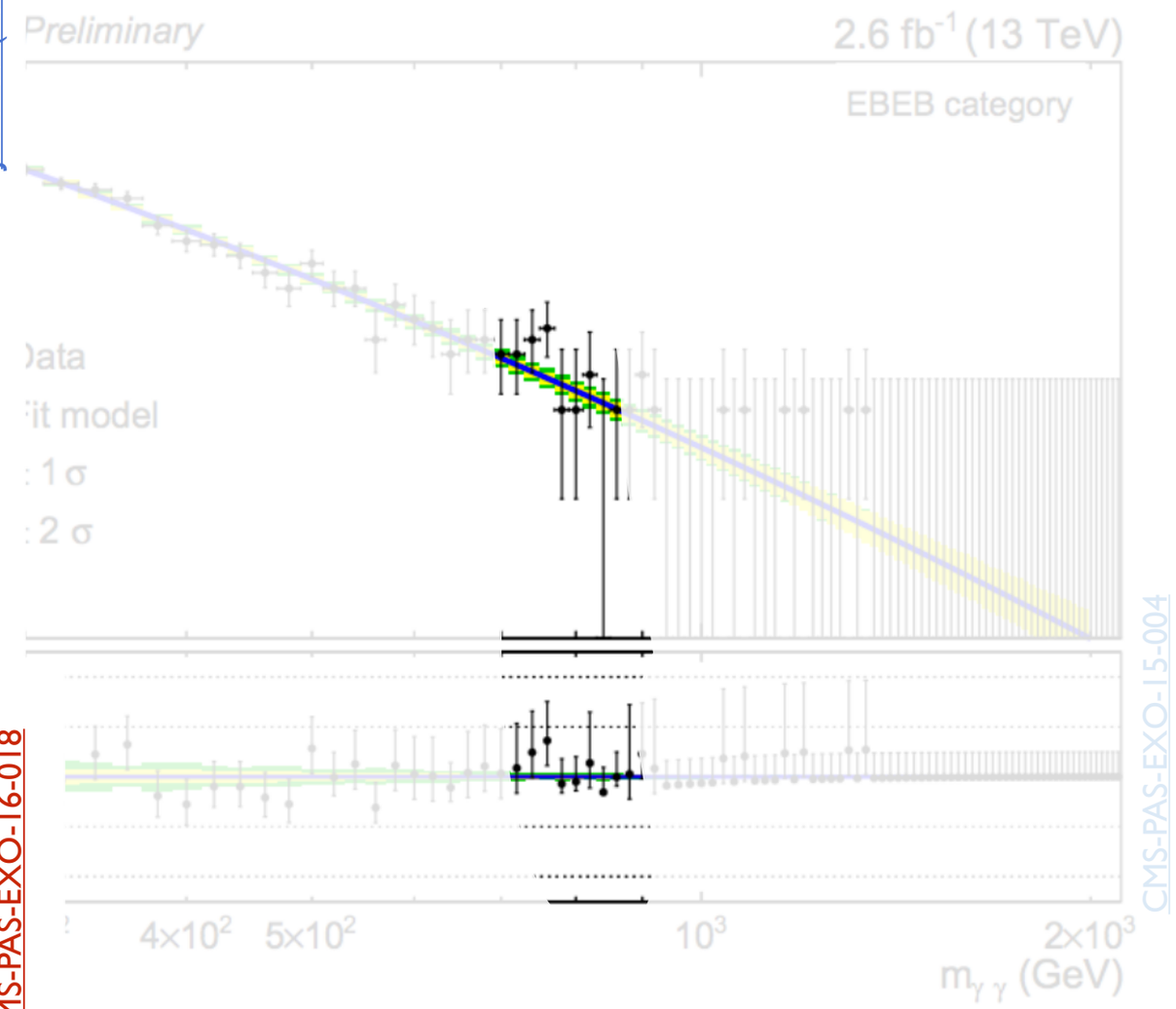
CMS-PAS-EXO-15-004

A parametrization $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$
models the main characteristics of the background.
Calibrated in simulation using several test regions:
extra correction terms added in order to keep the pulls bias <0.5.

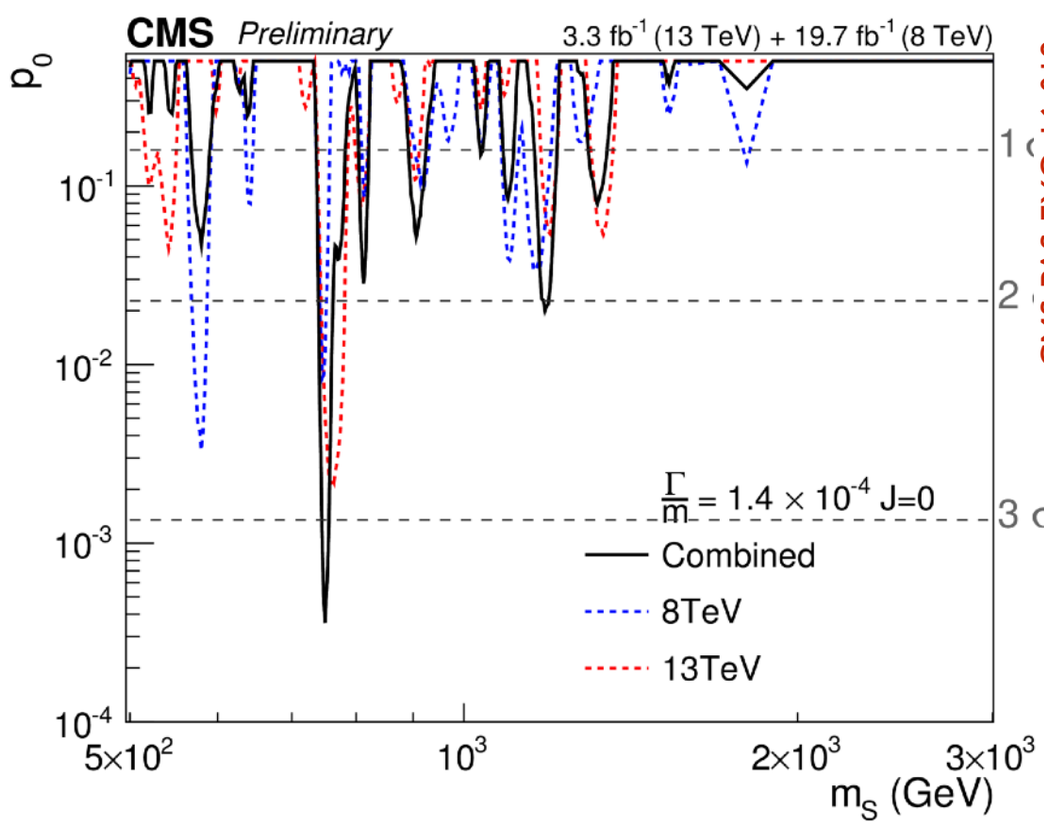
Modelling backgrounds and statistical flukes



