Top physics and top partners

2015 BND doctoral school

Heimbach, Germany

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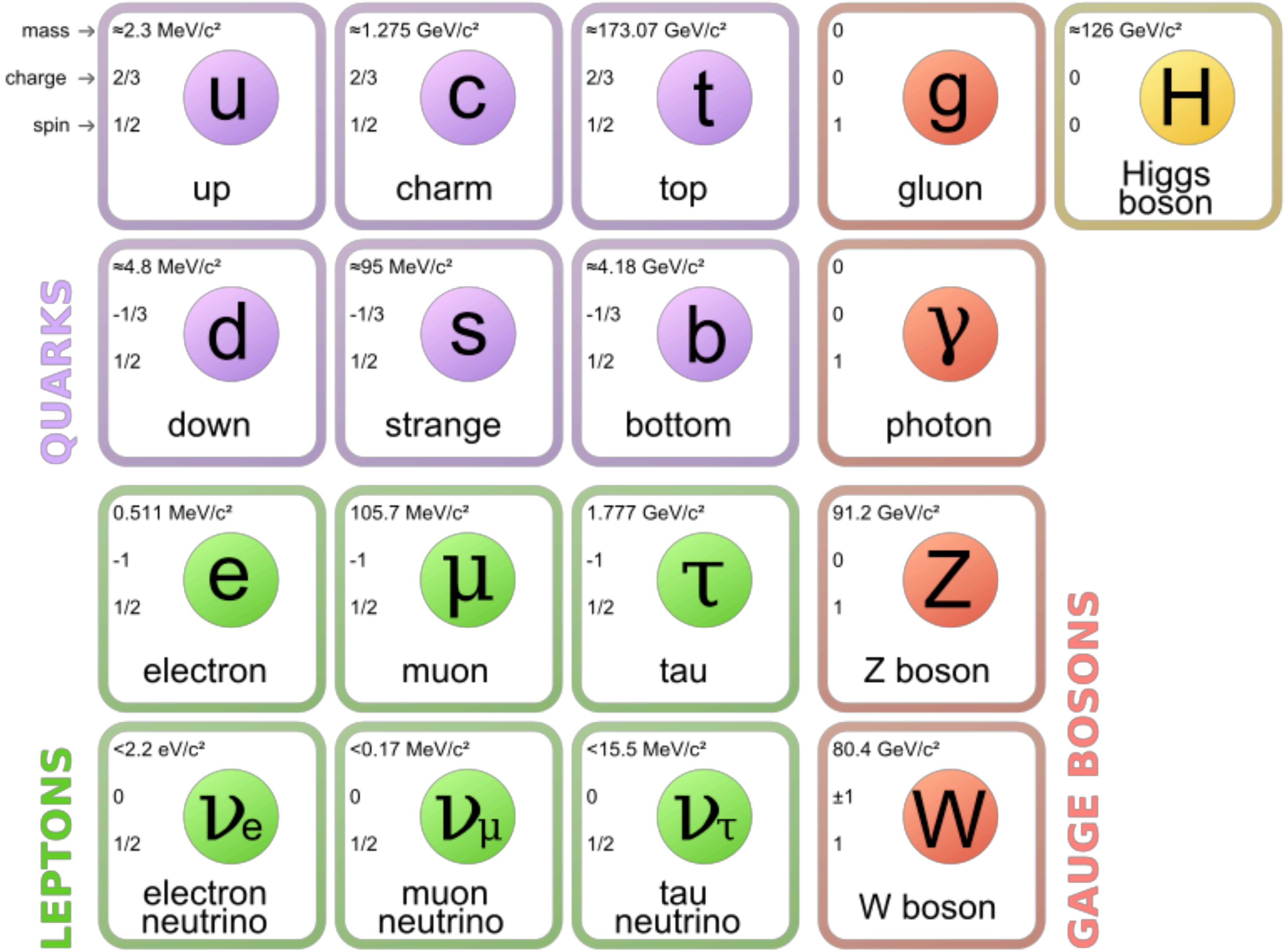
Outline

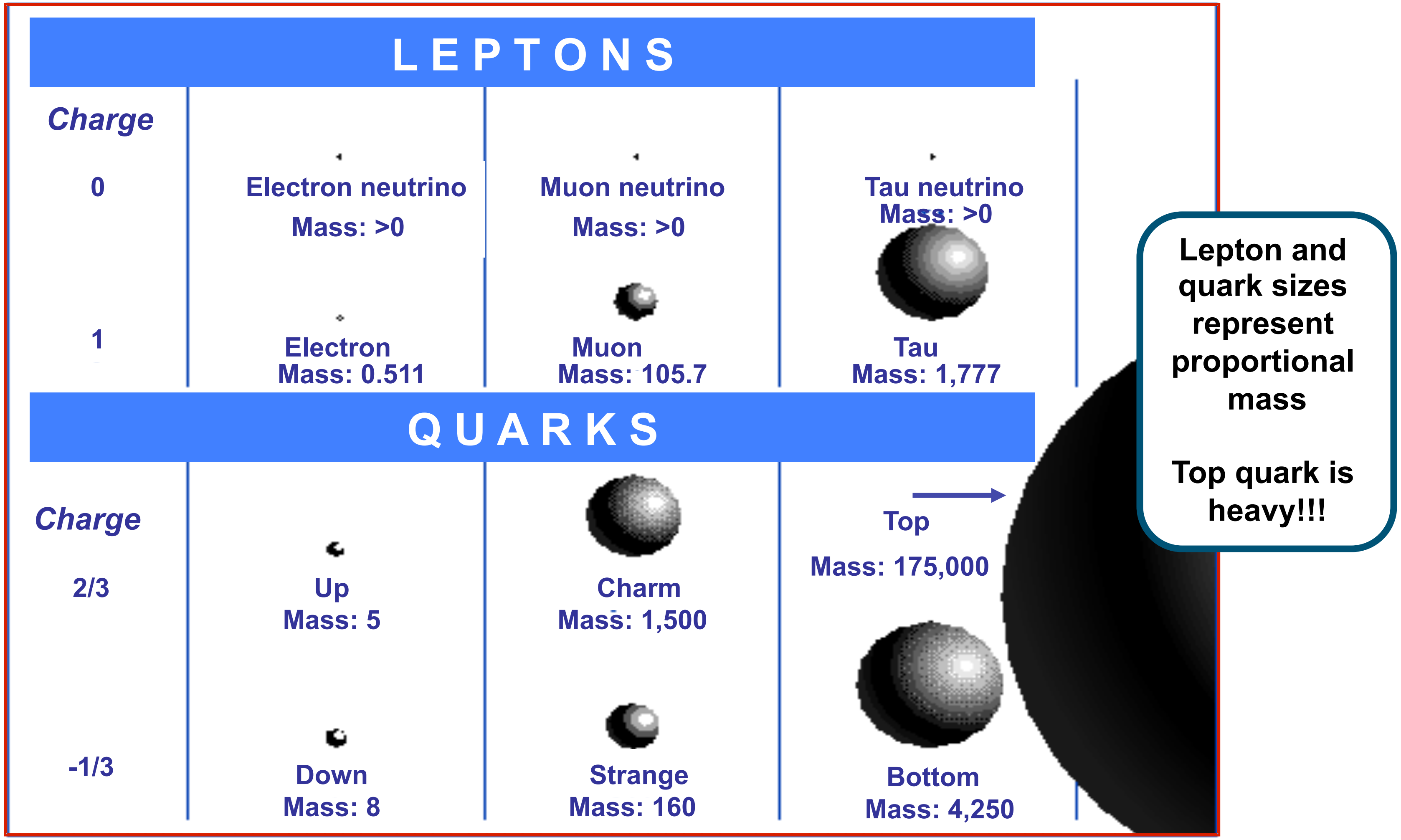
- Before the break: Intro to top physics and its jargon
  - Historic perspective
  - Experimental aspects
  - SM top physics and the top mass

- After the break: SM vs top physics, the portal to LHC physics searches beyond the standard model

The building blocks of matter



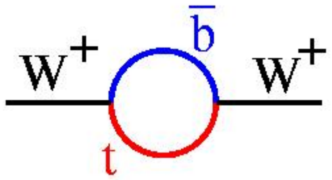
The building blocks of matter

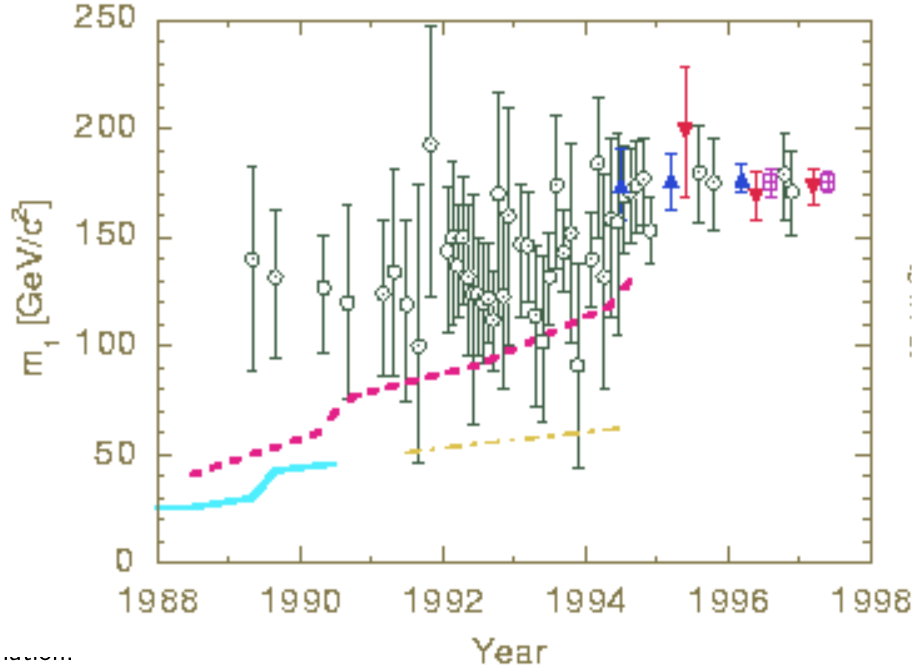


Masses are in millions of Electron Volts [MeV/c^2]

History of the top quark

- 1989: Indirect constraints on top from precision measurements at LEP





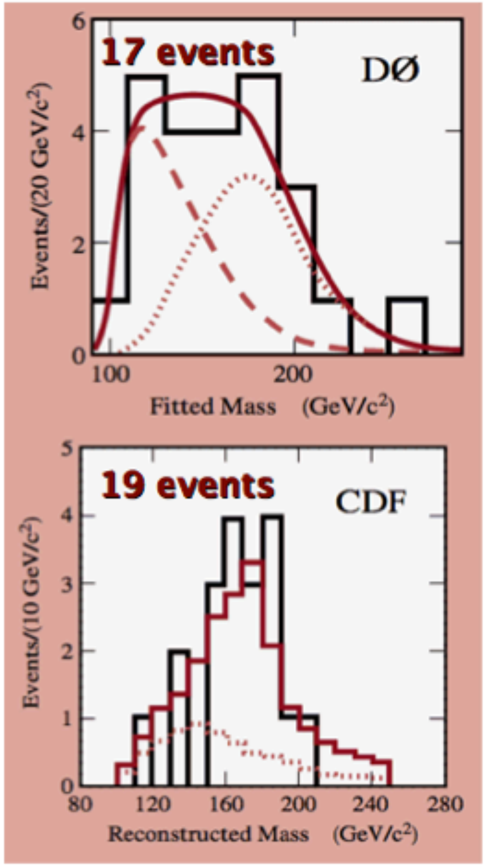
- 1995: Observation of Top-quark at the TeVatron collider at Fermilab
- Historic perspective indirect -> direct measurements -> precision

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.07 ± 0.52 ± 0.72	**OUR EVALUATION**			See comments in the header above.
174.5 ± 0.6 ± 2.3	[1] AAD	12I	ATLS	$\ell + \not{E}_T + \geq 4$ jets (≥ 1 b), MT
172.85 ± 0.71 ± 0.85	[2] AALTONEN	12AI	CDF	$\ell + \not{E}_T + \geq 4$j (0,1,2$b$) template
172.7 ± 9.3 ± 3.7	[3] AALTONEN	12AL	CDF	$\tau_h + \not{E}_T$ +4j ($\geq 1b$)
172.5 ± 1.4 ± 1.5	[4] AALTONEN	12G	CDF	6–8 jets with ≥ 1 b
173.9 ± 1.9 ± 1.6	[5] ABAZOV	12AB	D0	$\ell\ell + \not{E}_T + \geq 2$j ($\nu$WT+MWT)
172.5 ± 0.4 ± 1.5	[6] CHATRCHYAN	12BA	CMS	$\ell\ell + \not{E}_T + \geq 2$j ($\geq 1b$), AMWT
173.49 ± 0.43 ± 0.98	[7] CHATRCHYAN	12BP	CMS	$\ell + \not{E}_T + \geq 4$j ($\geq 2b$)
172.3 ± 2.4 ± 1.0	[8] AALTONEN	11AK	CDF	$\not{E}_T + \geq 4$ jets (≥ 1 b-tag)
172.1 ± 1.1 ± 0.9	[9] AALTONEN	11E	CDF	ℓ + jets and dilepton
174.94 ± 0.83 ± 1.24	[10] ABAZOV	11P	D0	$\ell + \not{E}_T + 4$ jets (≥ 1 b-tag)
173.0 ± 1.2	[11] AALTONEN	10AE	CDF	$\ell + \not{E}_T + 4$ jets (≥ 1 b-tag), ME method
170.7 ± 6.3 ± 2.6	[12] AALTONEN	10D	CDF	$\ell + \not{E}_T + 4$ jets (b-tag)

History of the top quark

discovery

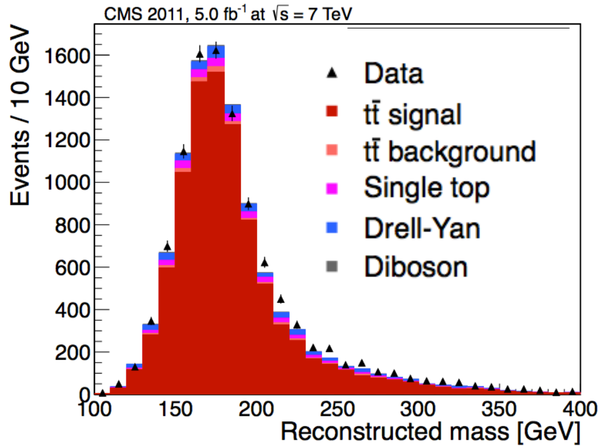
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