JHEP 09 (2016) 1



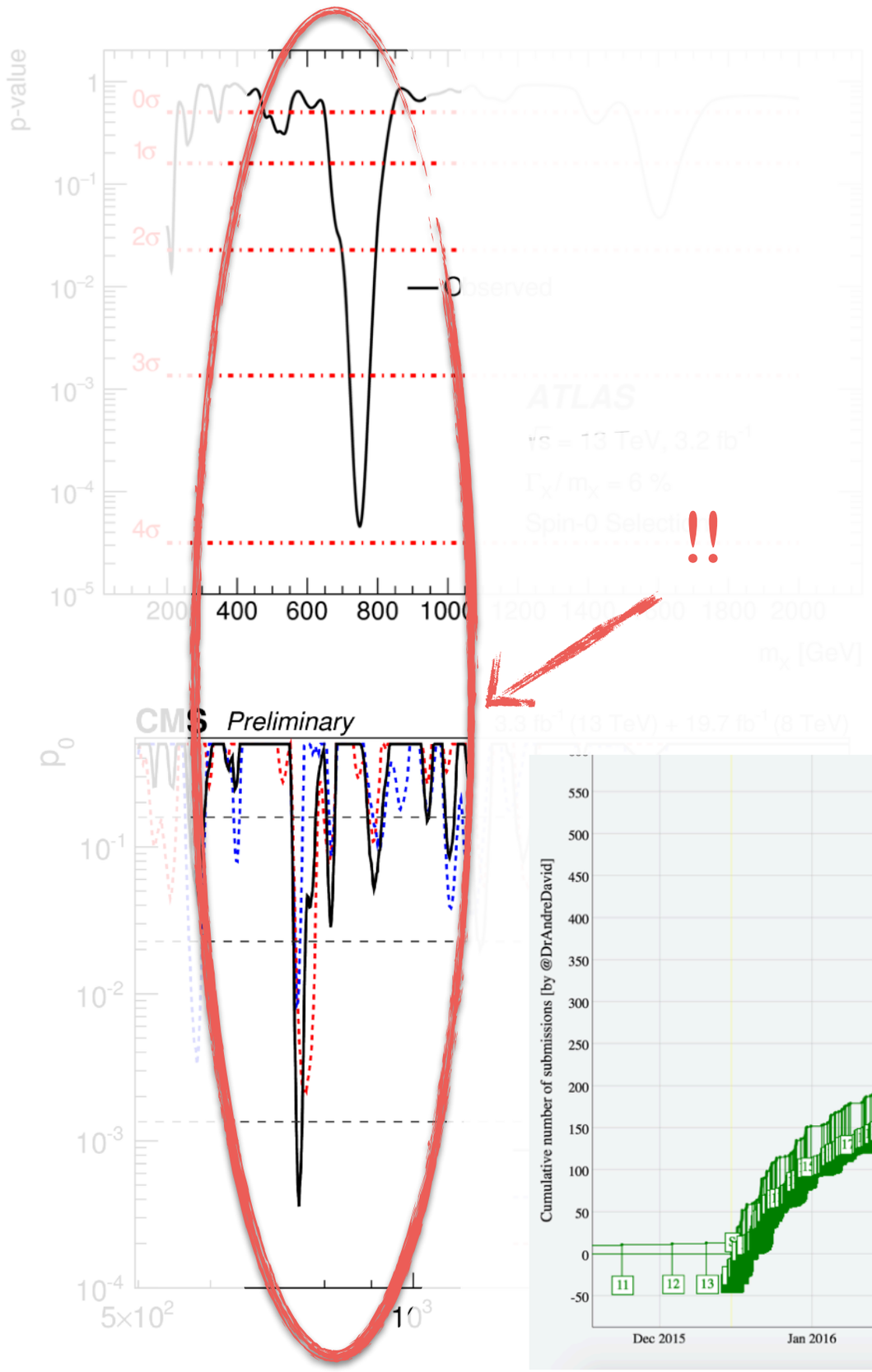
CMS-PAS-EXO-15-004

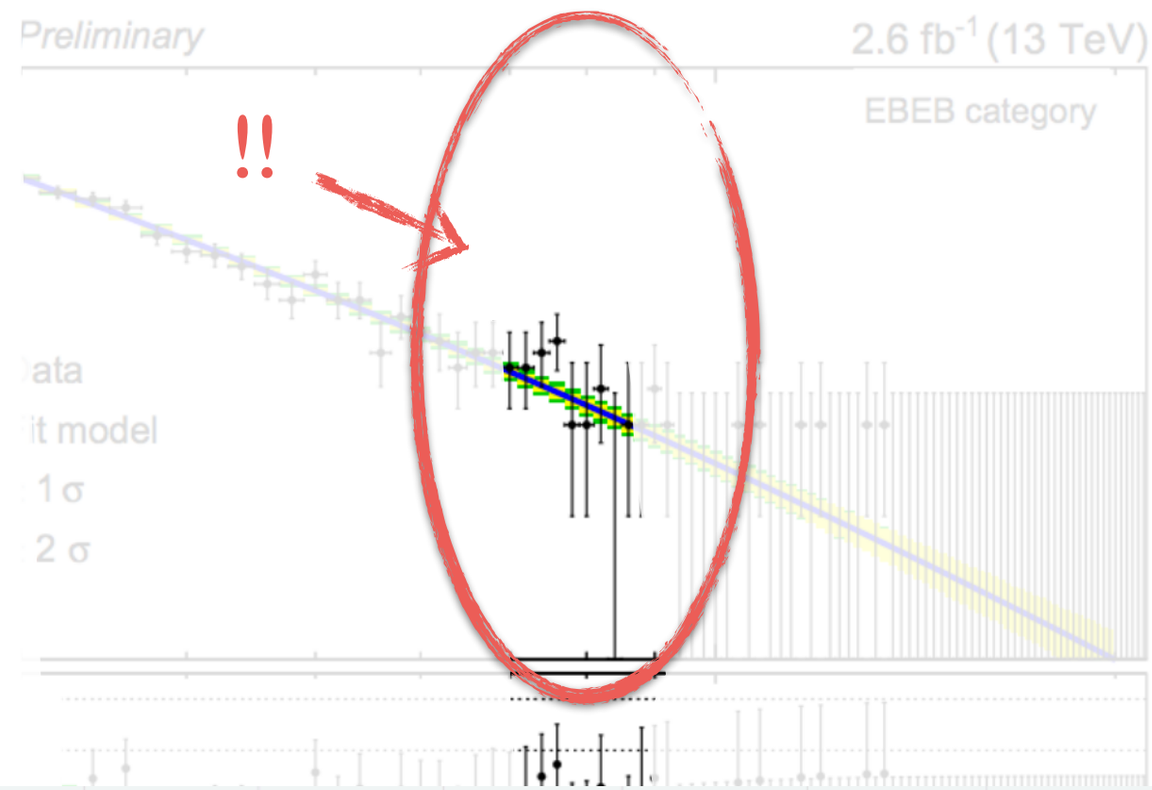


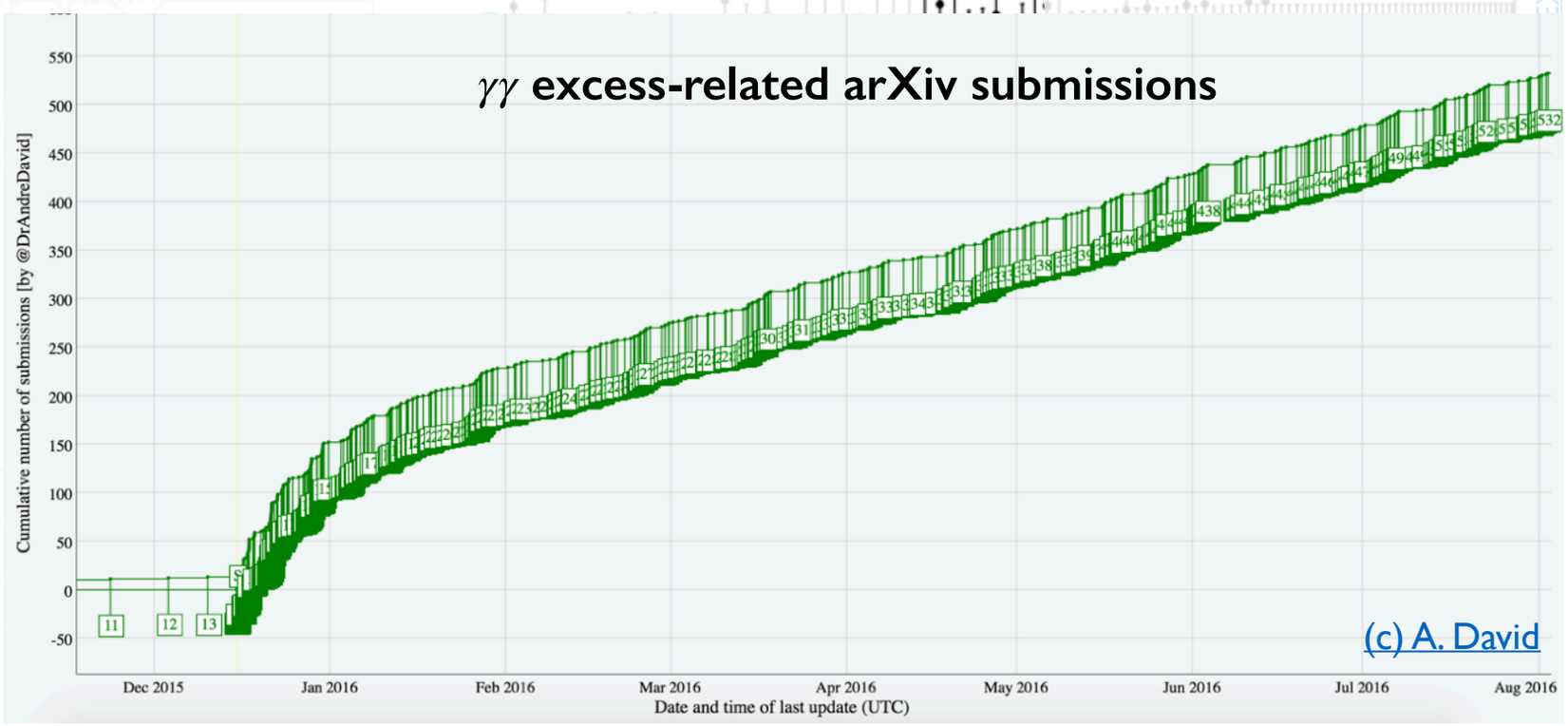
CMS-PAS-EXO-16-018

Largest deviation for narrow width at 750 GeV with local significance **3.9σ** (**3.4σ**).
Taking into account the effect of testing all the signal hypotheses considered, the global significance is approximately **2.1σ** (**1.6σ**).

Modelling backgrounds and statistical flukes

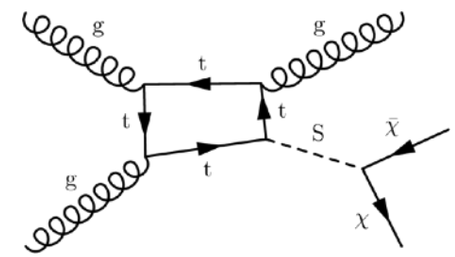




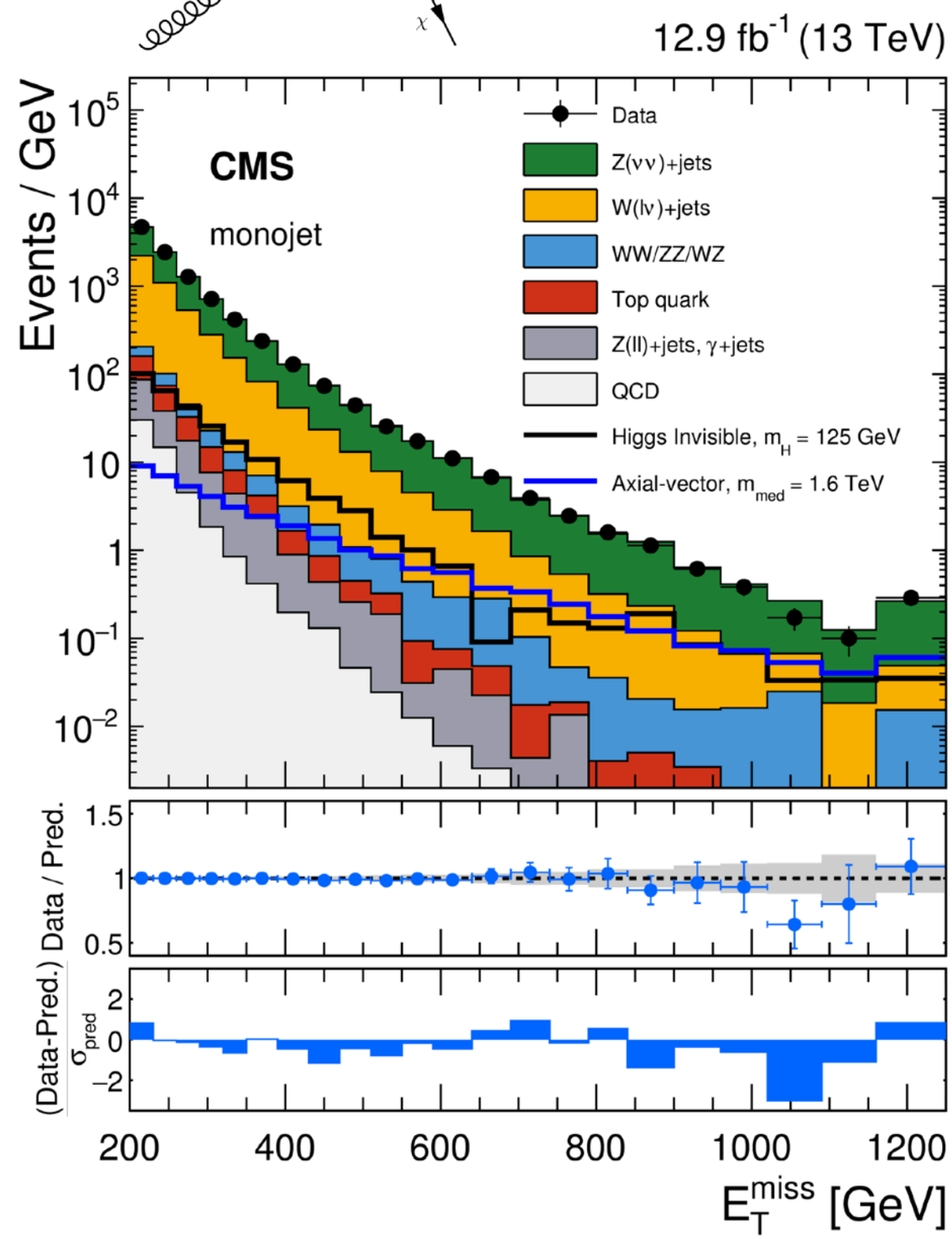


Modelling backgrounds

- **Reducible background can be understood**
  - from detector response
  - applying tighter filter procedures
- **Irreducible backgrounds mimic the signal**
  - usually generated by high σ processes
  - need extrapolation by several orders of magnitude
  - hard to believe (or generate) only simulated events
- **Blind analysis: often help to minimize bias**
  - optimize selection while understanding backgrounds
  - make sure uncertainties are in before opening box

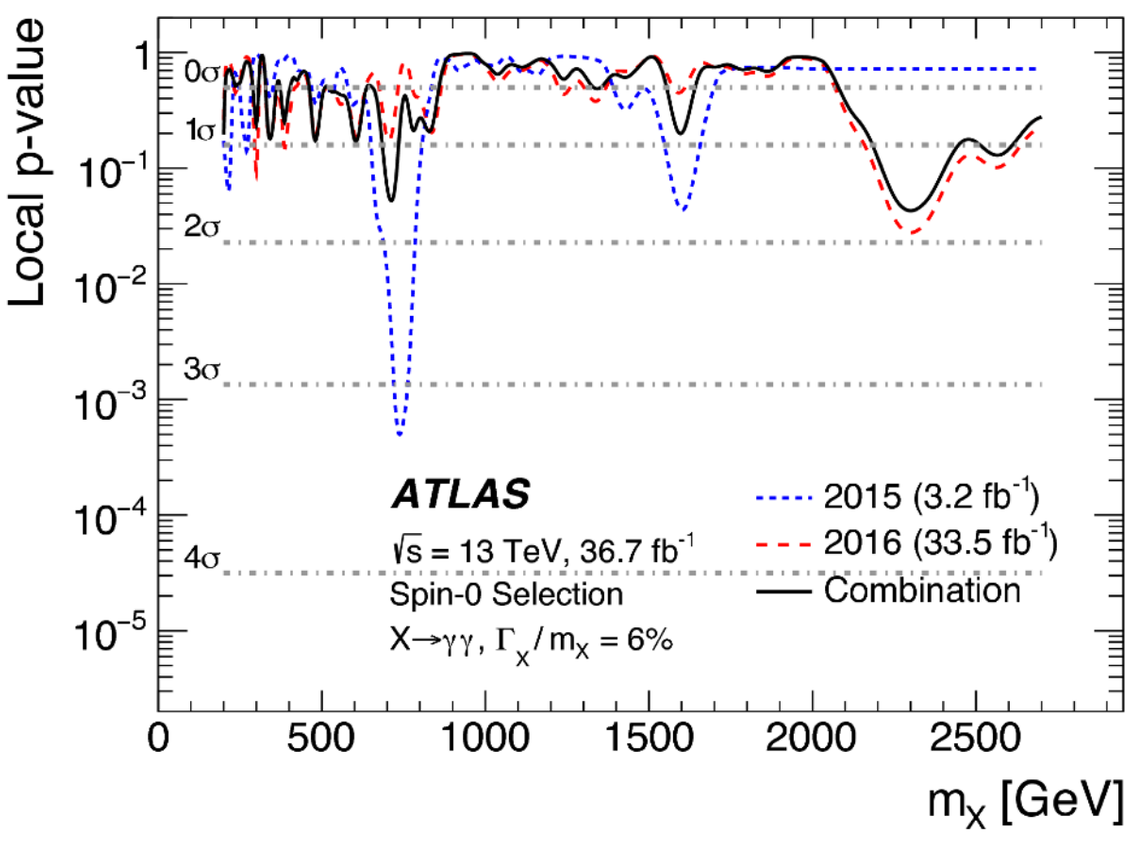


JHEP 07 (2017) 014

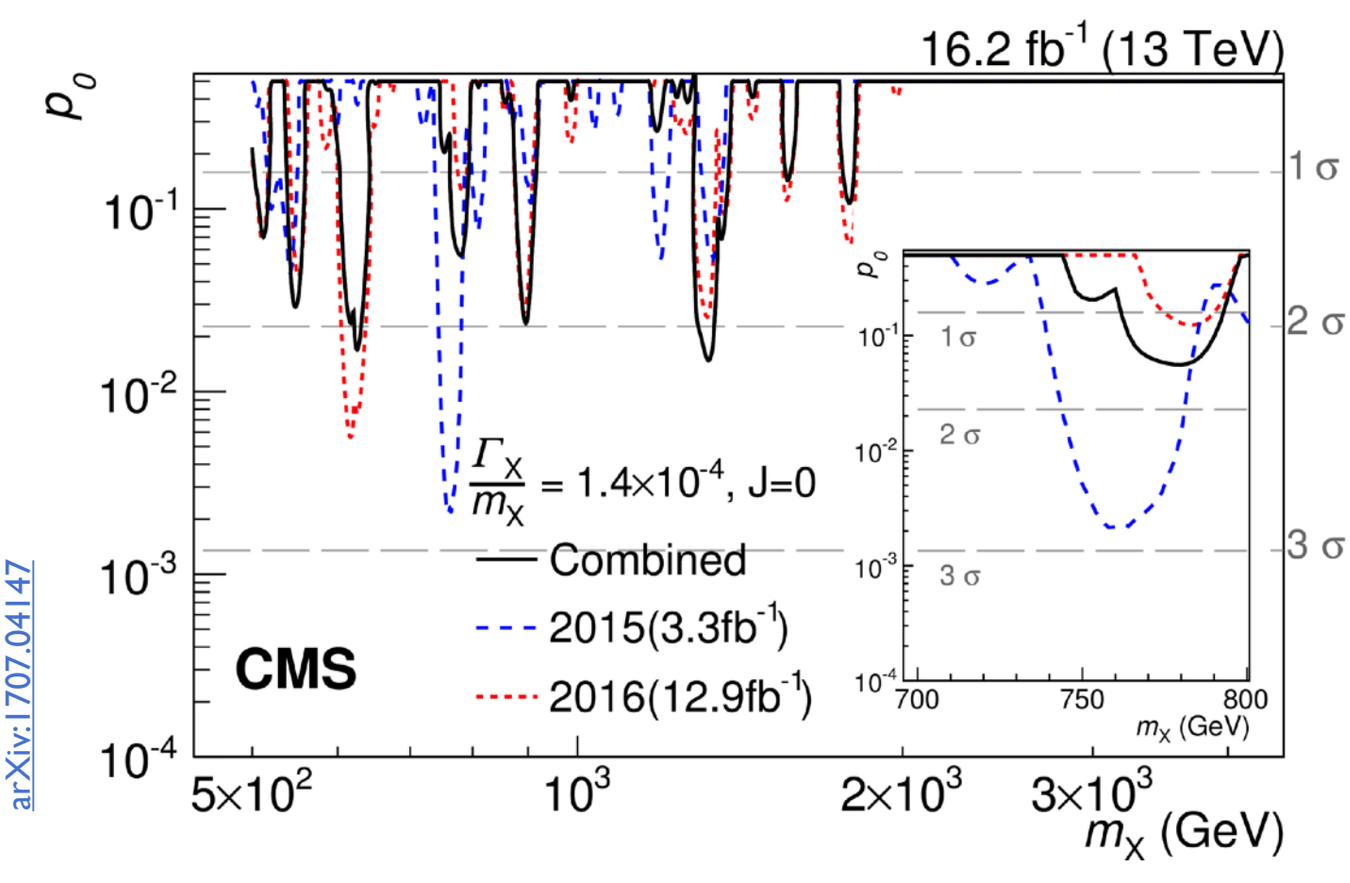


Statistical flukes

- **Anomalies shall appear!**
  - apply 5-σ criterium: P(data | null hypothesis) = 2.7×10^{-5} %
  - size of the parameter space (mass range, models…) enhances probability of observing local deviations
- **The look-elsewhere-effect can't be neglected** (see EPJC70:525-530,2010)
  - throw background-only toys and for each run background-only fit
  - how many of those trials surpassed the maximum local significance observed in data?



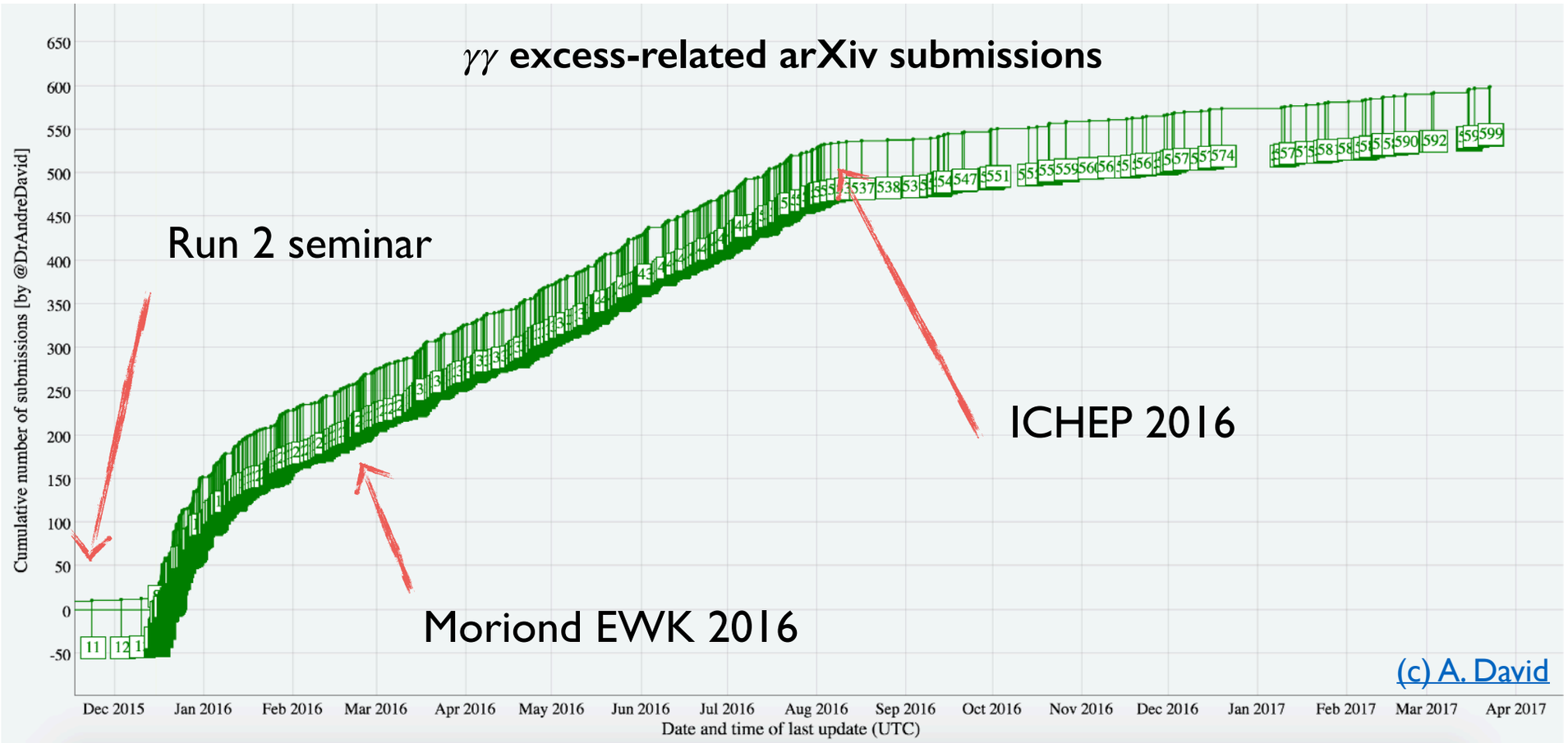
arXiv:1707.04147



Phys. Lett. B 767 (2017) 147

Modelling backgrounds and statistical flukes: epilogue

ATLAS+CMS: These are the most stringent limits on Randall-Sundrum graviton production to date.



Interpreting the 750 GeV digamma excess: a review

Alessandro Strumia

(Submitted on 30 May 2016 (v1), last revised 5 Aug 2016 (this version, v2))

We summarise the main experimental, phenomenological and theoretical issues related to the 750 GeV digamma excess

Comments: To appear in the proceedings of the Moriond 2016 conference version 2: note added, it's dead
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex); High Energy Physics – Theory (hep-th)
Report number: CERN-TH-2016-131
Cite as: **arXiv:1605.09401 [hep-ph]**
(or **arXiv:1605.09401v2 [hep-ph]** for this version)

Reprise: what do we measure at the LHC?

We count…

- **There is (almost) no measurement without a supporting theory**

$$\sigma_{tot} = \frac{1}{A}\sigma_{fid} = \frac{1}{A} \cdot \frac{N_{signal}}{\mathcal{L} \cdot \varepsilon \cdot SF}$$

theory⊗experiment?

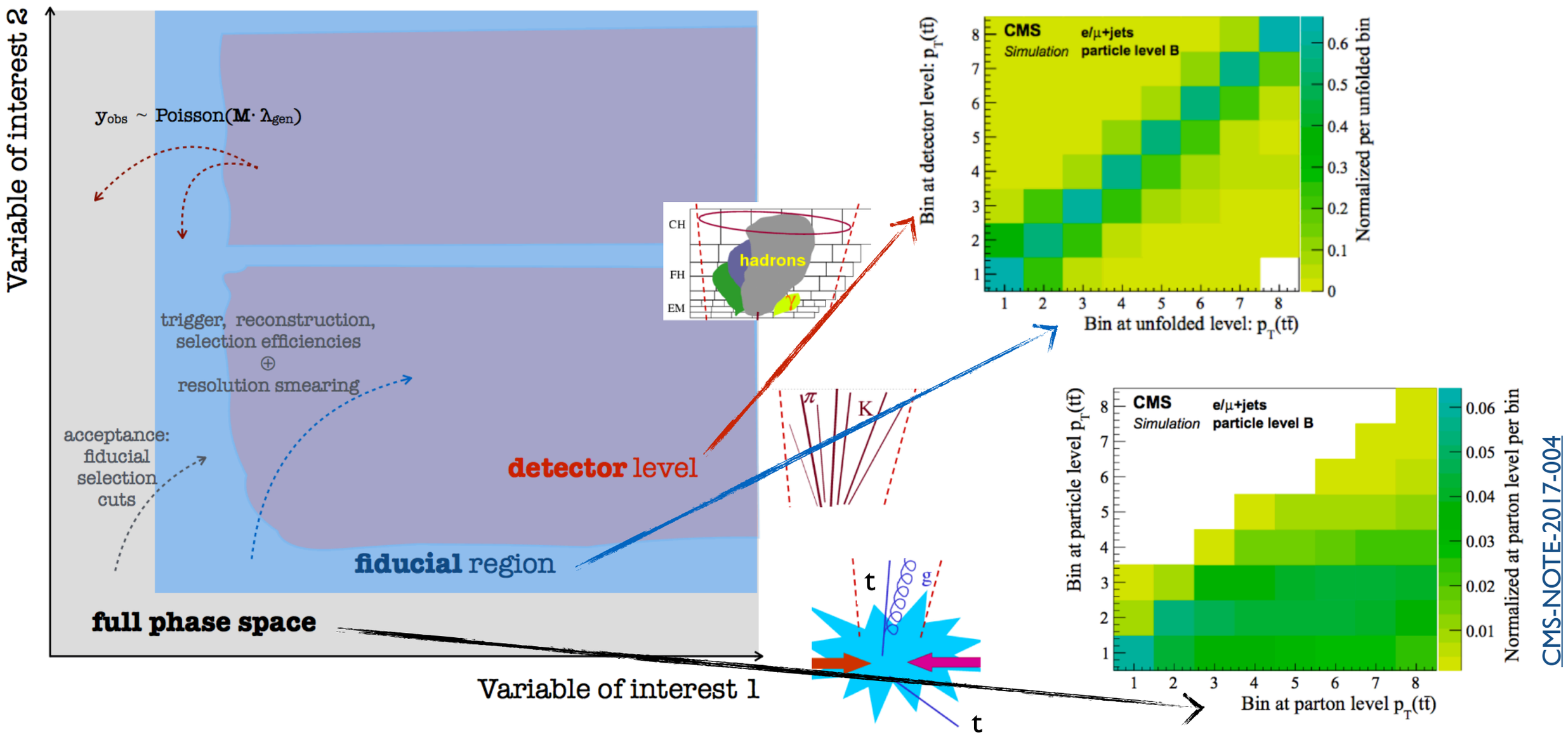
theory: acceptance $[N_{fid}/N_{tot}]_{gen}$

experiment: luminosity (see slide 51); efficiency $[N_{sel}/N_{gen}]_{fid}$; efficiency corrections (see slide 52)