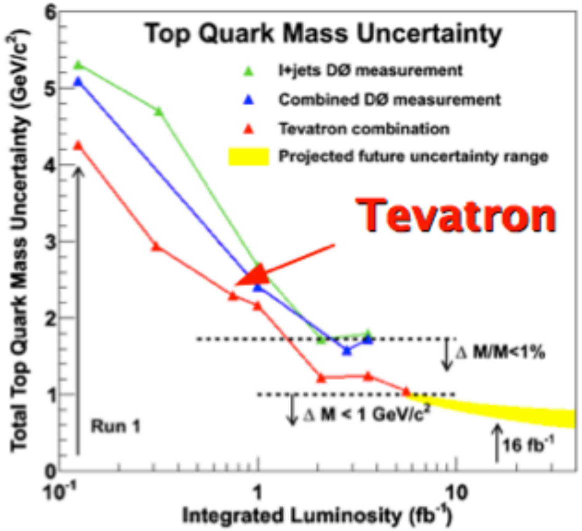
today

10000s of events



LHC: top quark factory

precision

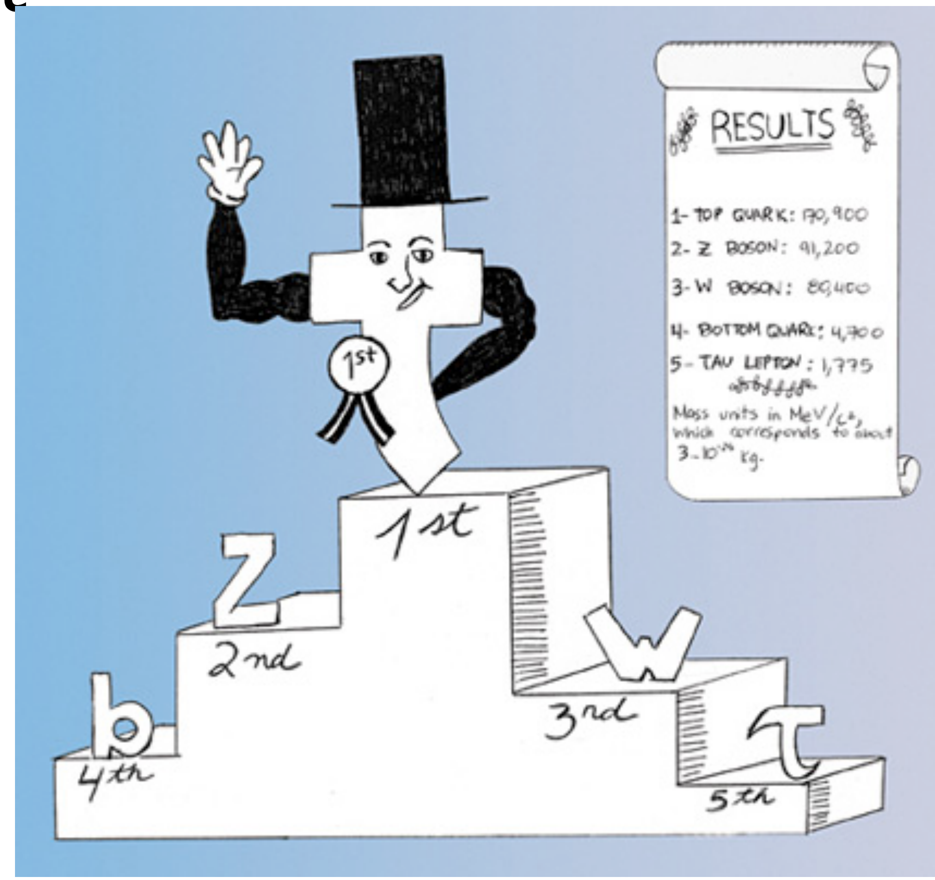


searches

Top quark – special?

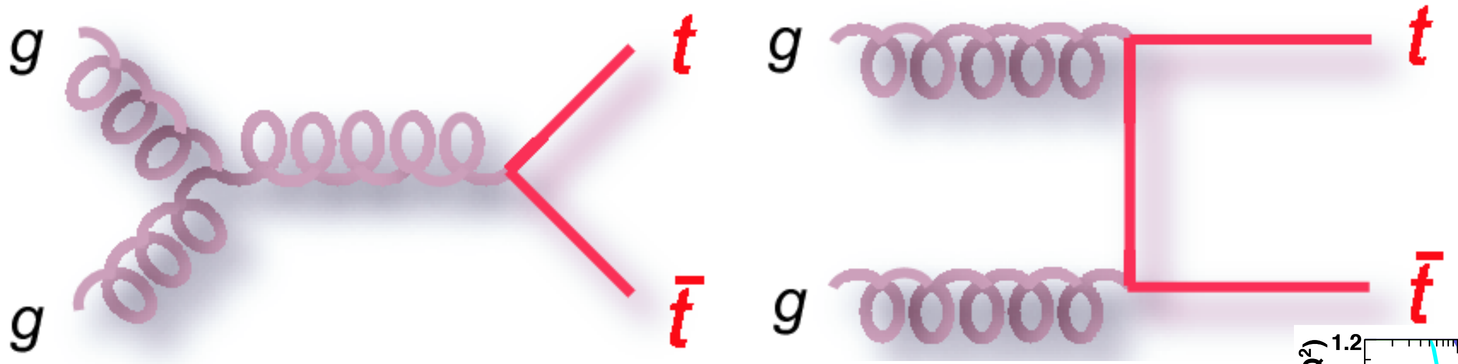
- Many models predict that top is special in order to explain large mass

- Or top quark has special role because of its large mass
  - some more in lecture 2

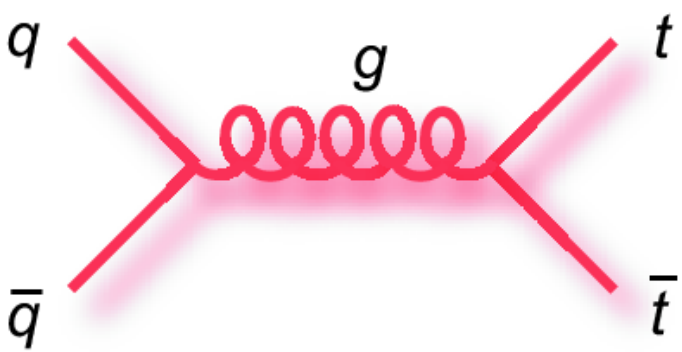


Top pair production at hadron colliders

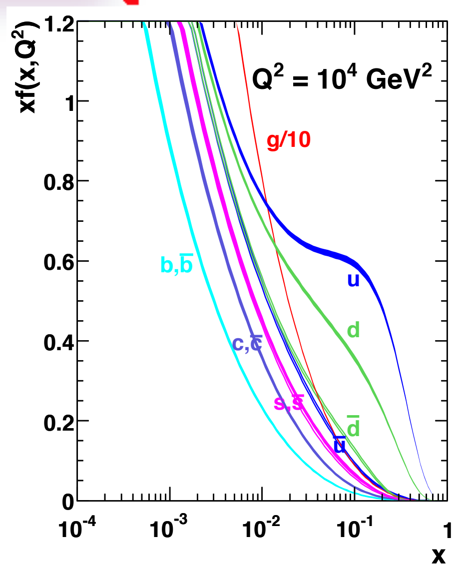
- Pair production in 8 TeV pp collisions:



~90%

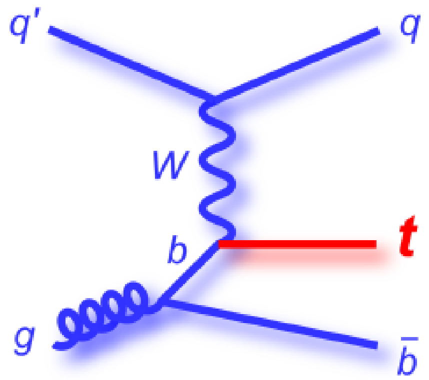


~10%

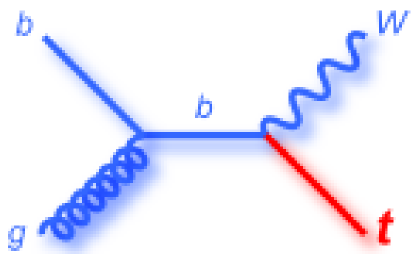


MSTW08:Eur.Phys.J.C63:189-285

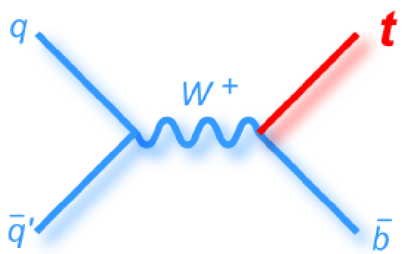
Single Top production



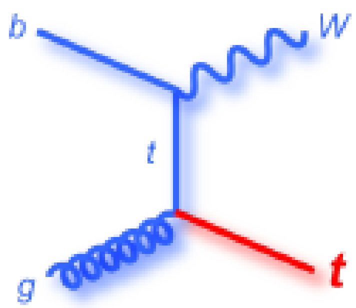
t-channel



tW-channel

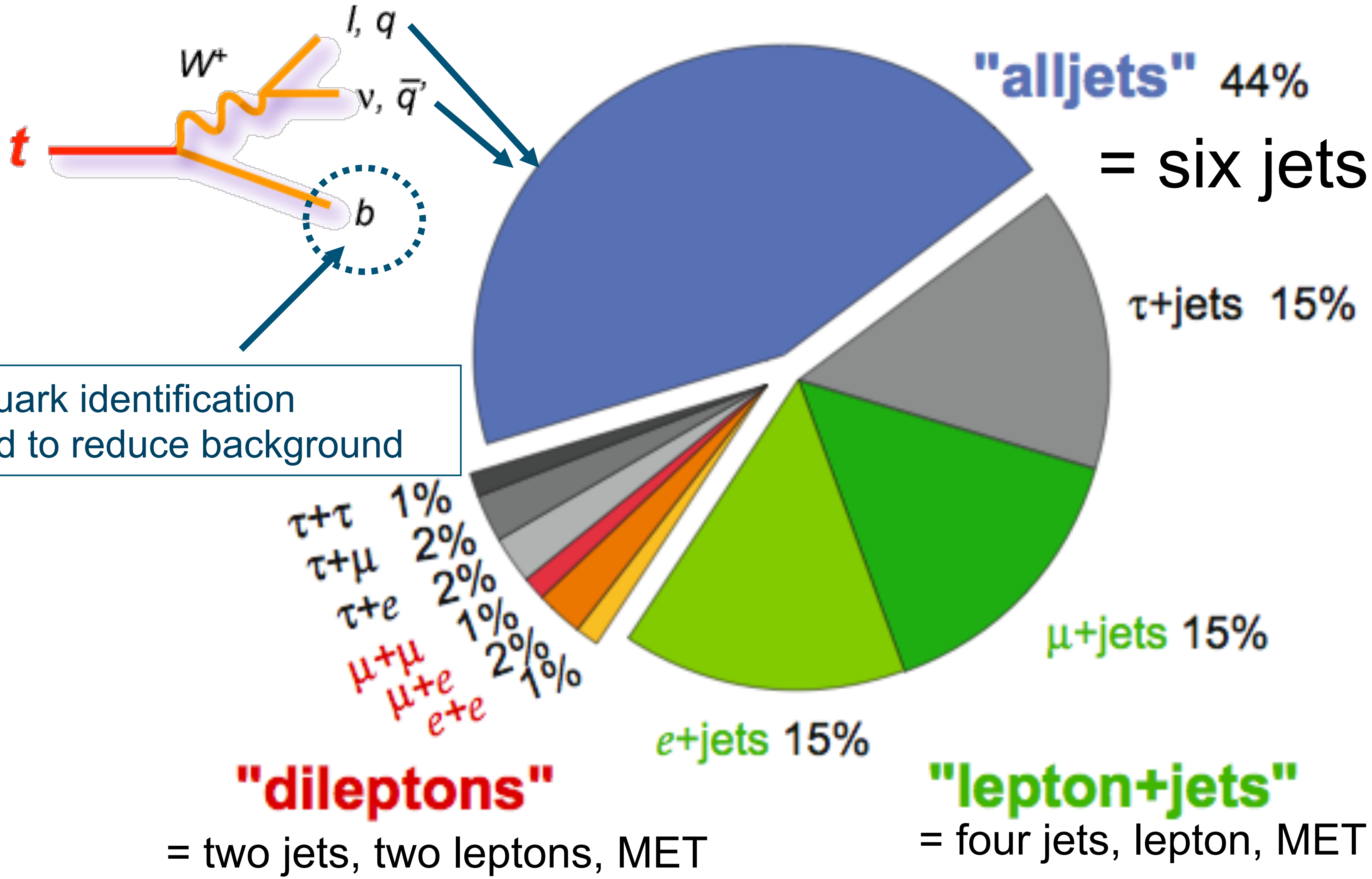


s-channel



- Electroweak production of top quarks
- Dominant channels at LHC @ 8 TeV:
  - t-channel: 87 pb
  - tW channel: 22 pb
  - s-channel: 5.6 pb

Top pair branching fractions



B-quark identification used to reduce background

Top physics: decay channel choice

– selection of top quark events inversely proportional to the complexity of the mass reconstruction

	Isolation signal	Reconstruction
Di-lepton	Relatively easy	Two neutrinos, ambiguities
Lepton+jets	Reasonable	One neutrino, use missing transverse energy
All-hadronic	Very difficult	Possibility to observe top as 'peak' in invariant mass spectrum, no energetic neutrinos

SINGLE TOP PRODUCTION

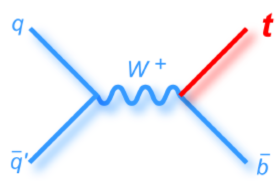
Observation of single top production:

- cross section $\propto V_{tb}^2$
- study top-polarization and EWK top interaction

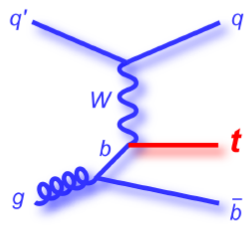
Test of non-SM phenomena:

- 4th generation
- FCNC couplings
- W' , $H^{\pm}$
- anomalous W_{tb} couplings

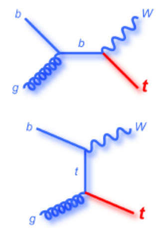
s-channel



t-channel



Wt-channel



Main backgrounds:

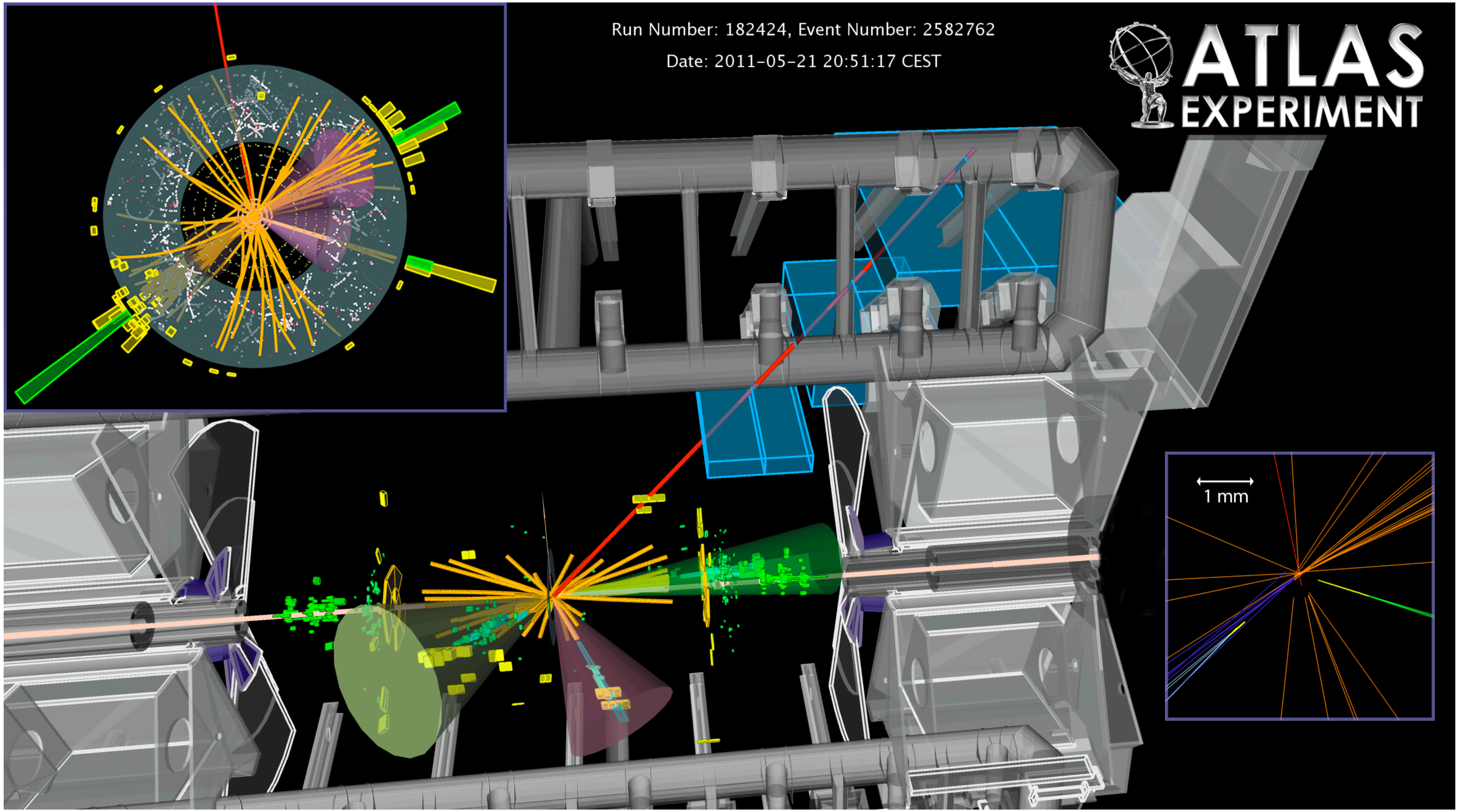
- s-channel: Top pair, W + (HF) jets, QCD
- t-channel: Top pair, W + (HF) jets, QCD
- Wt-channel: Top pair, Z + (HF) jets, QCD

Signal – background discrimination:

- Tevatron: multivariate methods (neural networks, boosted decision trees, matrix element method)
- LHC: cut-based or multivariate method

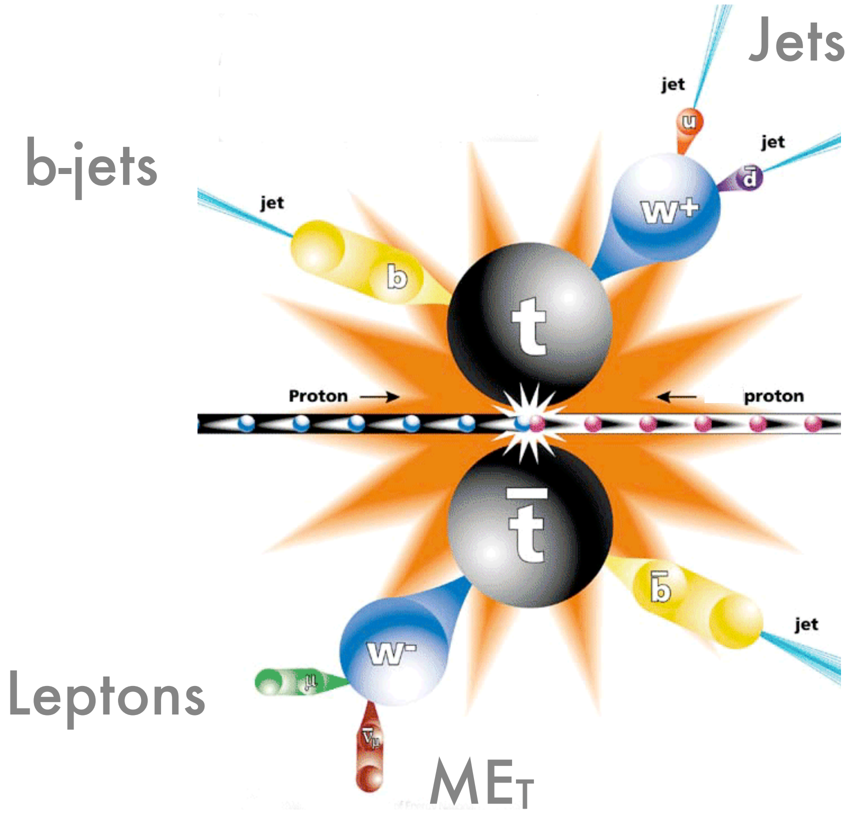
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.05 pb	2.08 pb	0.22 pb
LHC: pp (7 TeV)	4.6 pb	66 pb	15.7 pb

How to find top quarks?

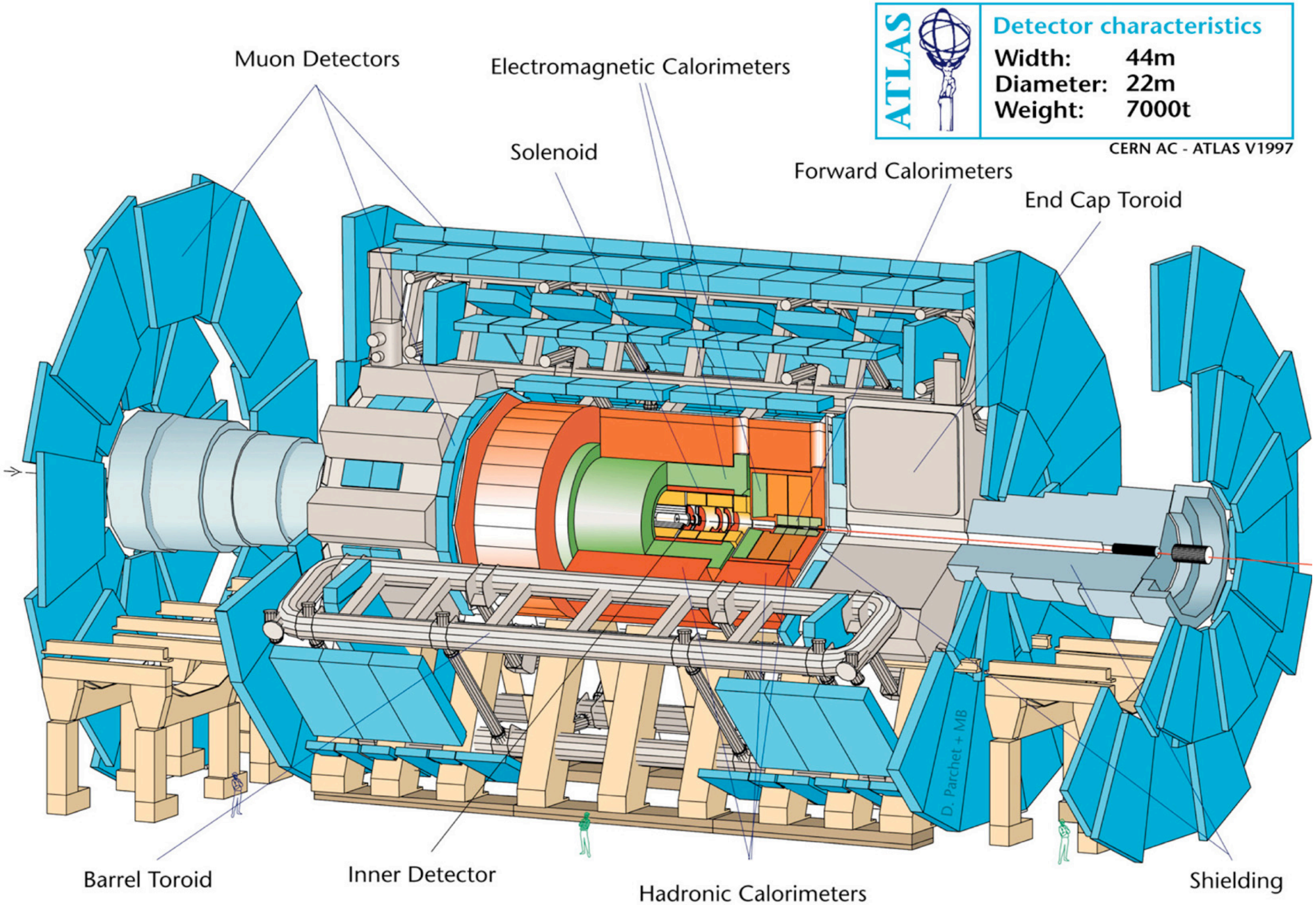


Top quark physics – benchmark physics

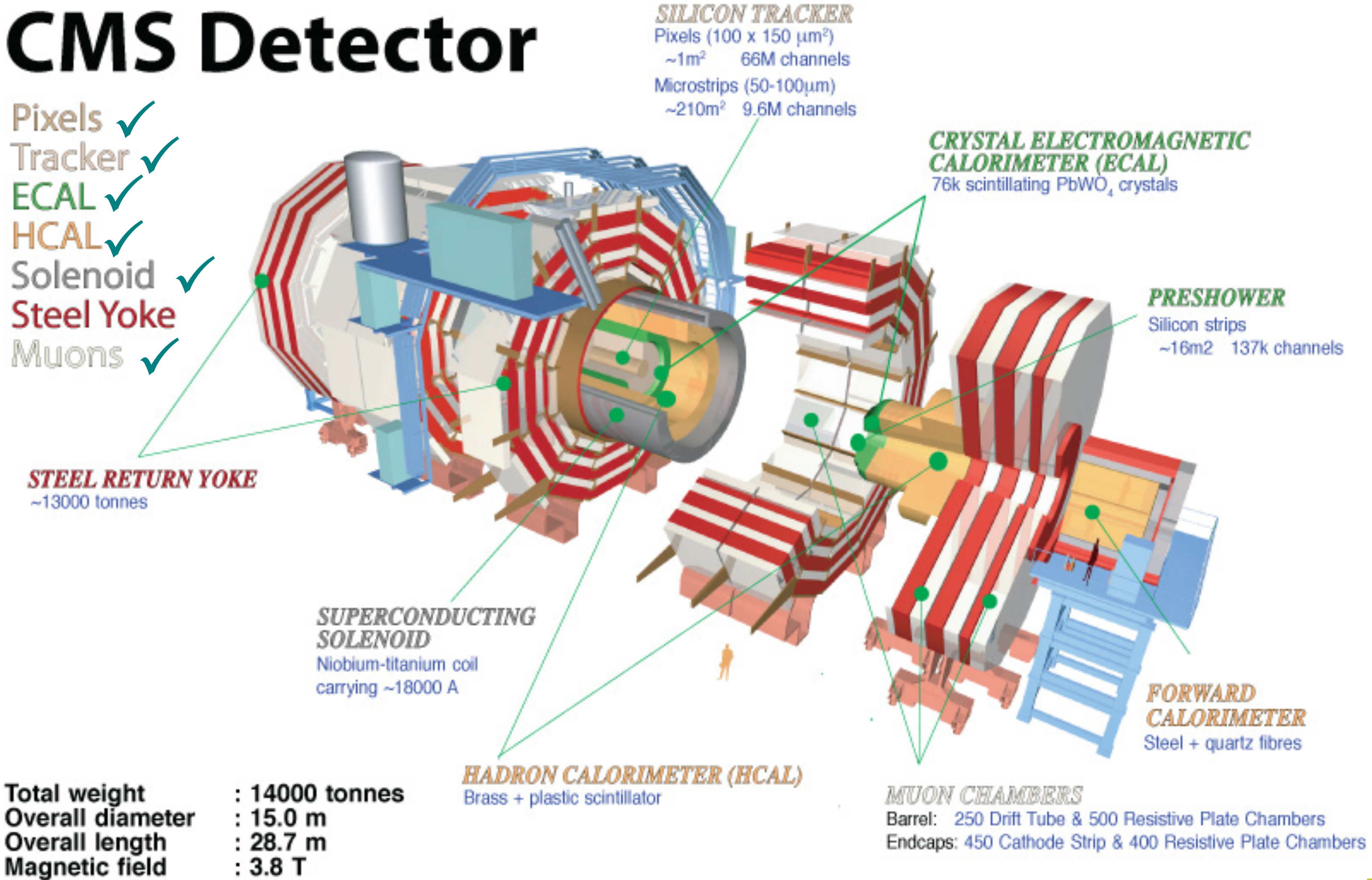
- To find and reconstruct top quarks, a fully operational and hermetic General Purpose Detector is needed
- This is why top quarks were used to confirm and check calibrations and detector performance at the start of the LHC runs at 7, 8 and 13 TeV