- **Result depends on the order of the calculation, non-perturbative models available**
  - extrapolation through acceptance needs a theory model behind
- **Theory may also enter in the fiducial measurement**
  - Rare signals often need signal vs. background discriminator to be constructed
  - expected signal kinematics may also enter through efficiency term

Comparing back to theory

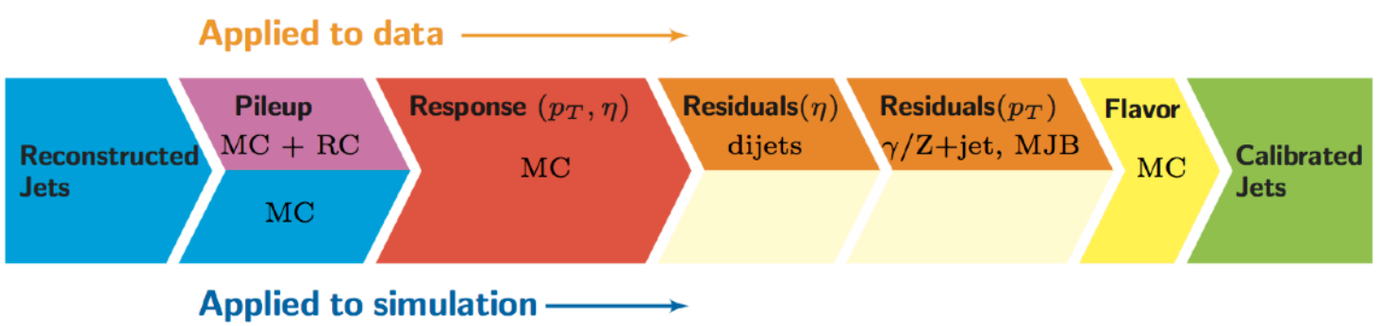
- **Correcting a differential measurement=unfolding**
  - brings in theory assumptions: (data) → (data⊗detector simulation+theory priors)
  - often requires regularisation procedures to allow for smooth matrix inversion



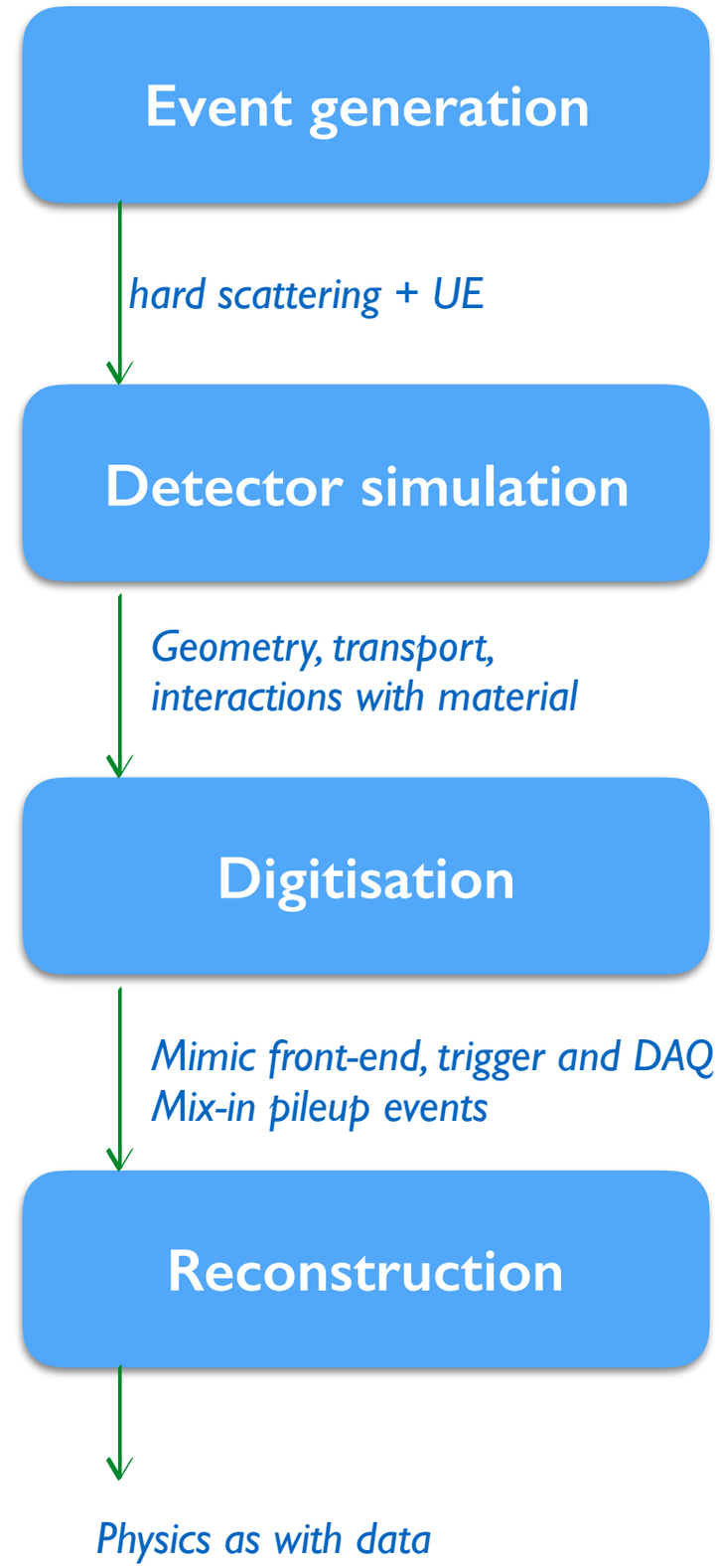
CMS-NOTE-2017-004

Simulation

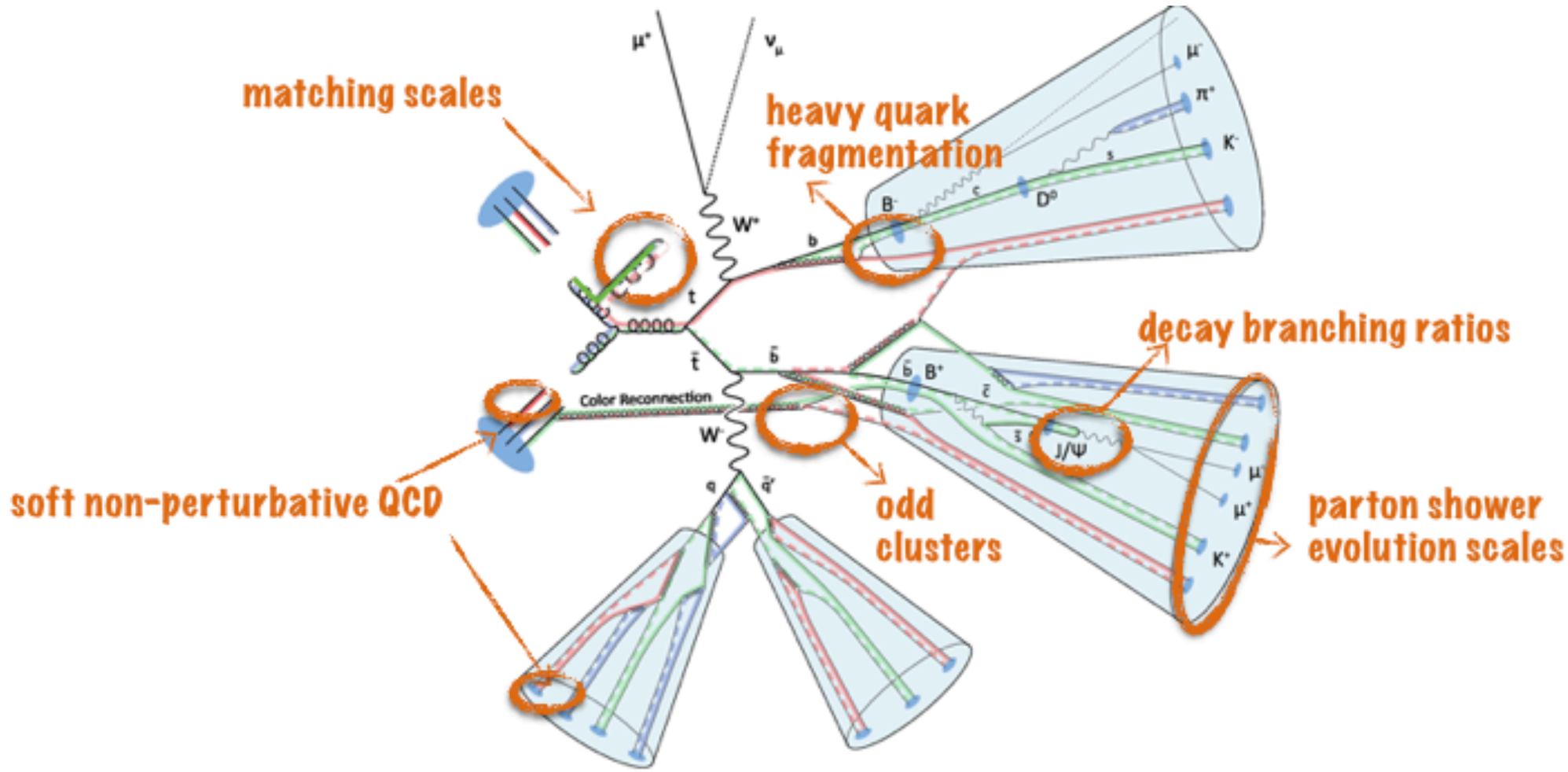
- **Event generation using state-of-the-art Monte-Carlo**
  - NLO (LO) QCD matrix elements up to 2 (5) partons
  - matching to parton showers (Pythia, Herwig, Sherpa,…)
- **Final state particles passed through detector simulation**
  - usually based on Geant4 (transport and interaction with matter)
  - crucial step to get the best calibrated objects, e.g. jets:



  - Simulated hits are used to emulate the electronics behavior
  - Reconstruction from "digis" as if standard data
- **Notice: most data volume stored on tape is simulation**
  - order 5 billion events needed in 2016 for 37 fb^{-1} of data

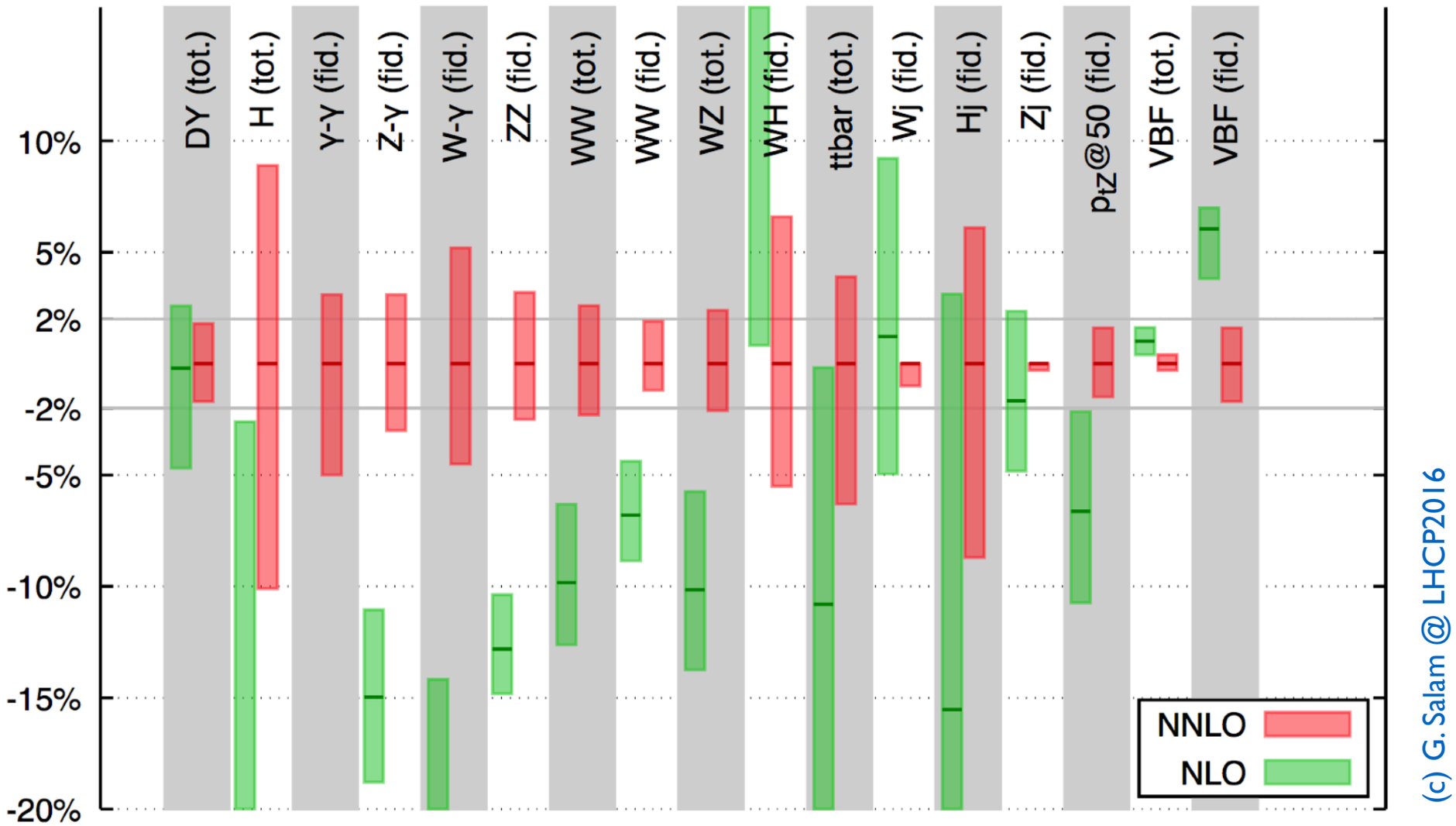


The ubiquity of parton shower generators



- **Widely used to predict the final outcome of a pp collision**
- **Hard process** (matrix element⊗PDF) **needs to be dressed with**
  - shower evolution of the leptons and partons (strong and EWK ISR/FSR) + ME to PS matching
  - intrinsic k_T, multi-parton interactions, beam remnants and associated colour (re)-connections, etc.
- **Phenomenological models used to model non-perturbative QCD regime**
  - can be tuned but are ultimately an "uncertainty barrier for measurements"