A Toroidal Lhc ApparatuS



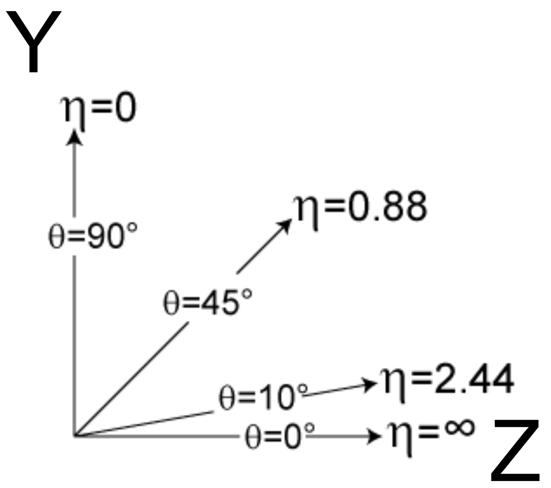
Compact Muon Solenoid

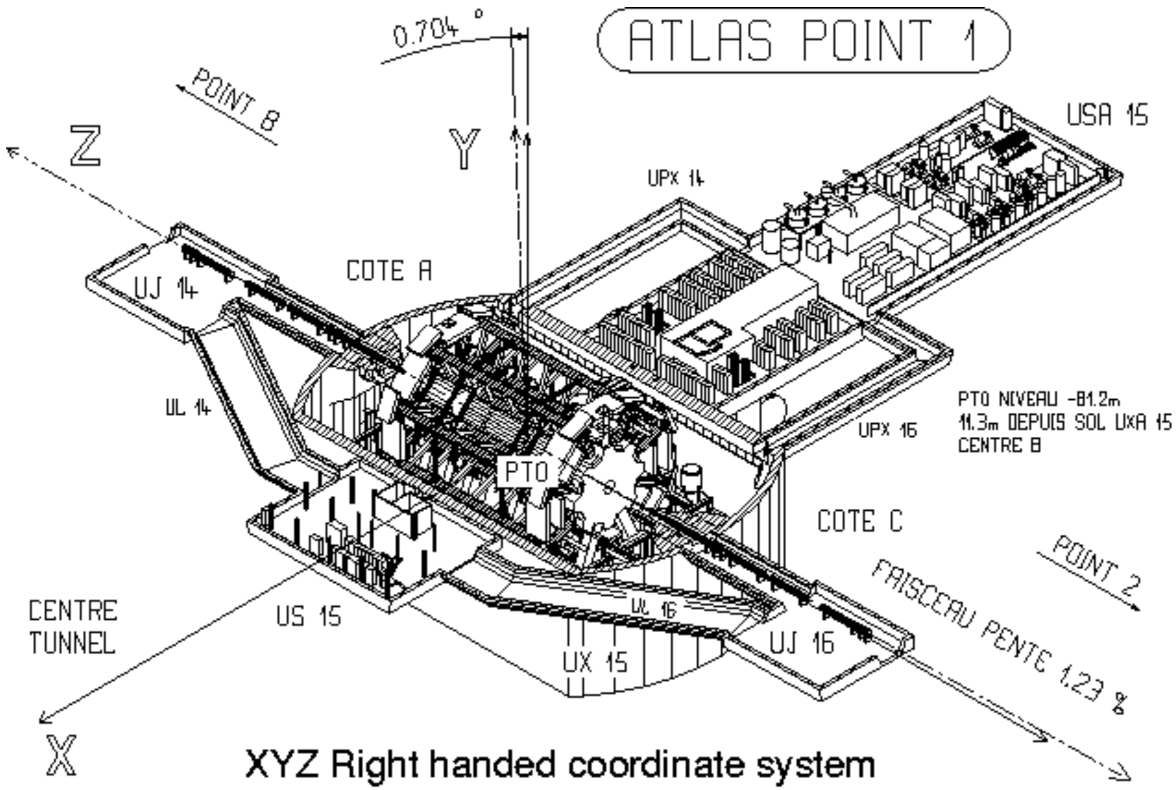


Typical GPD coordinate system

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

$$y = \frac{1}{2}\ln\left(\frac{E + p_L}{E - p_L}\right)$$



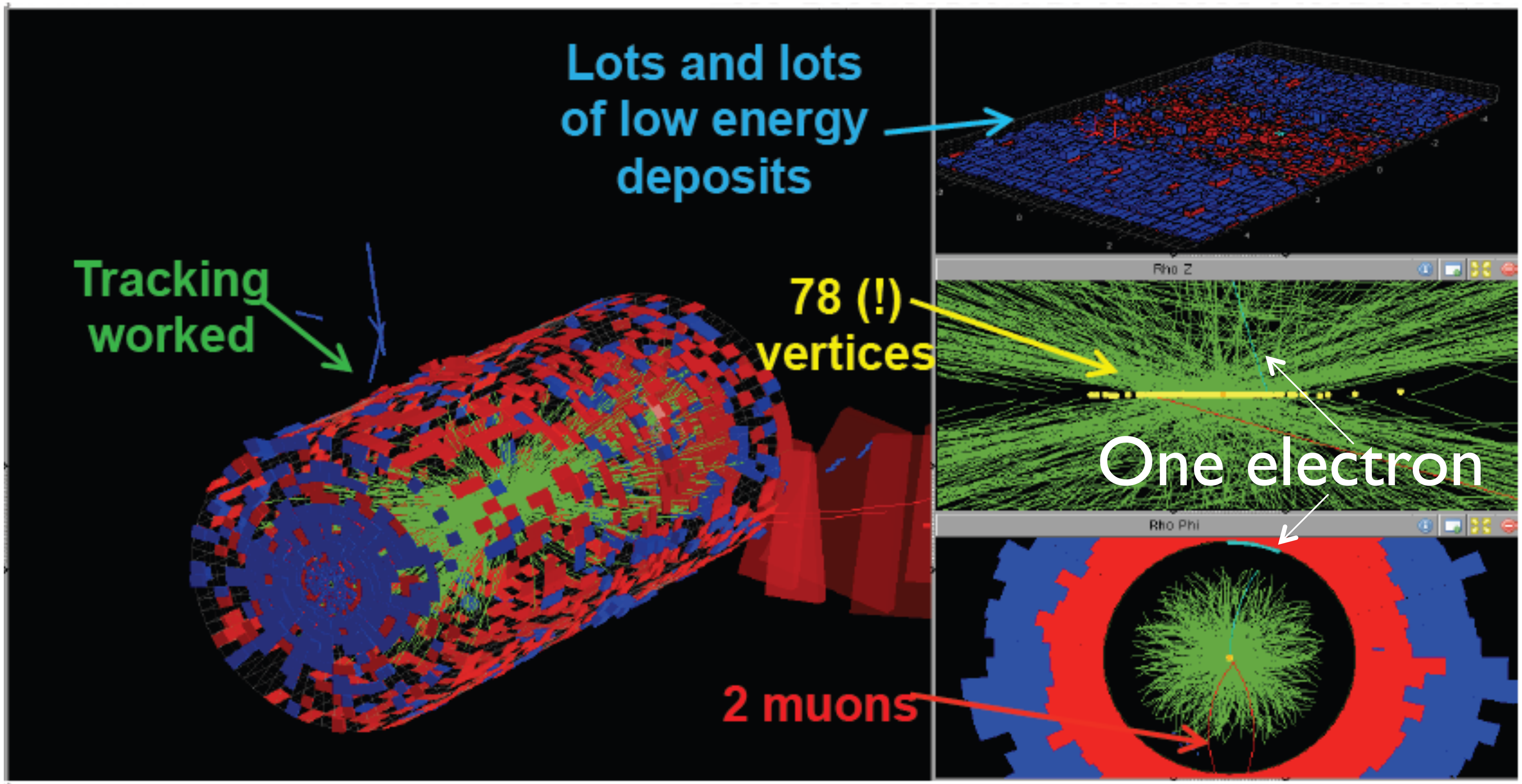


XYZ Right handed coordinate system
with z in beam direction

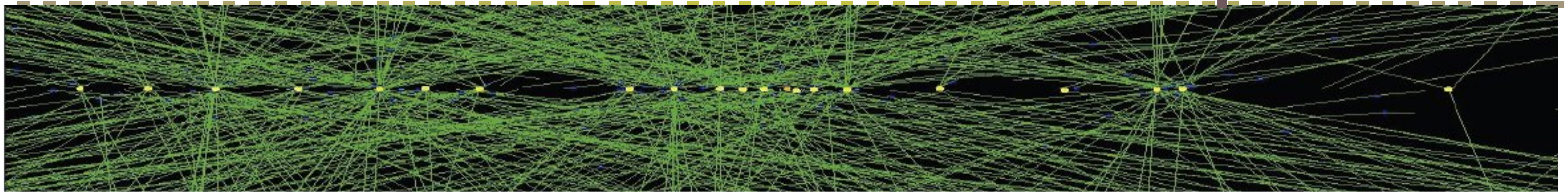
+ cylindrical coordinates around Z axis

Typical inputs of 4-vector:
pT, phi, eta, E

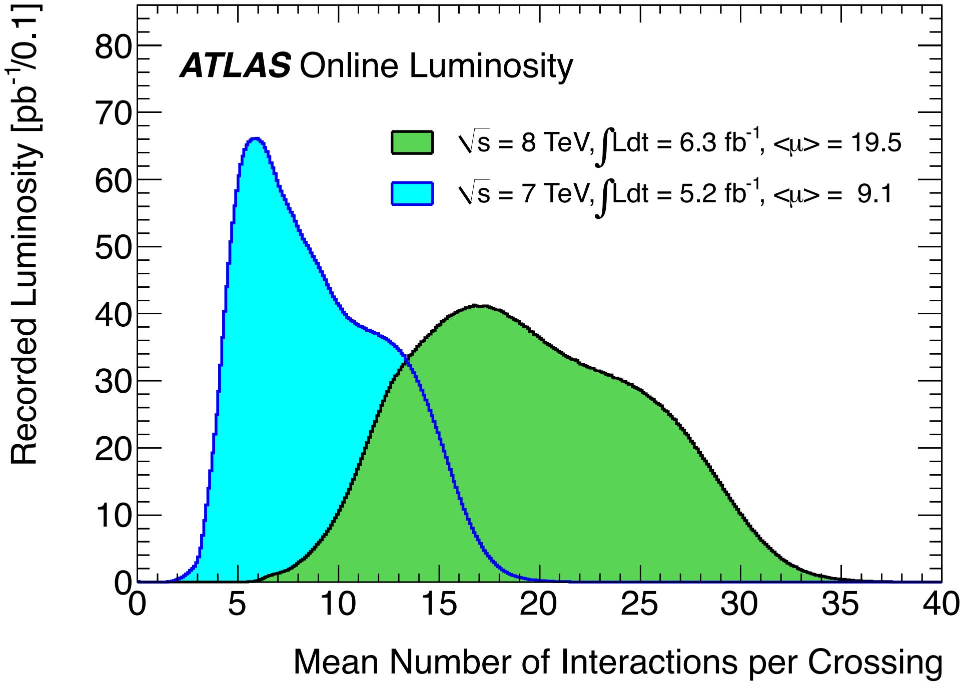
Luminosity comes at a price:Pileup



LHC 2012 run: Pile-Up

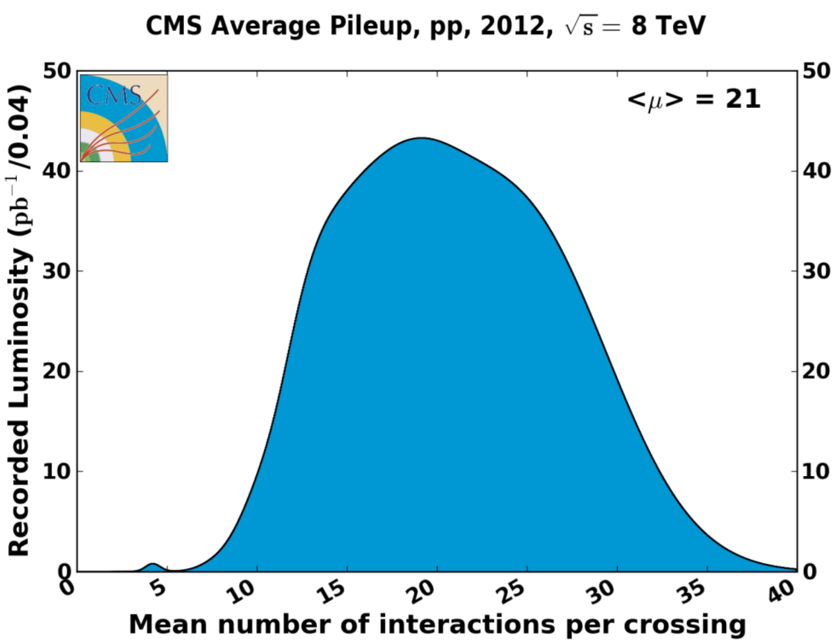


- Outstanding LHC performance comes at a price:
- 2011:
  - Run A: 5 PU
  - Run B: 8 PU
- 2012:
  - Average: 21 PU
- 2015: 20-50 PU expected depending on accelerator performance



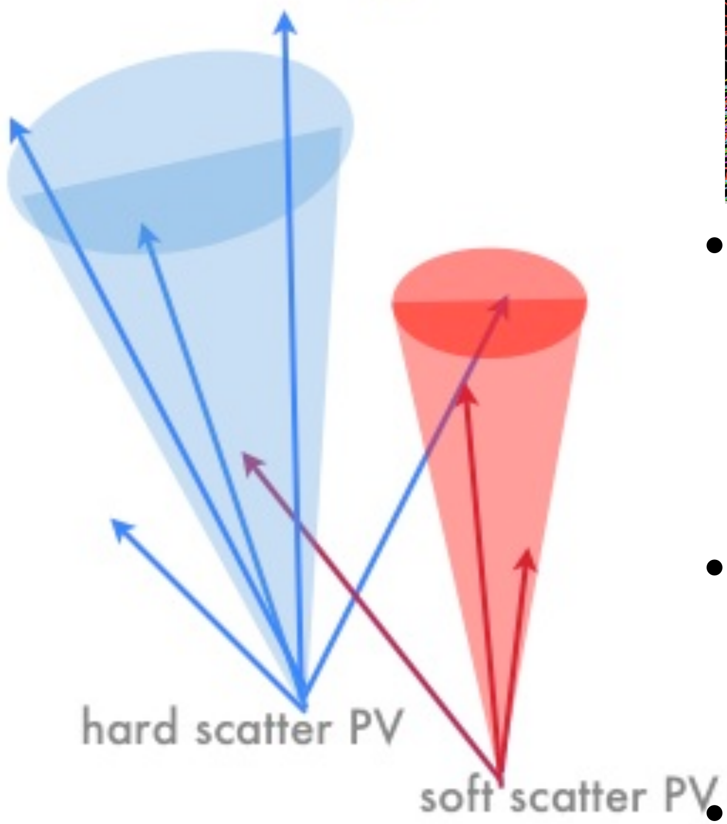
Freya Blekman (IIHE-VUB)

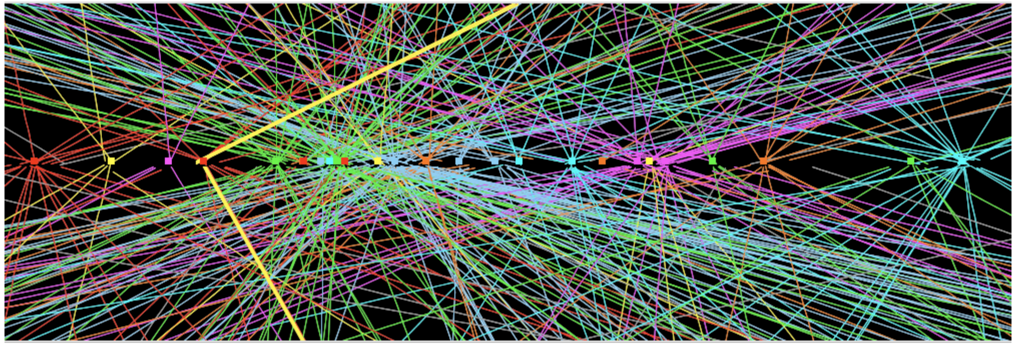
Two kinds of pile-up



- In-time pile-up:
  - Multiple interactions from a single LHC bunch crossing
- Out-of-time pile-up:
  - Particles from previous bunch – 50 ns bunch spacing
  - But detectors can have much longer response time so there might still be some 'remaining' signal from previous collision

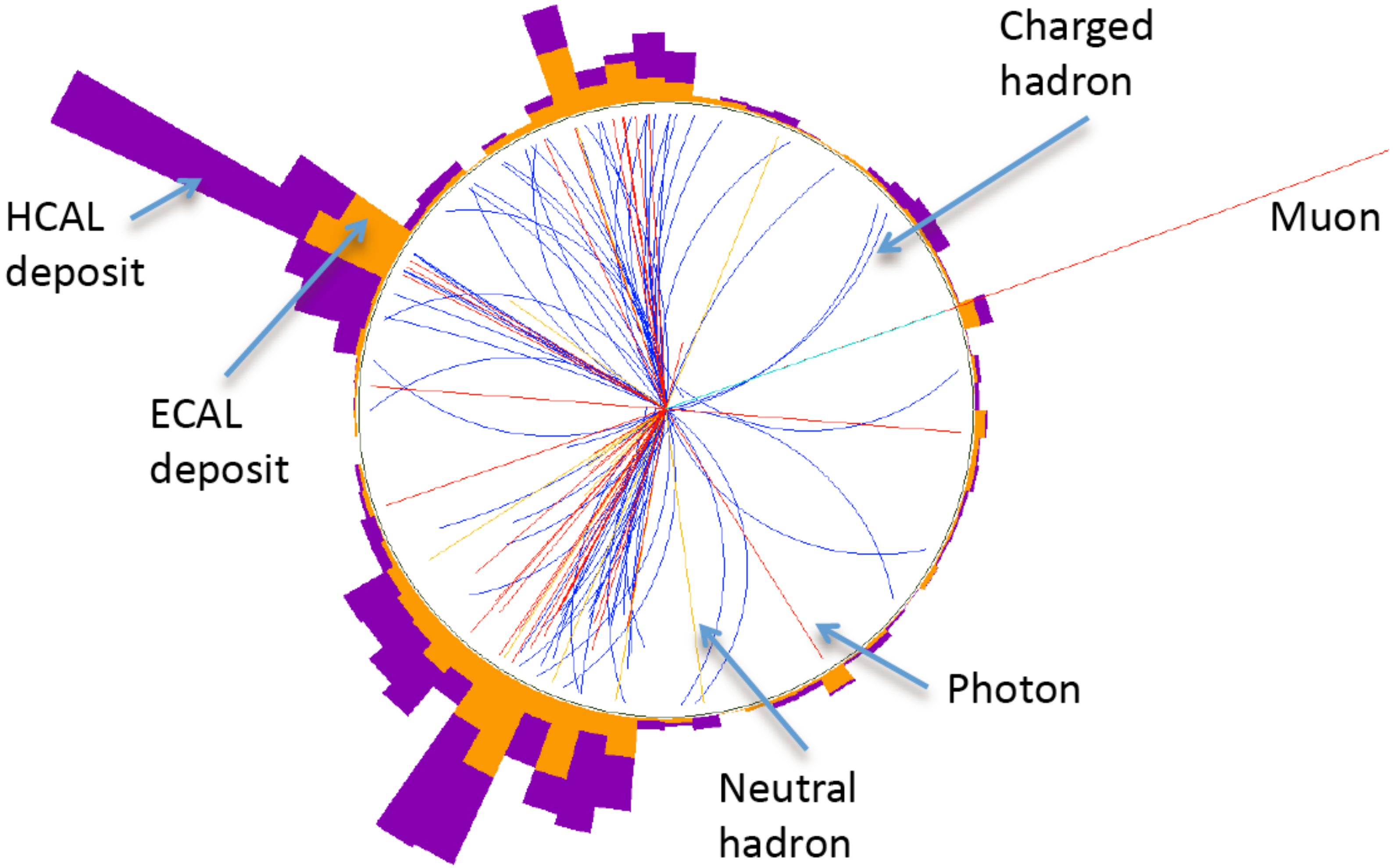
Identify pile-up



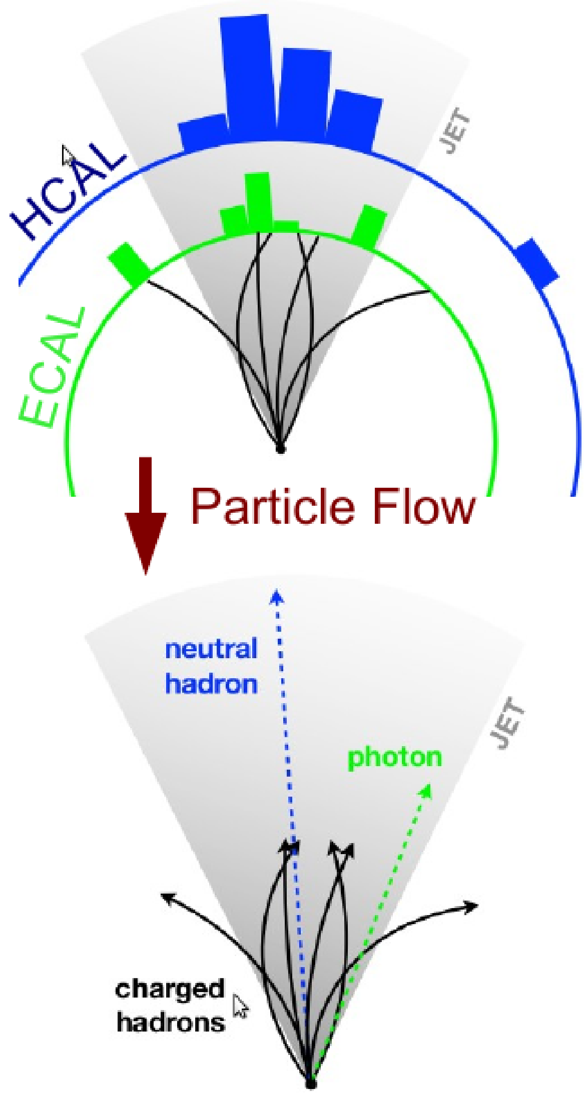


- Tracking and identification of primary vertices used to identify which particle belongs to which collision
- Evident for charged particles but more difficult for neutral hadrons…
- ATLAS uses fraction of tracks in jet associated with hard scatter interaction

Particle flow



Particle flow in practice

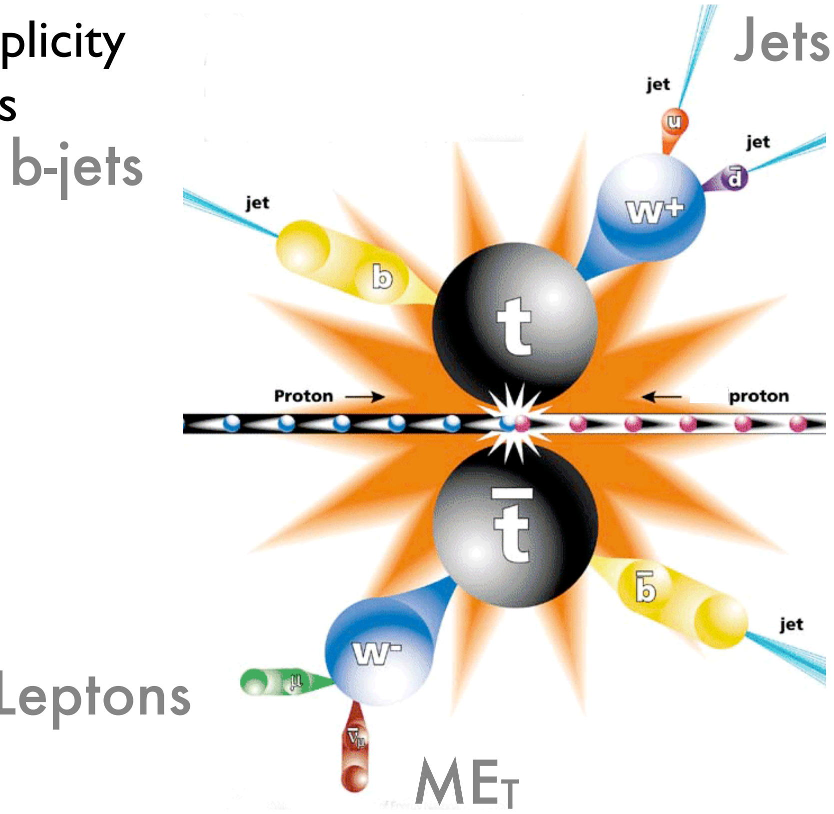


- PF combines information from all subdetectors in a global event description
  - reconstruct 'particles' such as charged/neutral hadrons, photons, muons, electrons
- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles
- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,

Object reconstruction

Background from long lived non-b jets?
Increased track multiplicity from pile-up degrades performance?

Good enough resolution to see W mass peak?



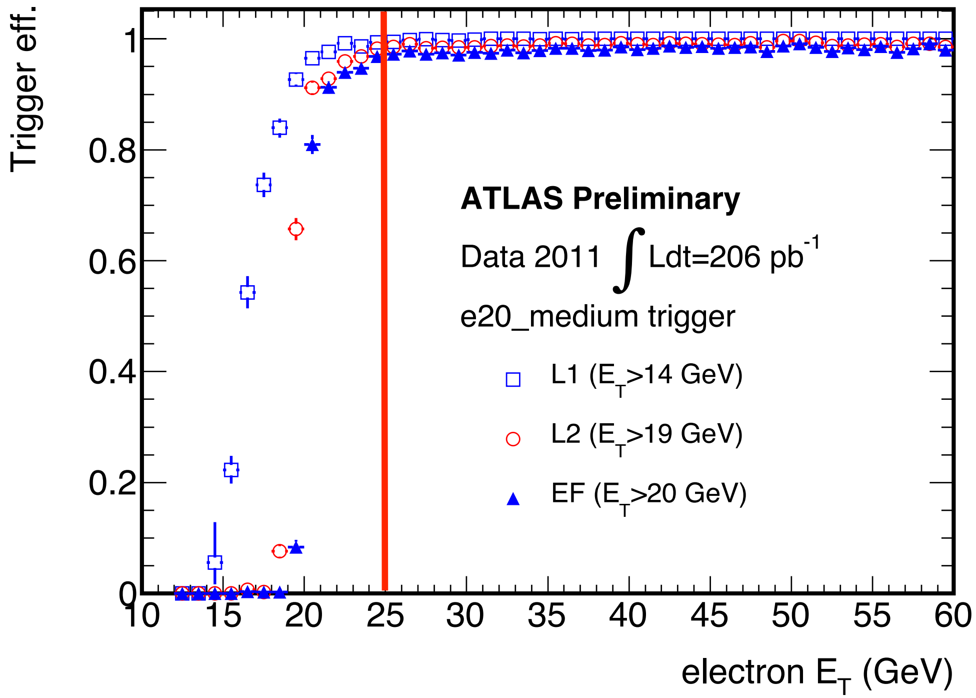
Pile-up affects reconstruction?
Jets where only lepton seen?
Actual fakes?

From pile-up?
Electronics/ detector noise?

Affected by pile-up?
Electronics/detector noise?