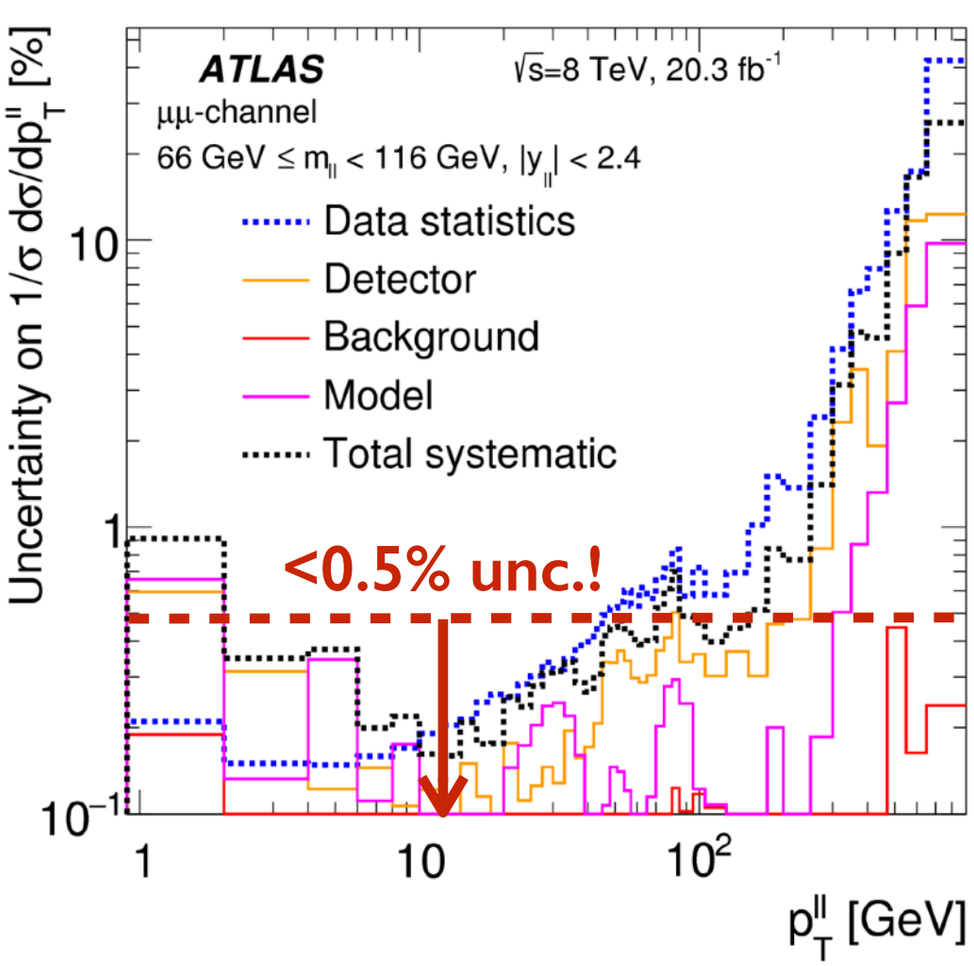
Cross sections I



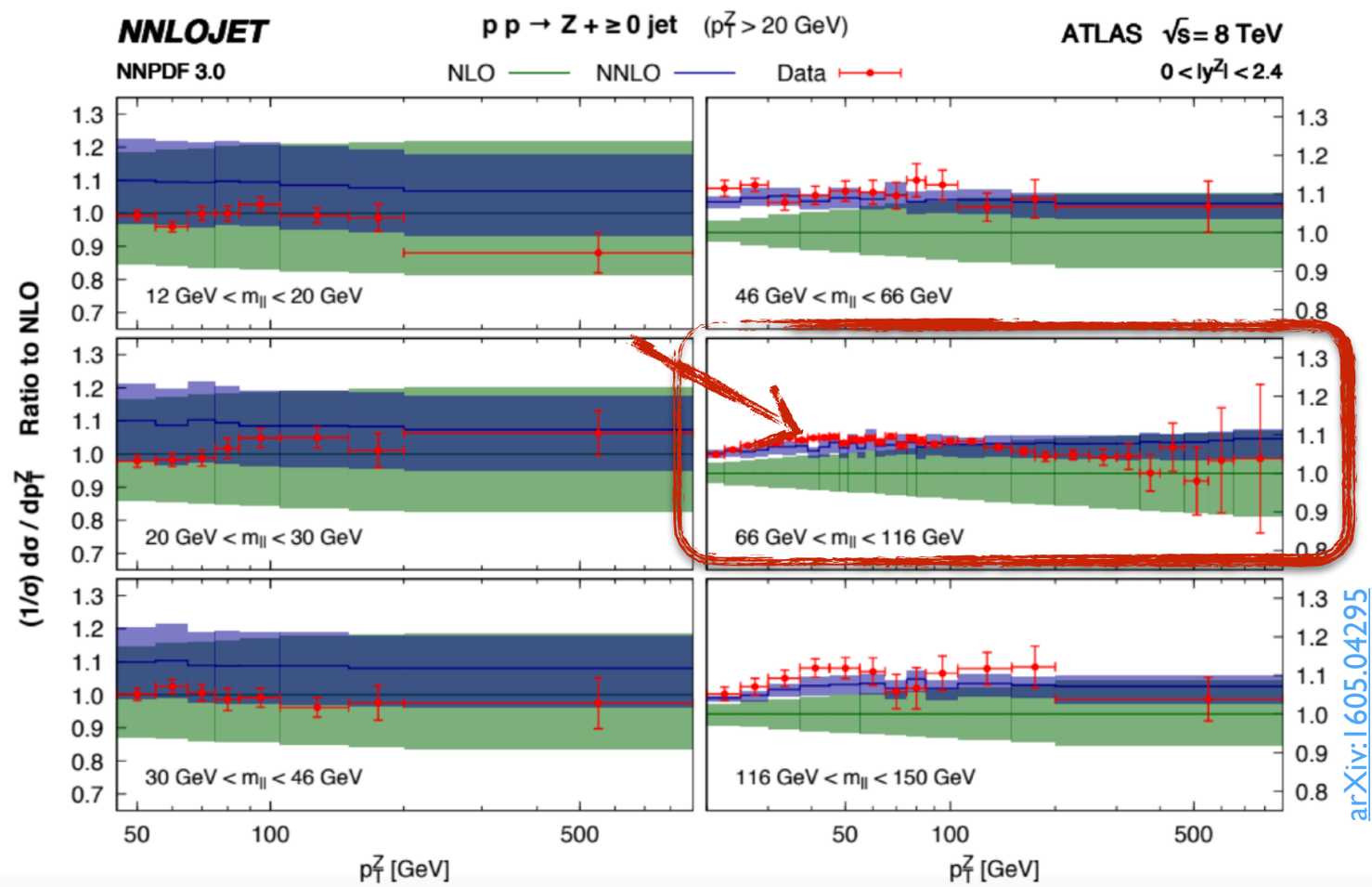
- **Several processes have been computed at NNLO QCD**
  - scale band is 2-10% but in many cases does not encompass NLO!
- **EWK corrections start to matter:**
  - e.g. at high p_T can contribute O(10%) to dijet rate

Cross sections II

- p_T distributions span a wide range in theory predictions
- Small (large) p_T dominated by resummed higher order (QCD at fixed-order)
  - electroweak corrections become also non-negligible at high p_T
  - are non-perturbative QCD effects under control down to <1%?
- Experimental precision competitive with NNLO (Z p_T, top p_T)
  - use to extract PDFs, α_S, couplings or are we biasing future measurements/searches?



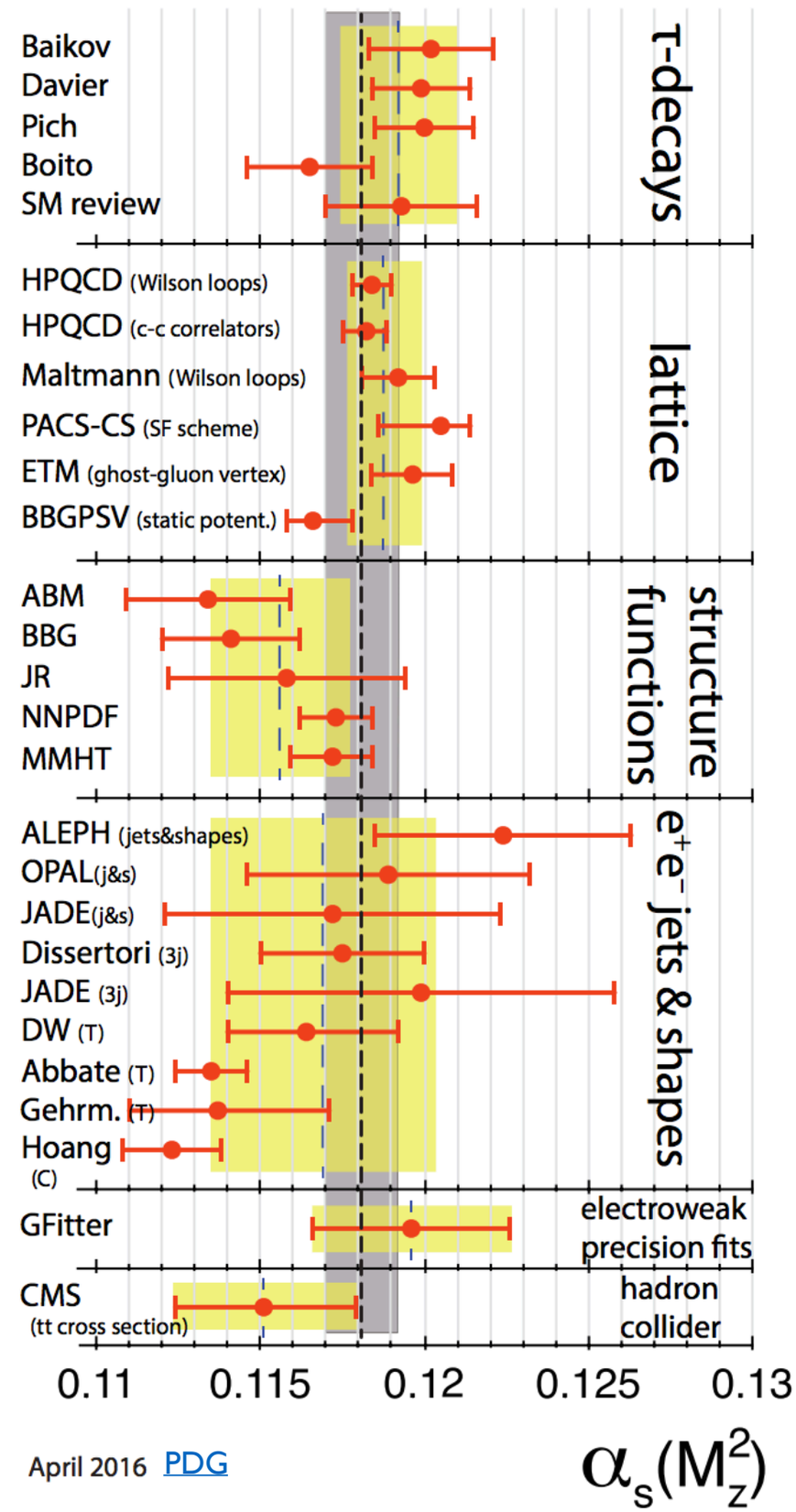
Eur. Phys. J. C 76(5), 1-61 (2016)



arXiv:1605.04295

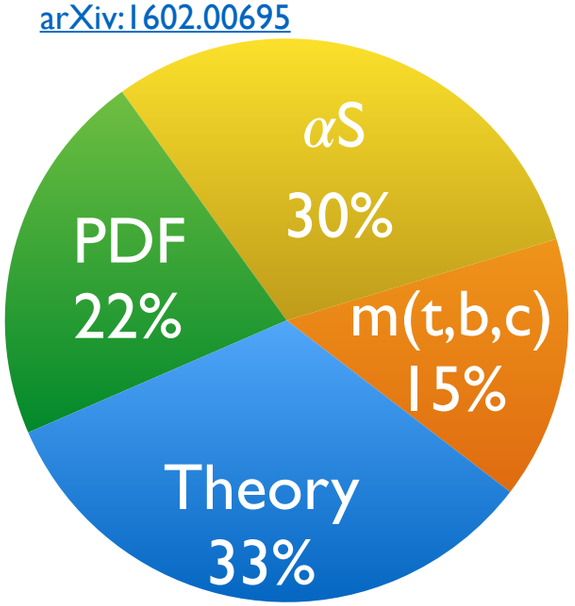
Strong coupling constant

- **Contributes with relevant uncertainty at the LHC**
  - world average yields 1.1% unc. on $\alpha_S(M_Z)$
  - expansion parameter in PDFs, matrix elements, …
  - increasingly relevant to probe new physics more accurately