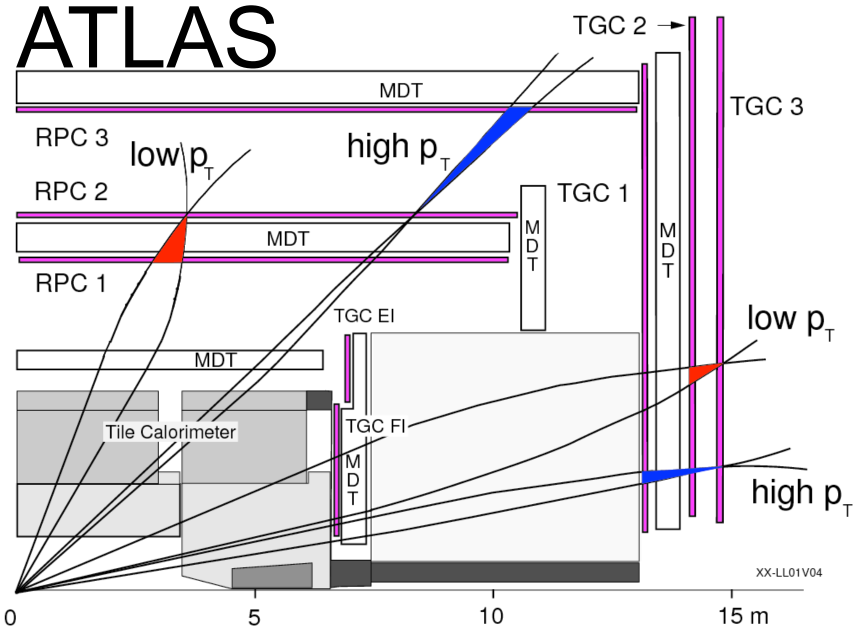
Leptons – trigger

- Most important: **trigger** and get the events on tape

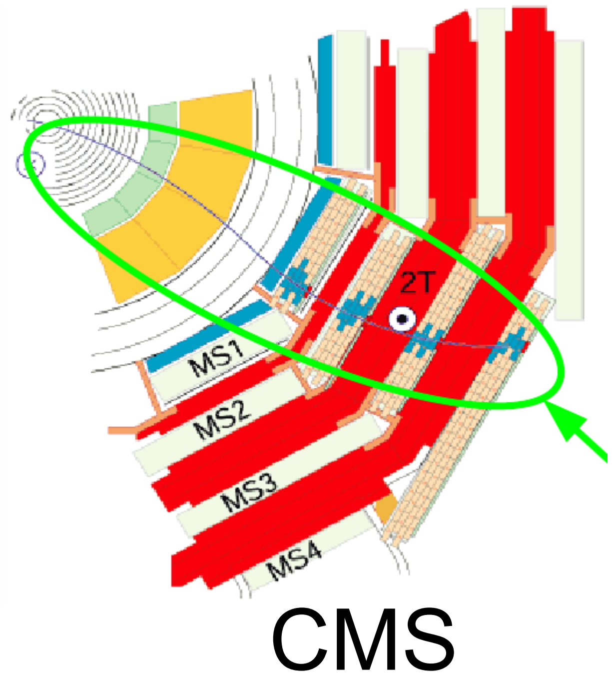


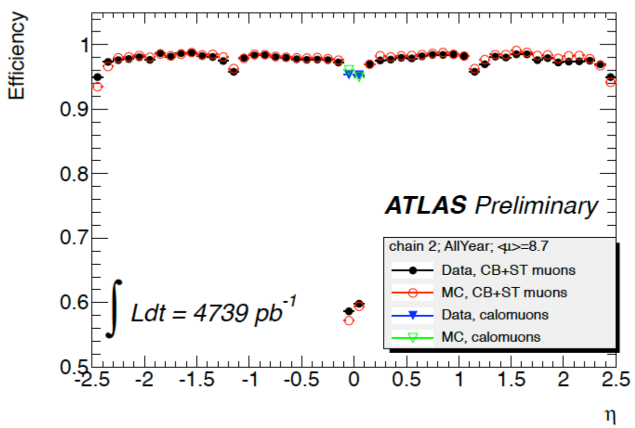
- Different triggers used for different channels
  - ATLAS: extremely good one-lepton triggers
    - pT thresholds of 20 GeV or lower
  - CMS: strong at lepton+jets triggers
    - pT thresholds of 24-27 GeV for single leptons
    - Lower lepton pT thresholds using lepton+jets requirements
  - Di-lepton triggers have low thresholds and high priority
  - Multijet triggers need very stringent requirements and tuning to keep rate low

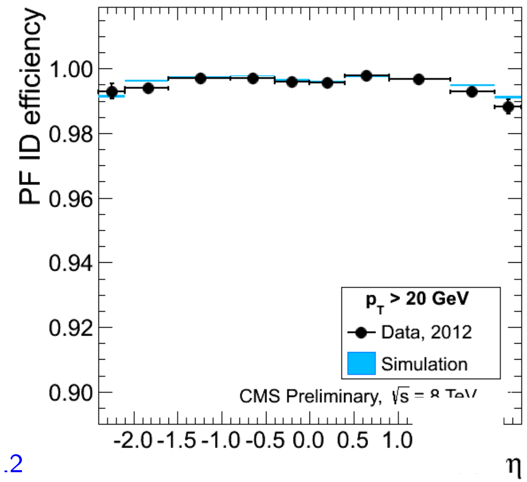
muons



- Muons combine inner tracking and outer muon system information in track fit

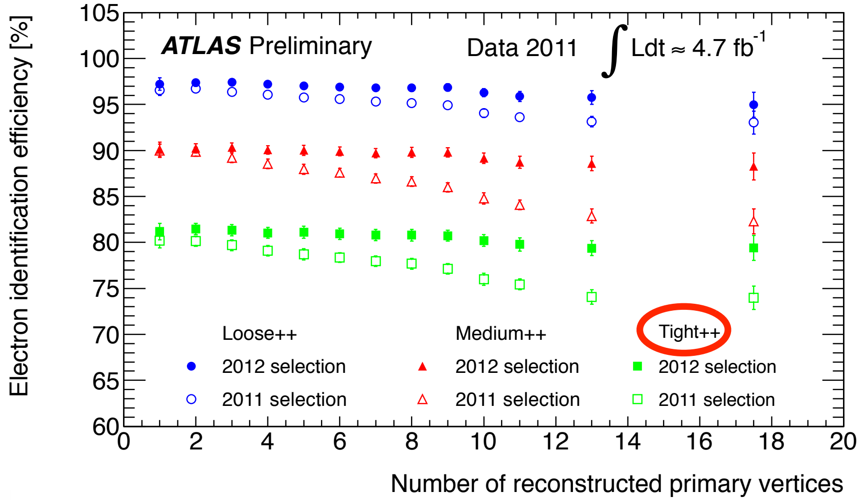


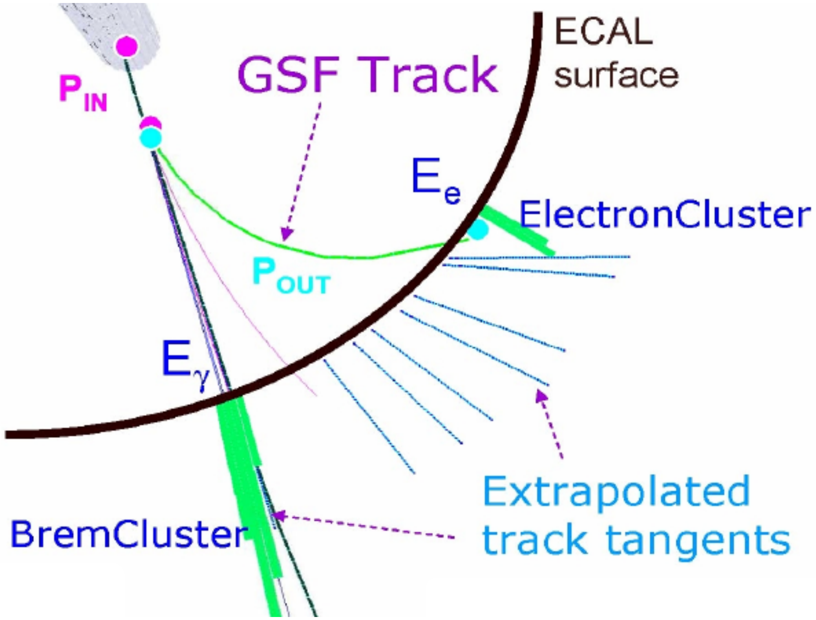


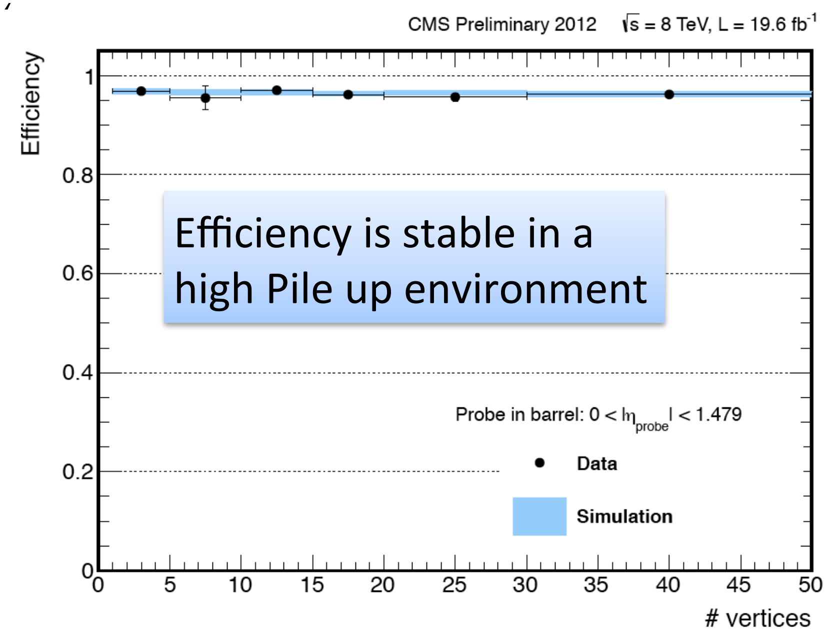


electrons

- Both ATLAS and CMS combine info from tracking and (em) shower shape calorimeter in multivariate technique