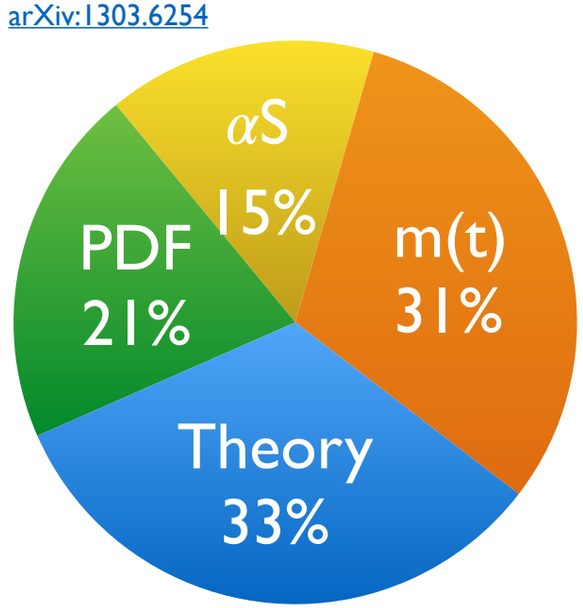
$\sigma(gg \to H)$ at N^3LO

arXiv:1602.00695

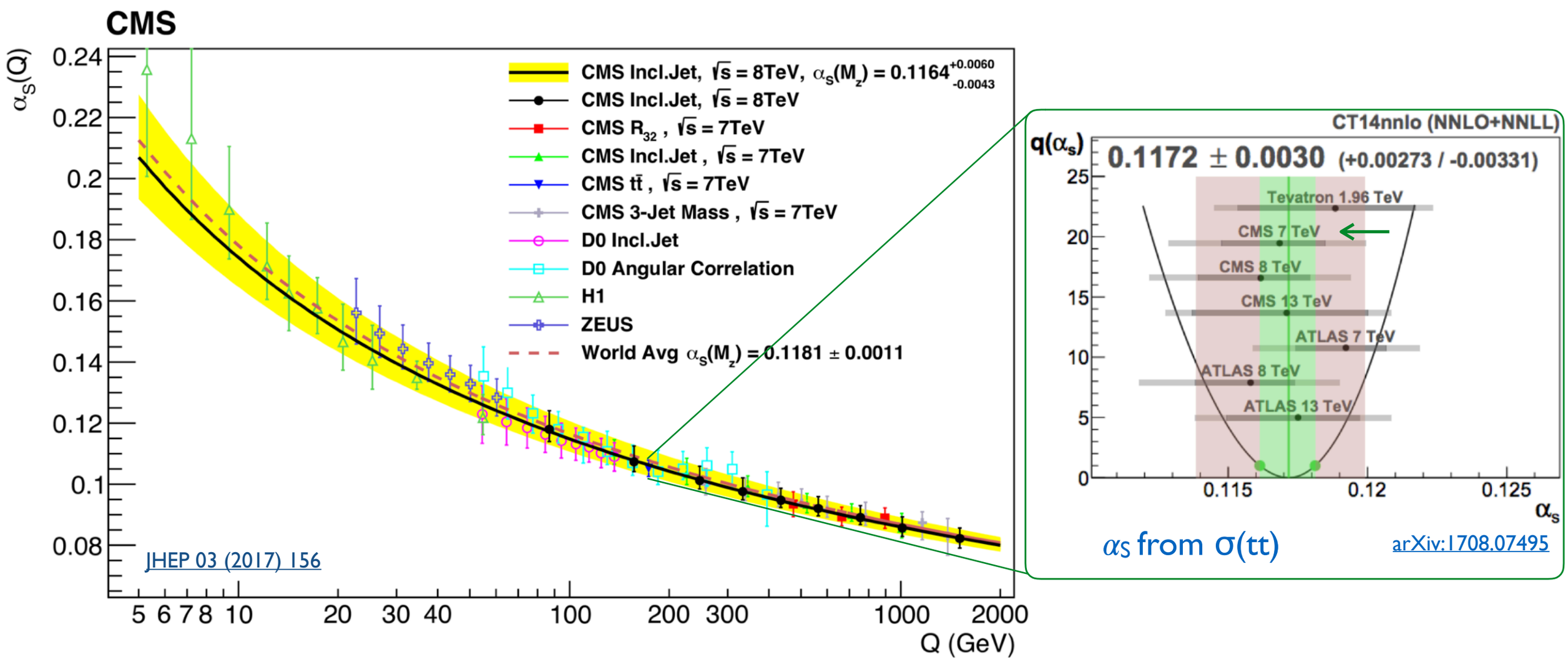


$\sigma(tt)$ at $N^2LO+NNLL$

arXiv:1303.6254



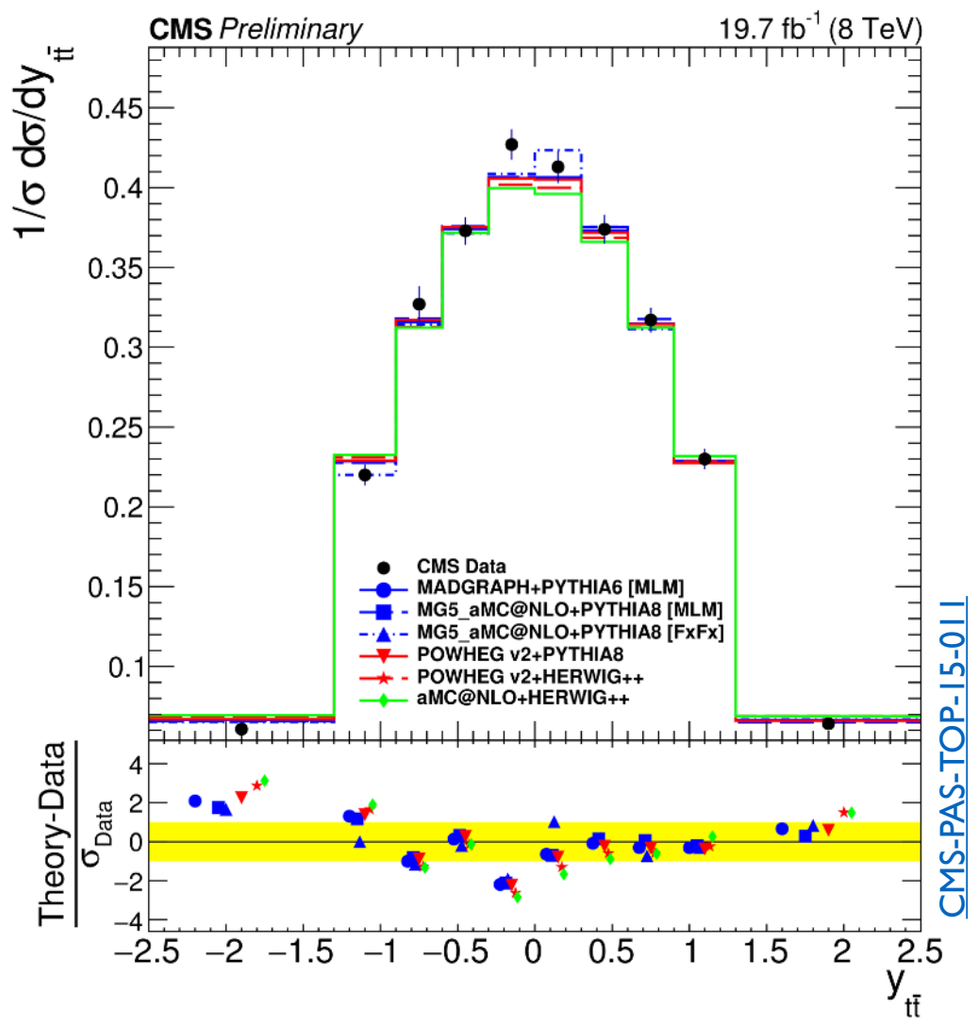
Strong coupling constant



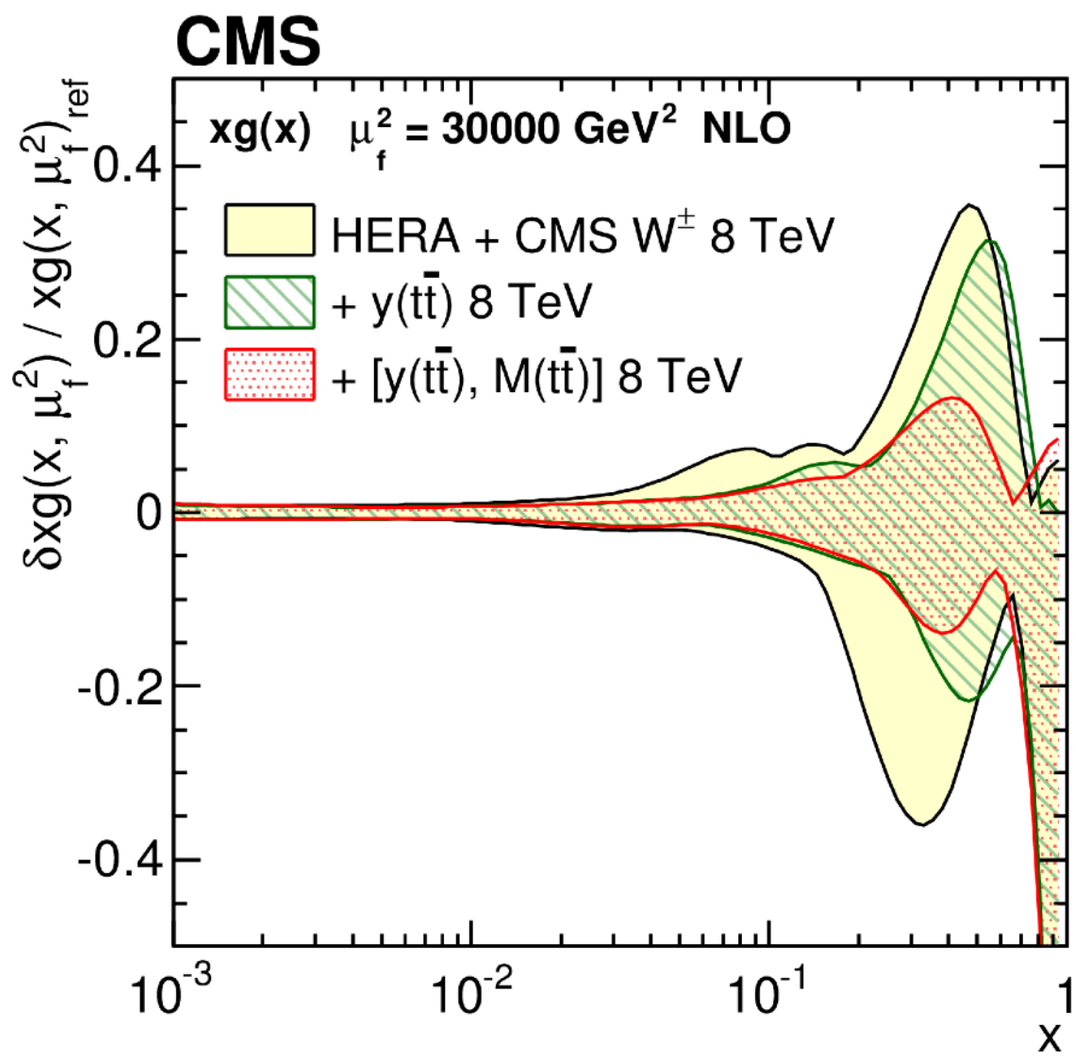
- **Measurements at different Q^2 brought to M_Z reference**
  - use the running of α_S : $\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$
  - extrapolation from LHC data limited by theory : 5% jets, 3% tt data
  - is going beyond 1% in the hands of lattice QCD?