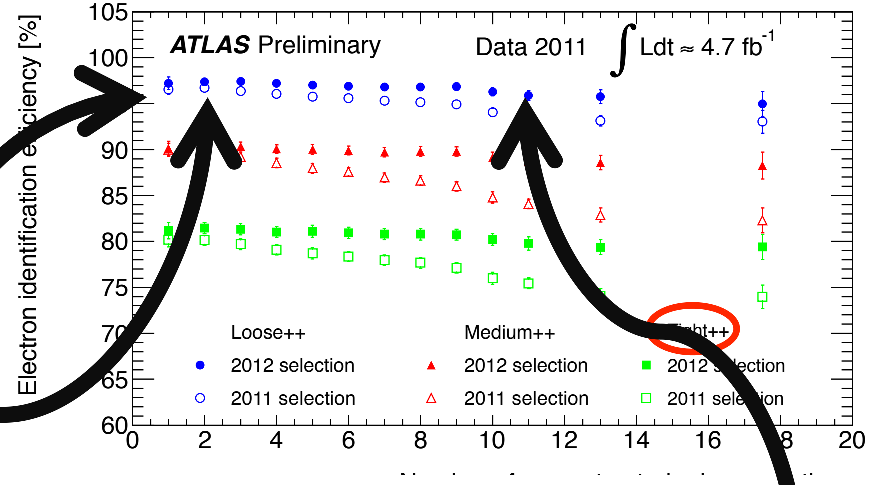


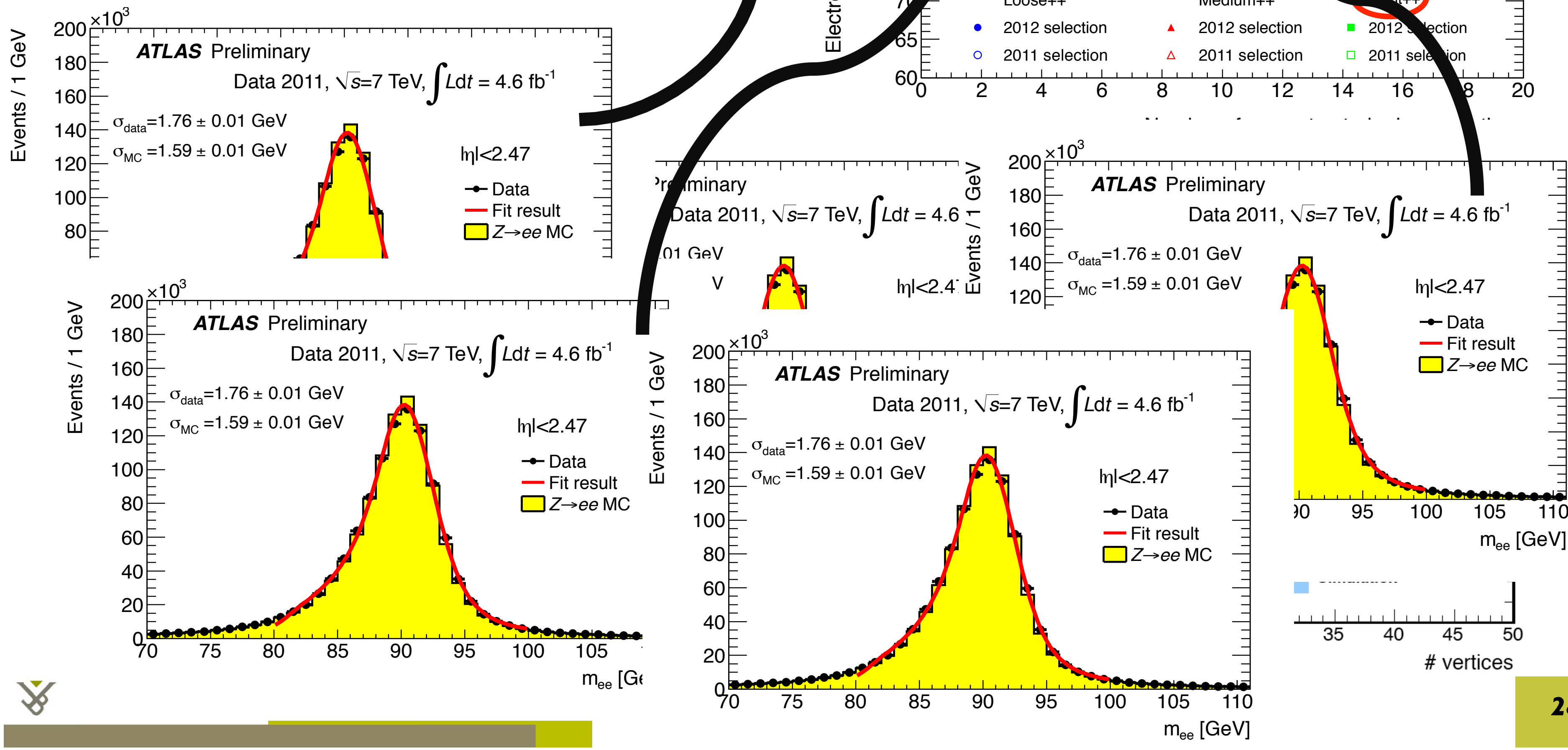




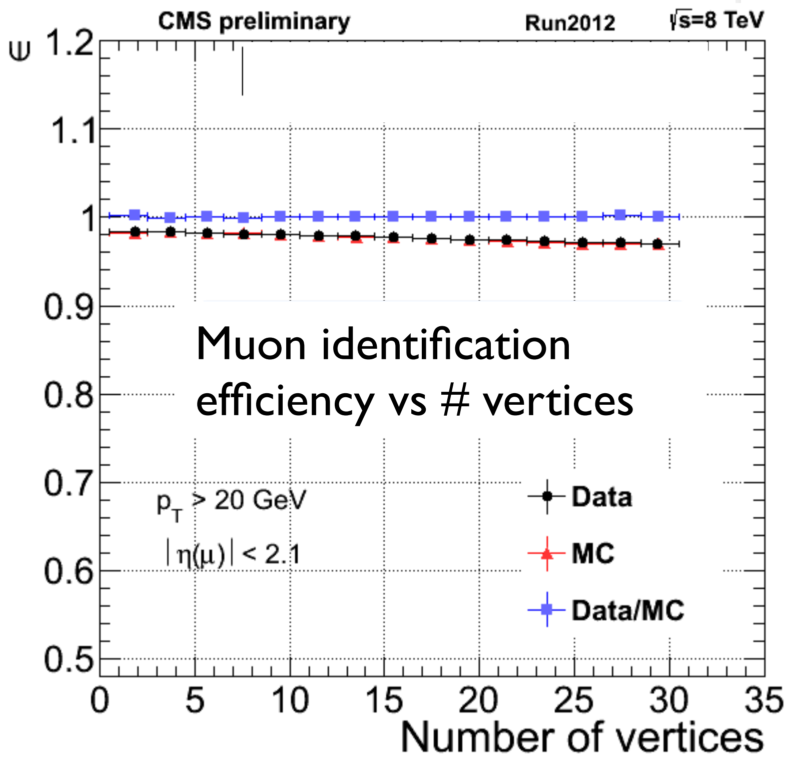
electrons

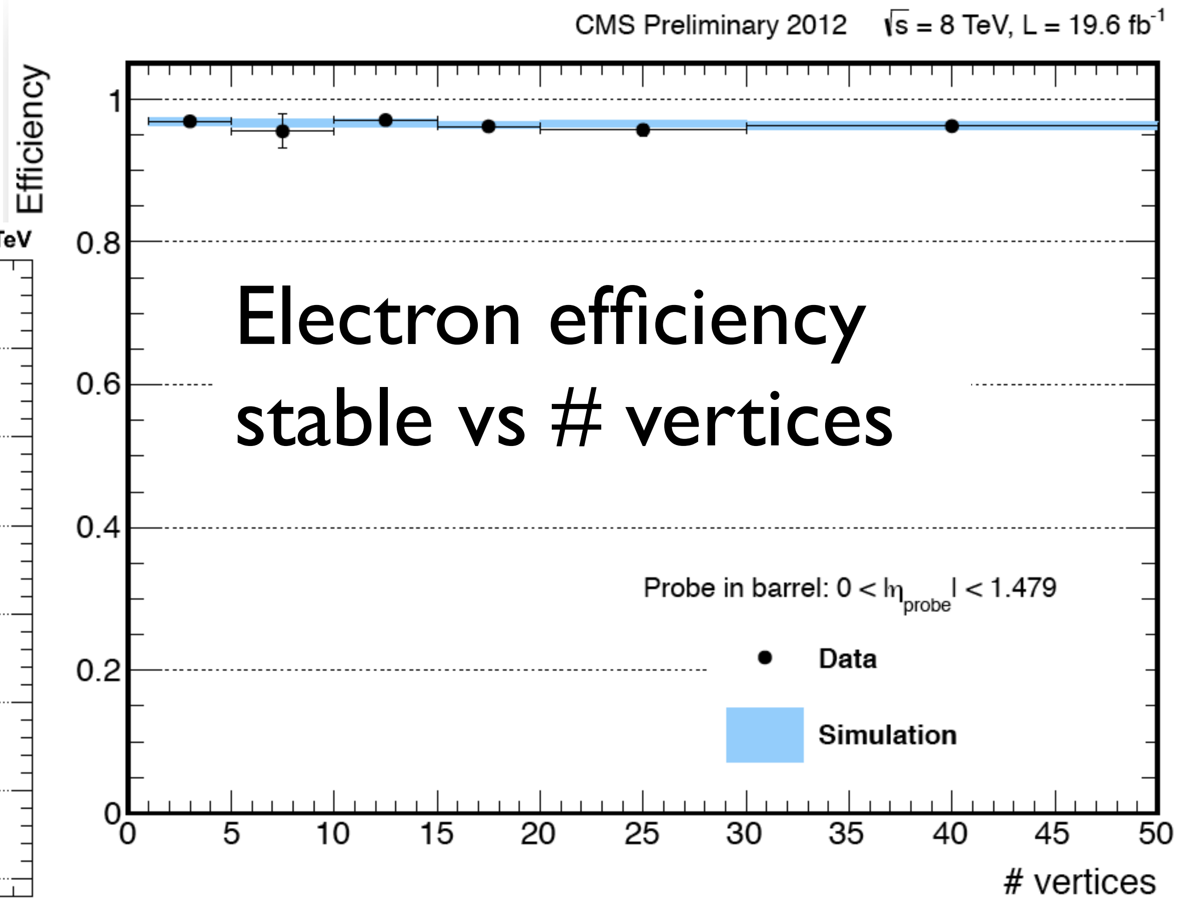
- Both ATLAS and CMS use Z bosons to check performance for muons and electrons





Leptons and pileup

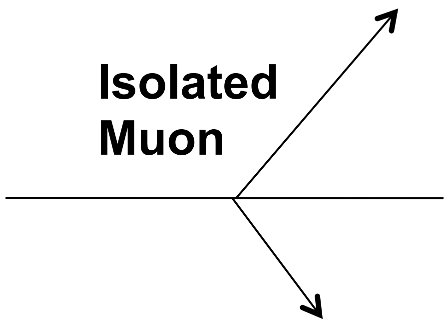


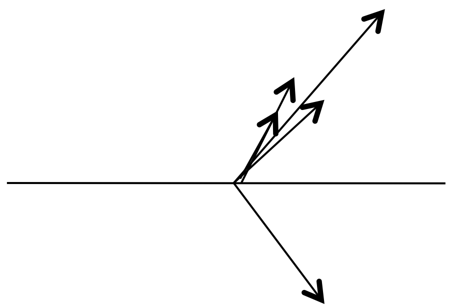


- Substantial effort necessary to achieve this stability

Isolation

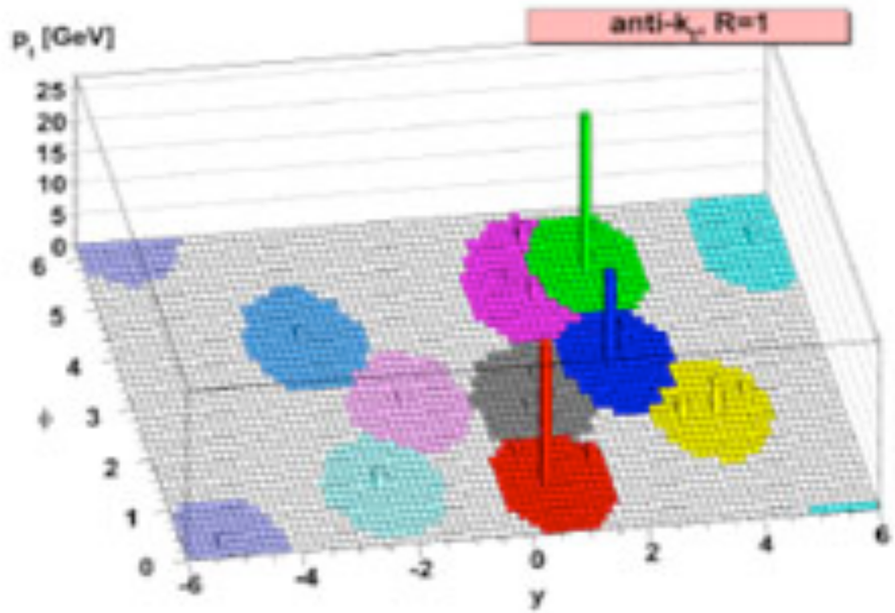
- Since hard processes produce large angles between the final state partons and the beam remnant jets stay close to the beam line, the objects we are interested in for our studies are usually well separated or "isolated" from other objects in the event
- Isolation is applied by drawing a cone around the object of interest in η-ϕ space; adding up the extra E_T in the cone (exclusive of the E_T of the candidate); and rejecting the object if the "extra E_T" is more than a certain fraction of the E_T of the candidate
- Example of isolation: discriminating an isolated muon from a W from a muon coming from the semileptonic decay inside a b-jet

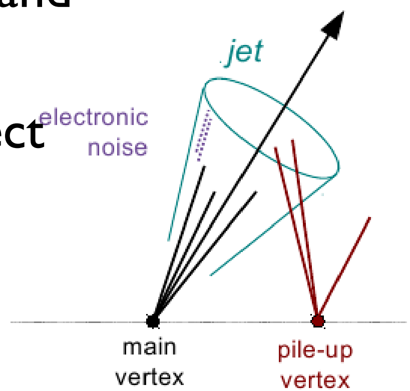


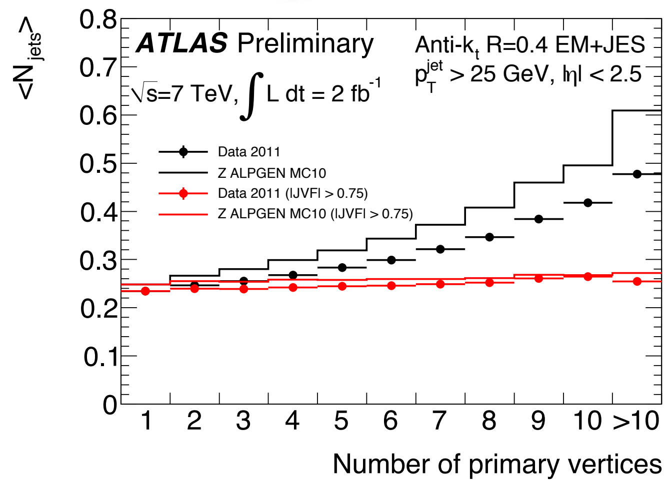


Jets

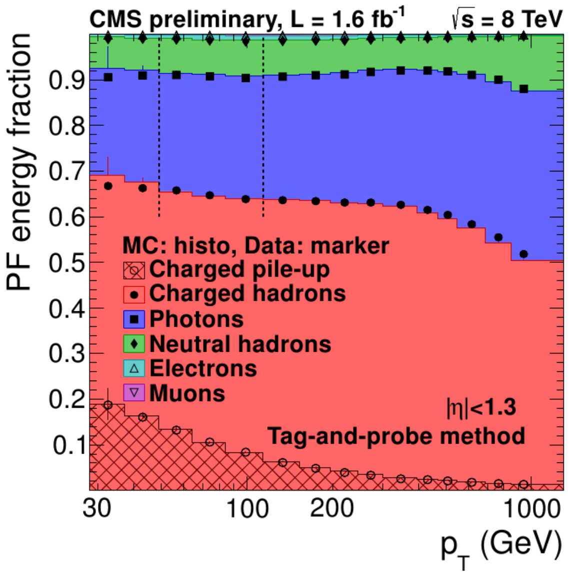
- For most analyses, CMS and ATLAS use anti-k_T jets with a distance parameter d
  - ATLAS Run1 : d=0.4
  - CMS Run 1: d=0.5
  - CMS & ATLAS Run 2: d=0.4 ☺
- ATLAS relies on outstanding quality of calorimeter to get good jet performances
- CMS Particle flow algorithm allows very good agreement between data and MC with small uncertainties and good resolution
- Both experiments carefully correct for pile-up vertices





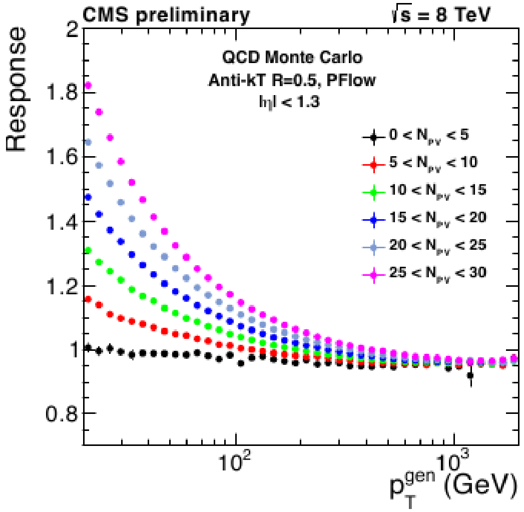


Jets - CMS

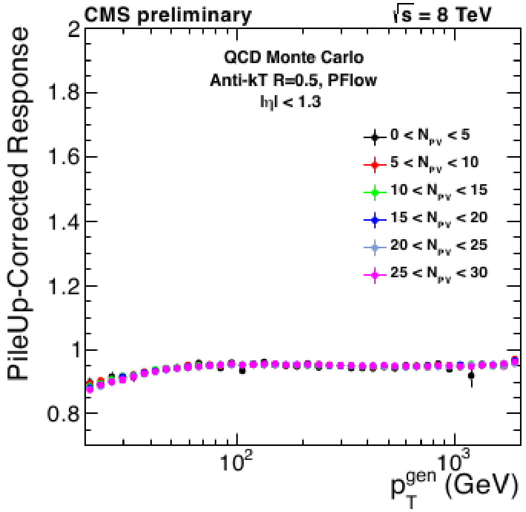


- CMS has need for very detailed understanding of fraction of different particles per jet and fraction of pile-up particles in jet as these are subtracted by the particle flow algorithm

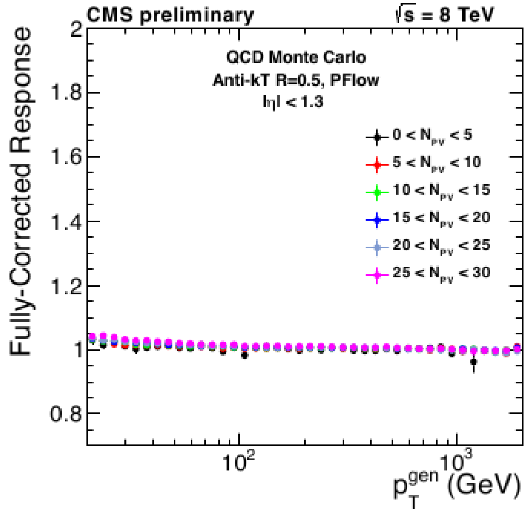
Before corrections



PU corrections



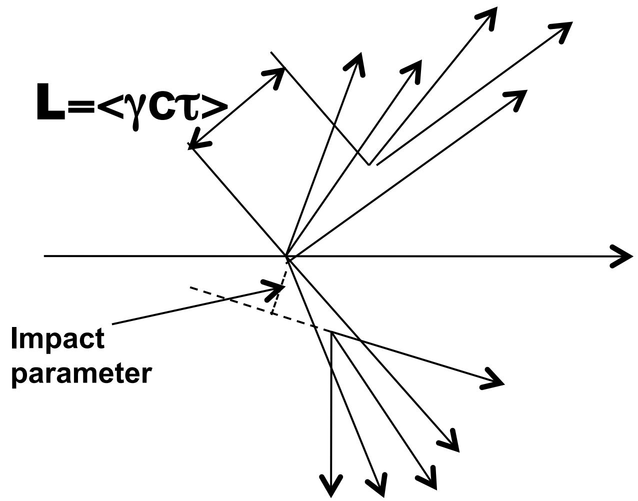
PU+MC truth



b-quark jets (same idea for charm)