PDF uncertainties

- **Inclusive jet production, W/Z, top measurements from Run I**
  - provide different sensitivity to gluon and quark PDFs



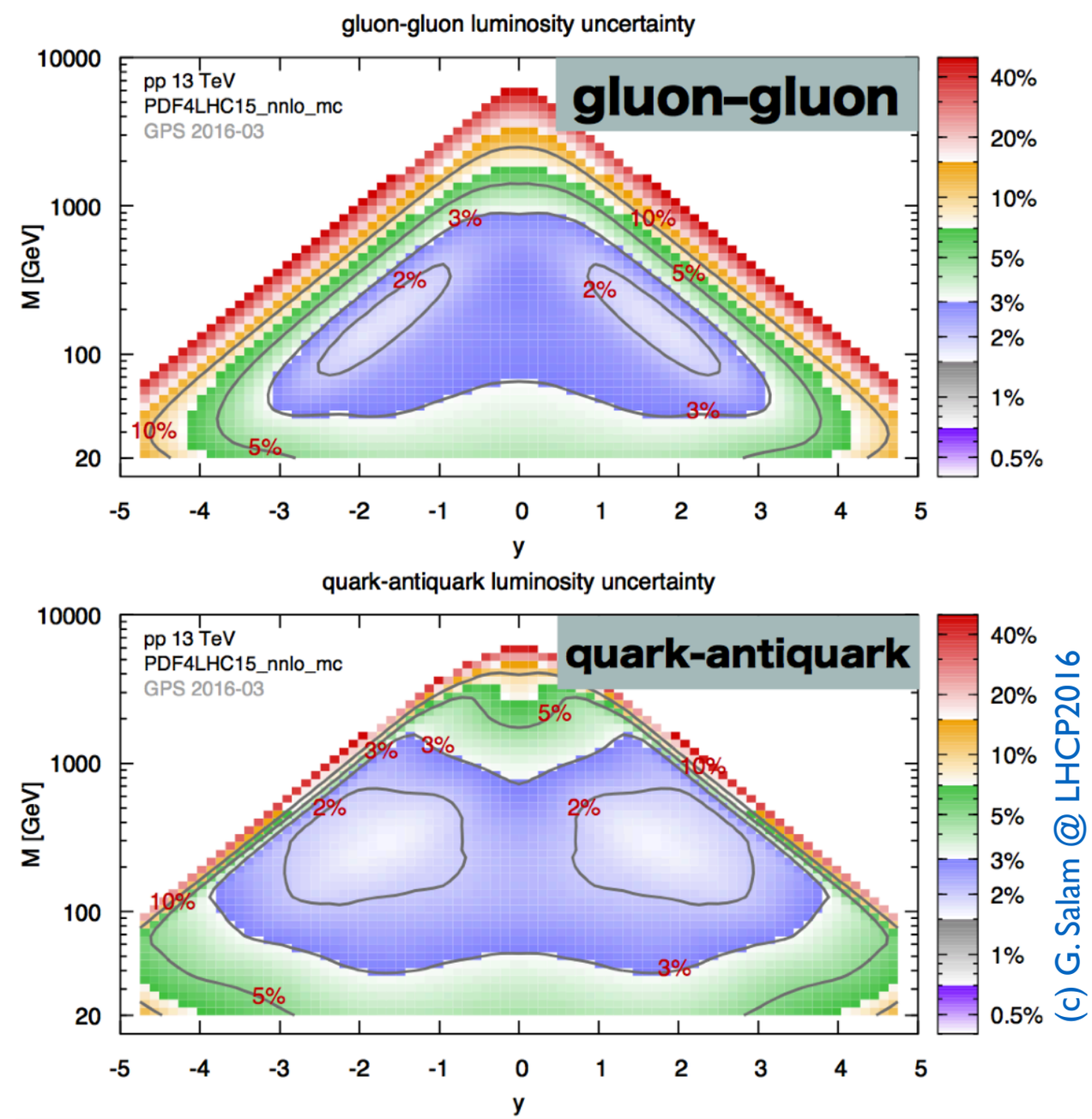
CMS-PAS-TOP-15-011



EPJC 77 (2017) 459

PDF uncertainties

- **Inclusive jet production, W/Z, top measurements from Run I**
  - provide different sensitivity to gluon and quark PDFs
- **Currently O(2-3%) parton luminosity unc.**
  - significant improvement from Run I results
  - but we need more, to profit from new data
- **Further improvements need**
  - improved luminosity determinations
  - reducing np-QCD uncertainties
  - reduce circularities in measure→fit/tune
  - precision determination of α_S, m_c, m_b, m_t



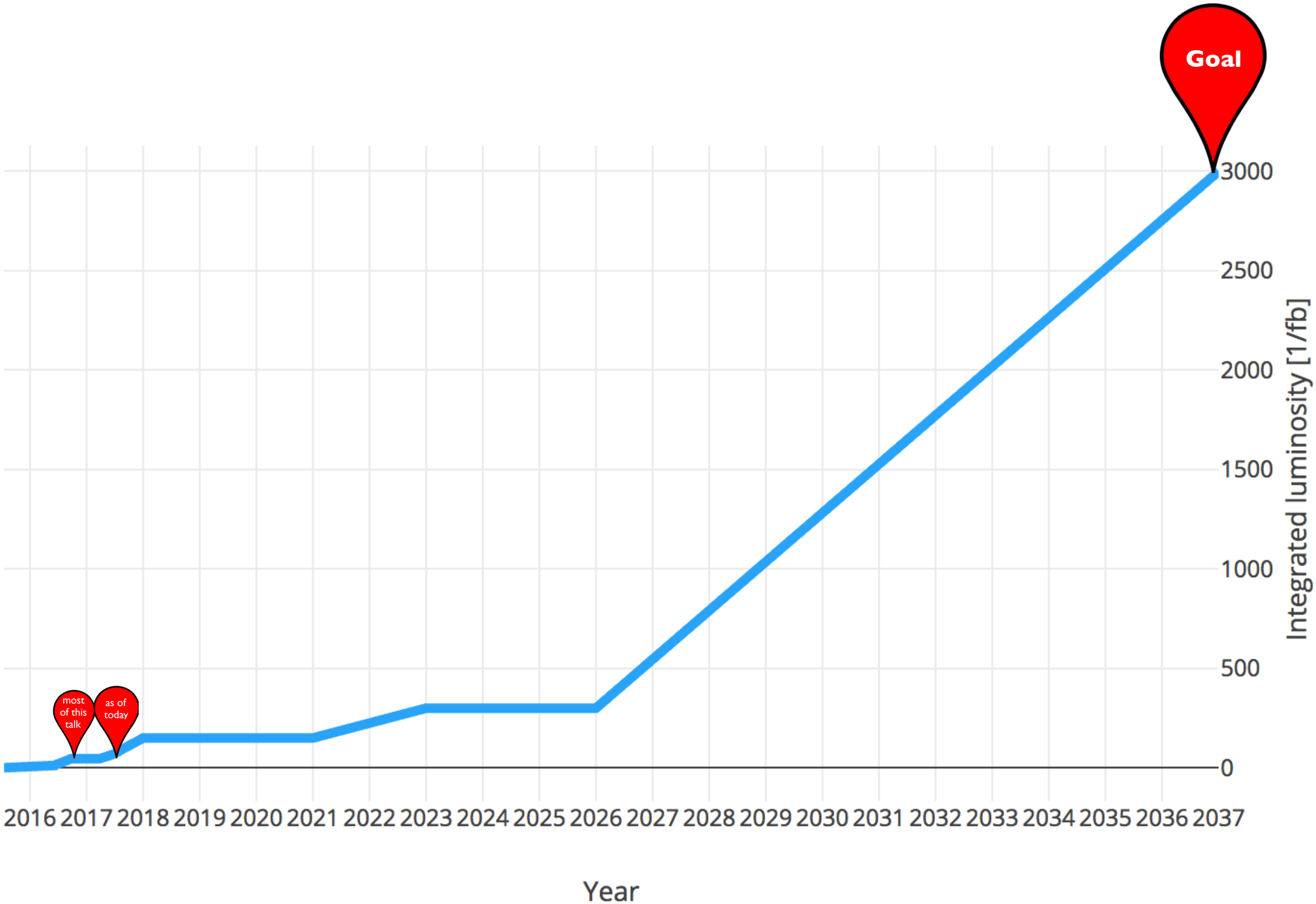
Summary

"Não procures a noite por não suportares o dia."

"If the day is beyond your endurance, do not seek the night."

V. Ferreira


as of
today
most
of this
talk
70
60
50
40
30
20
10
0
Integrated luminosity [1/fb]
2016
2017
Year


Goal
most of this talk
as of today
3000
2500
2000
1500
1000
500
0
Integrated luminosity [1/fb]
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037
Year

Summary

- **The LHC has been shedding light on the missing pieces of matter and interactions**
  - Higgs boson is definitely the greatest achievement so far
  - direct searches haven't yet uncovered striking new phenomena
  - precision measurements (many not referred here) are a crucial piece in the hunt

- **Detector development is a fundamental part of the experiments physics programme**
  - to reach successfully the goal of measuring Higgs couplings, probe fully the TeV scale
  - new proposals including new trackers, calorimeters, trigger/DAQ systems under development

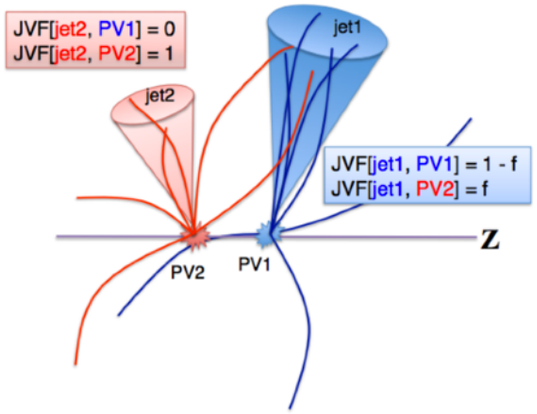
The goal is clear, the path to get there is open to your imagination!

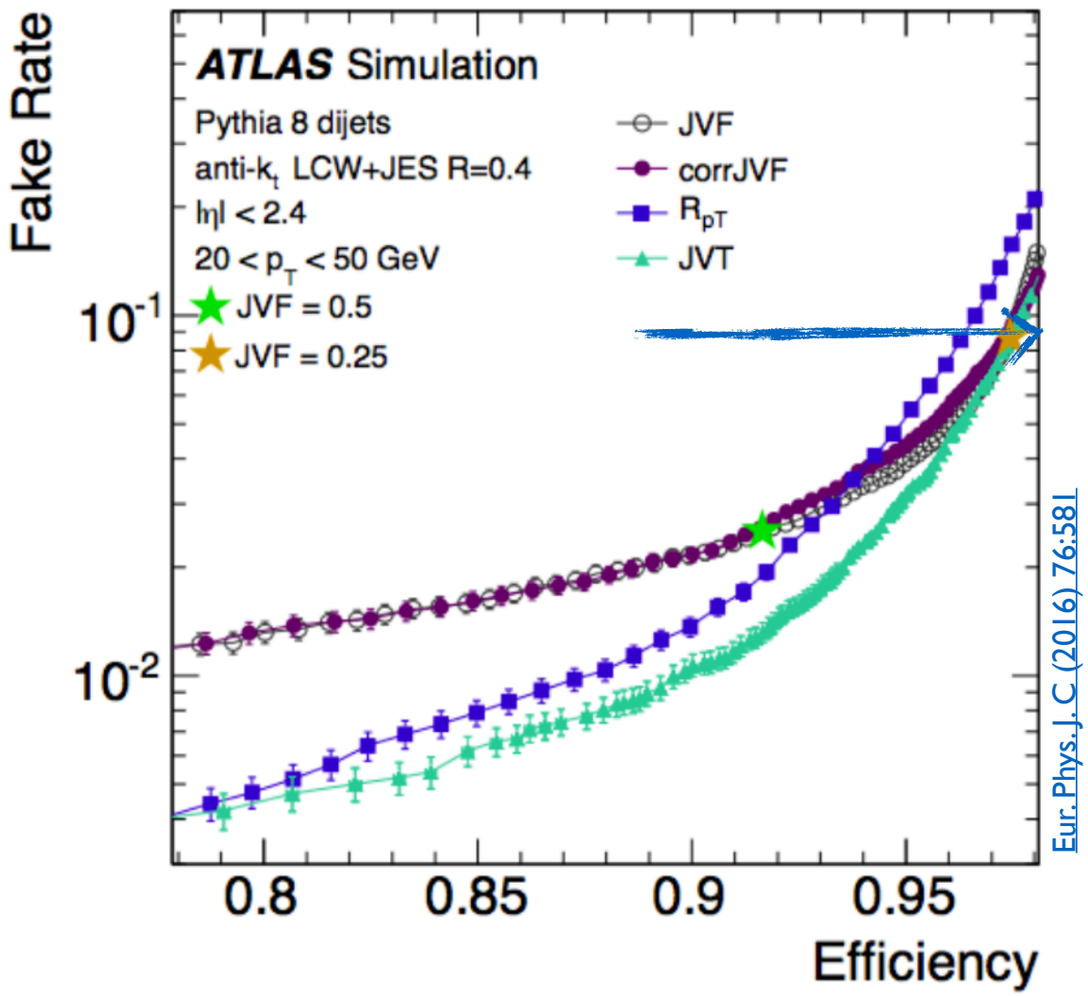
Spares

Pileup mitigation techniques I

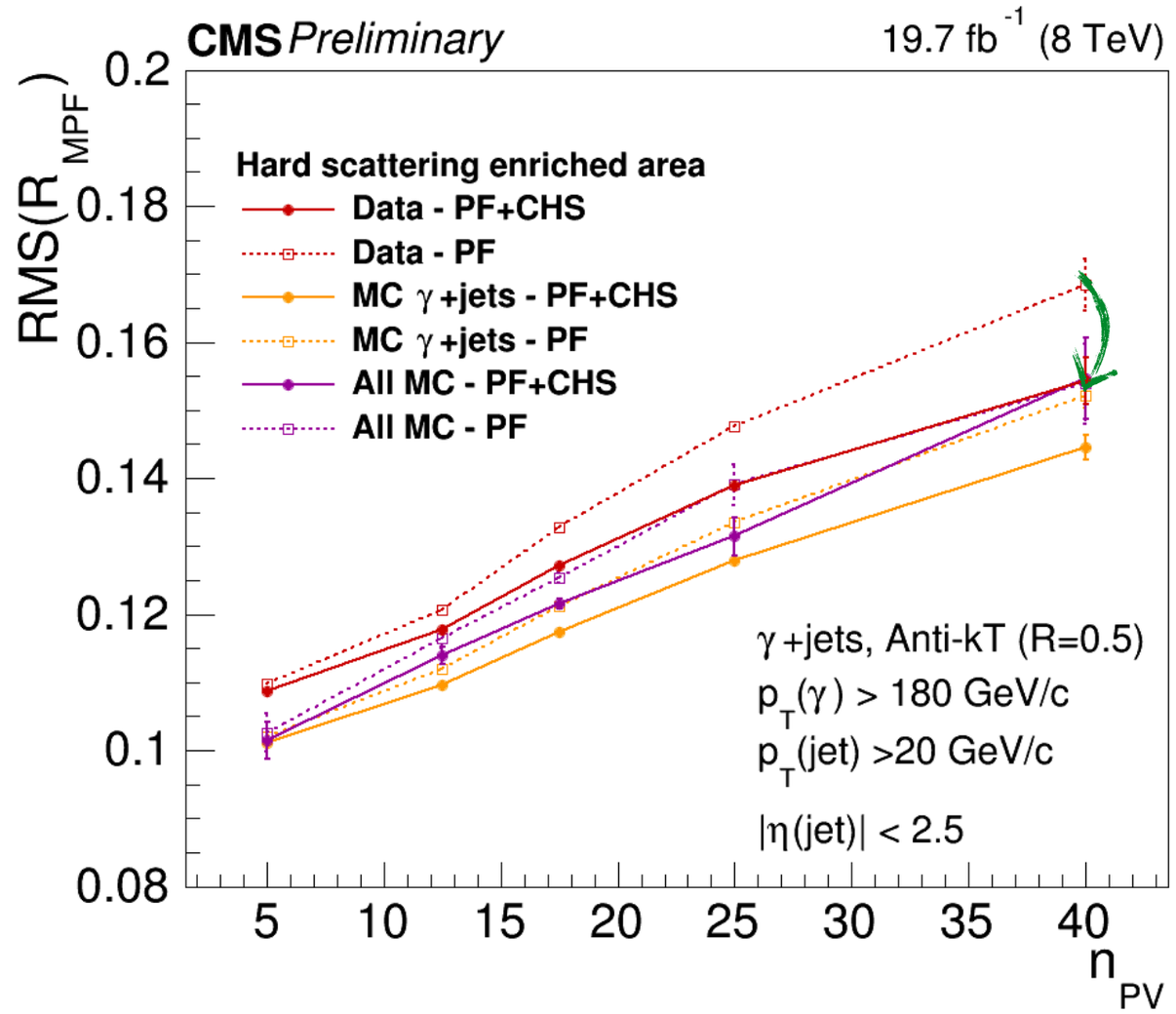
- **Pileup can be mitigated using track association to the primary vertex (PV)**
  - identify jets from pileup based on the fraction of tracks associated to PVs
  - can also remove tracks entering the fits of other PVs before clustering

  (improves resolution over standard particle flow, in particular at high pileup)





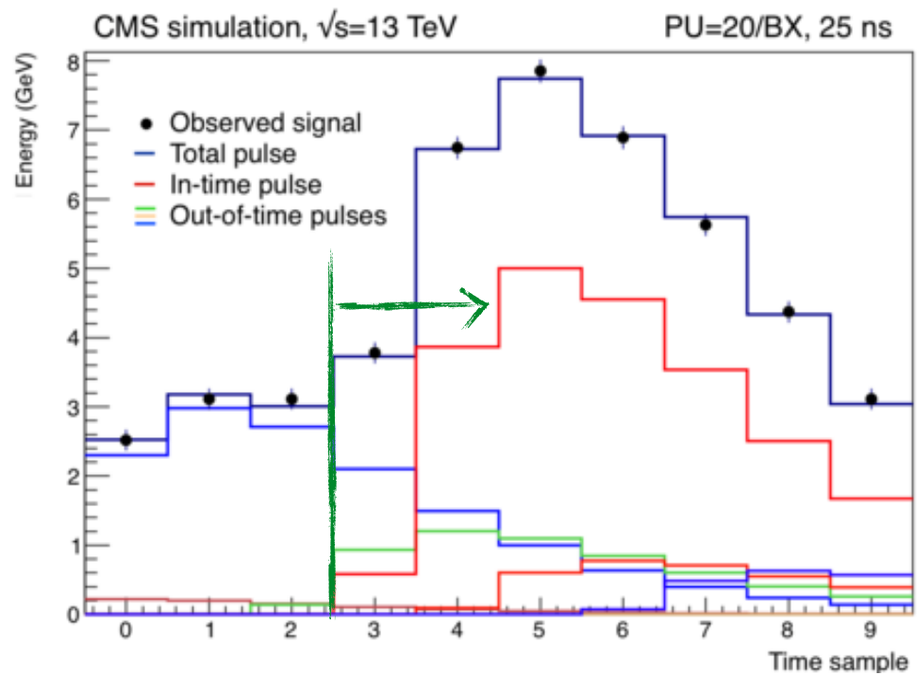
Eur. Phys. J. C (2016) 76:581



CMS-PAS-JME-14-001

Pileup mitigation techniques II

- At calorimeter level PV association is more difficult (needs pointing and timing capabilities)
  - combined fit of pulses from different bunch crossings: mitigate out-of-time pileup
  - topological clustering: start from seeds above noise and iterate to add high significance neighbours



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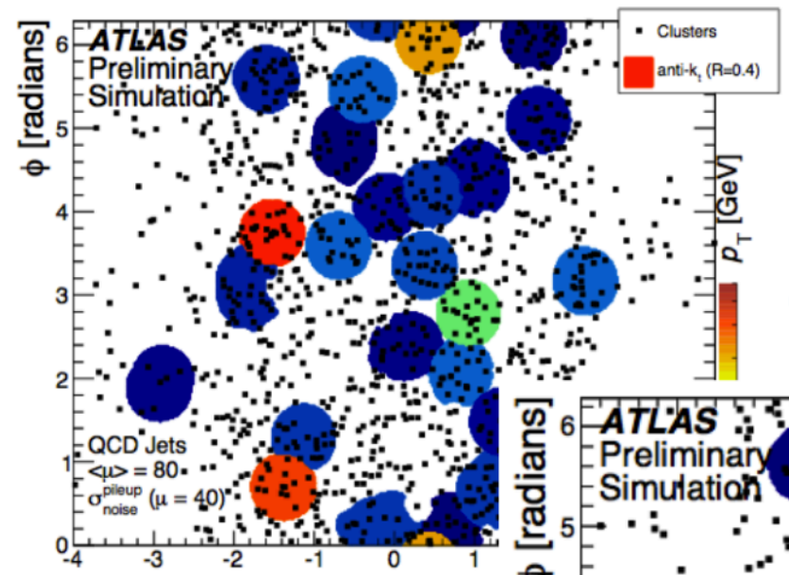
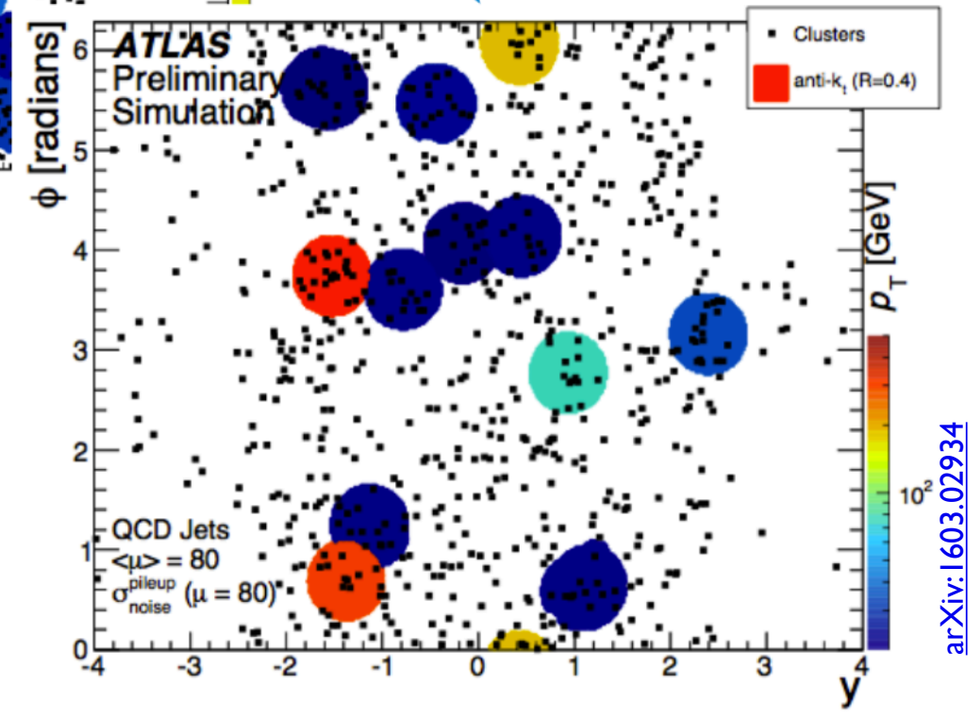
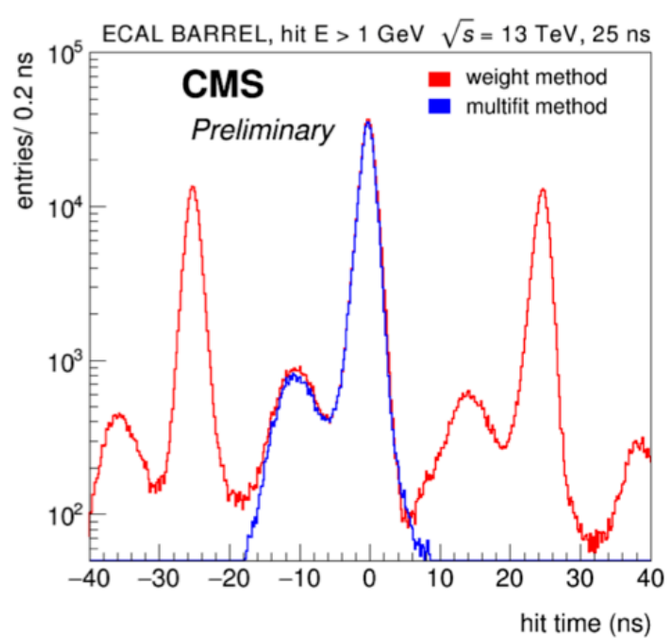


after topological clustering with σ(μ=40)



arXiv:1603.02934



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