Discriminants of b jets from light quark or gluon jets based on

- Long lifetime of b-hadrons in them
  - $\tau = 1.512 \times 10^{-12}$ s, $c\tau = 455.4\ \mu$m
- High masses
- High fraction of semi-leptonic decays
  - ~10% e, μ (and from charm)
- Hard fragmentation



$\theta \sim 1/\gamma$

$\sigma_L \sim 1/$

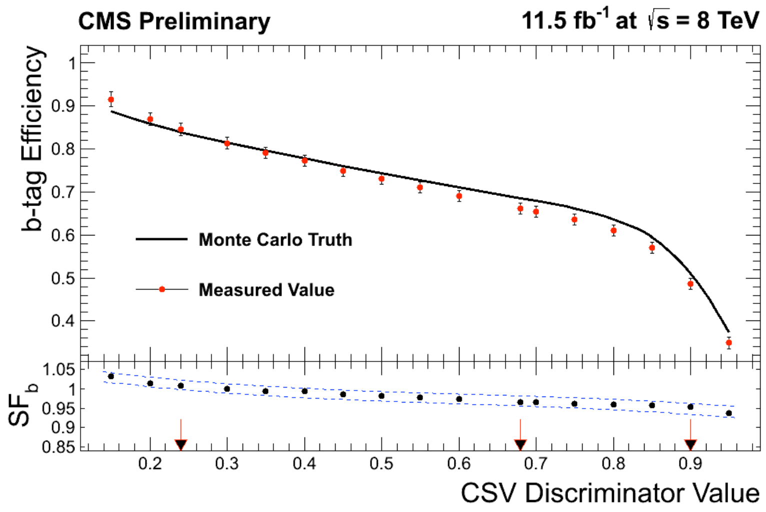
$\theta \sim \gamma$

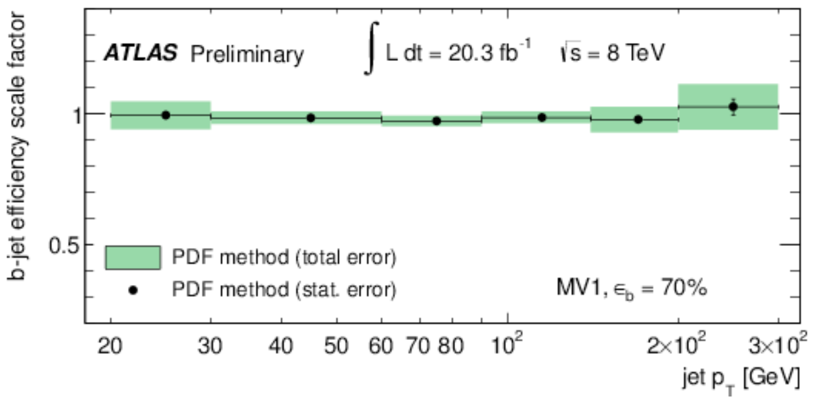
L/σ_L ~ independent of p of B

Impact parameter ~$1/2\pi c\tau$ independent of p

- Methods for discrimination
  - Impact parameter based
    - Track counting high efficiency
    - Track counting high purity
    - Jet probability
    - Jet B probability
  - Secondary vertices
    - Simple secondary vertex
    - Combined secondary vertex
  - Lepton based algorithms
    - Soft muon by PTrel
    - Soft muon by IP signficance
    - Soft electron
  - Combined algorithm
    - Combined MVA

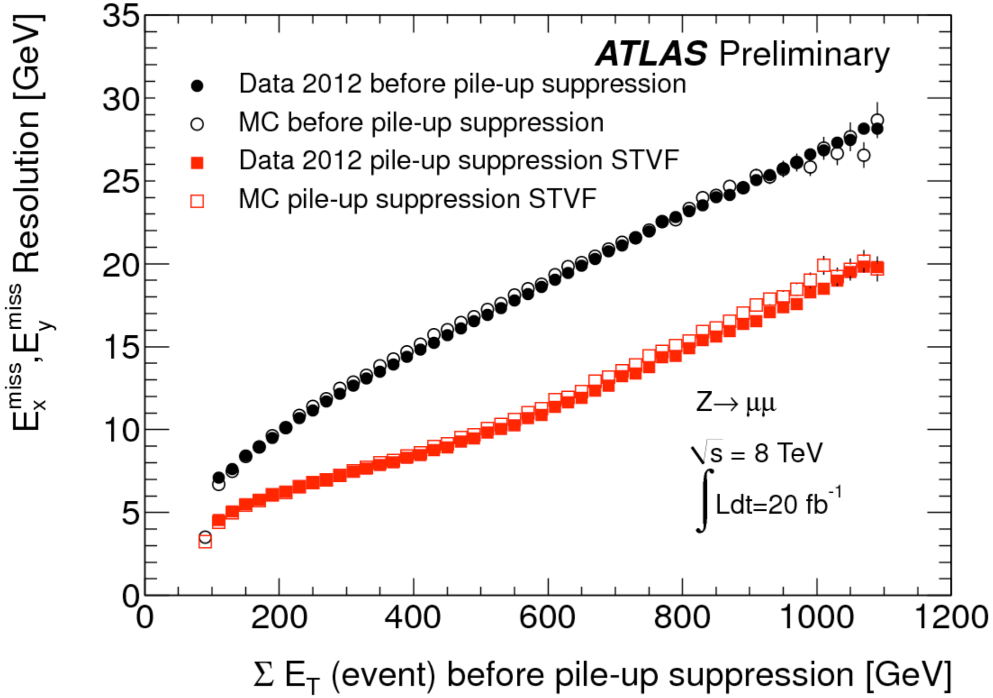
Jets with b-tagging





- Long lifetime of b-hadrons in b-jets
  - τ= 1.512 x 10^{-12} s
  - $c\tau$ = 455.4 μm
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods

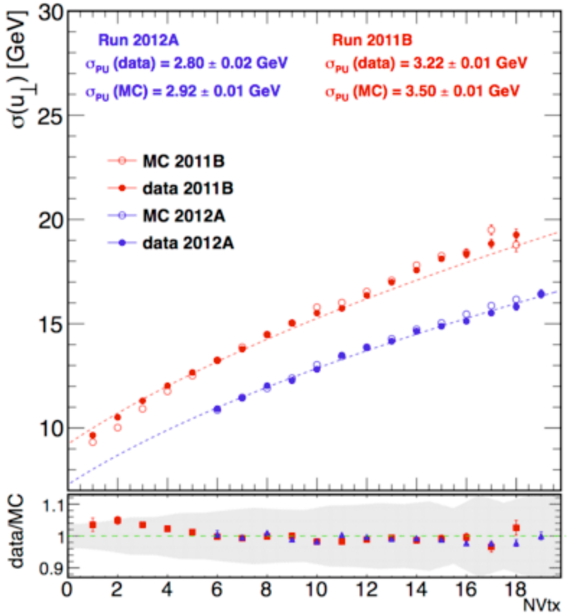
Missing ET



Particle flow extremely powerful approach for missing ET reconstruction

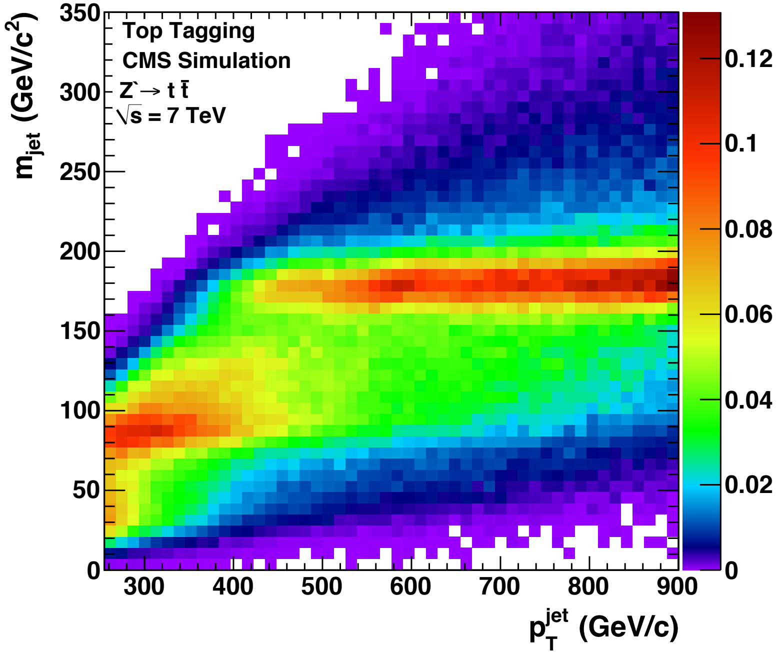
Missing ET sensitivity to PU irreducible

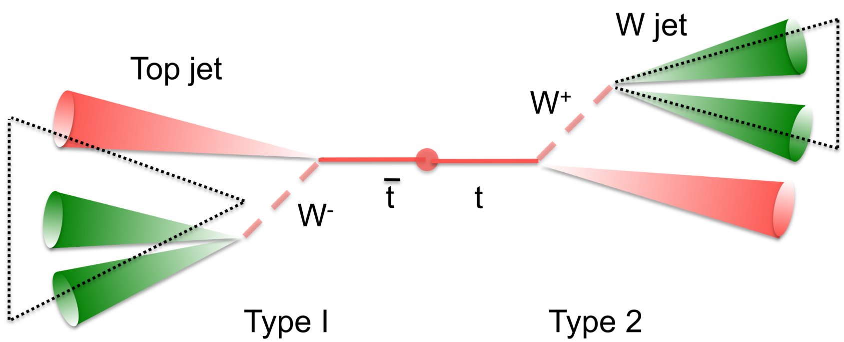
– But well reproduced in MC



On the momentum of top quarks

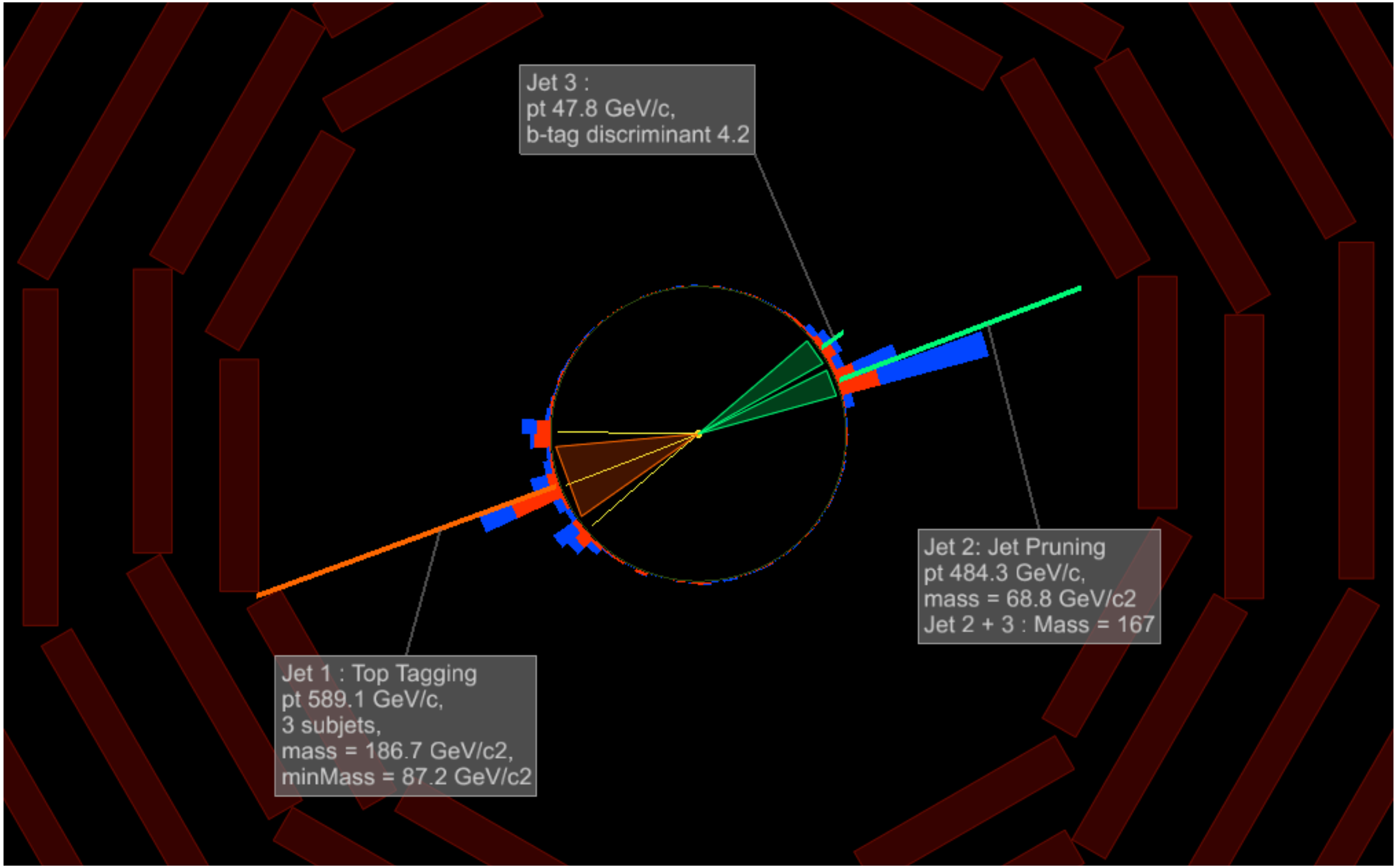
PAS JME-10-013



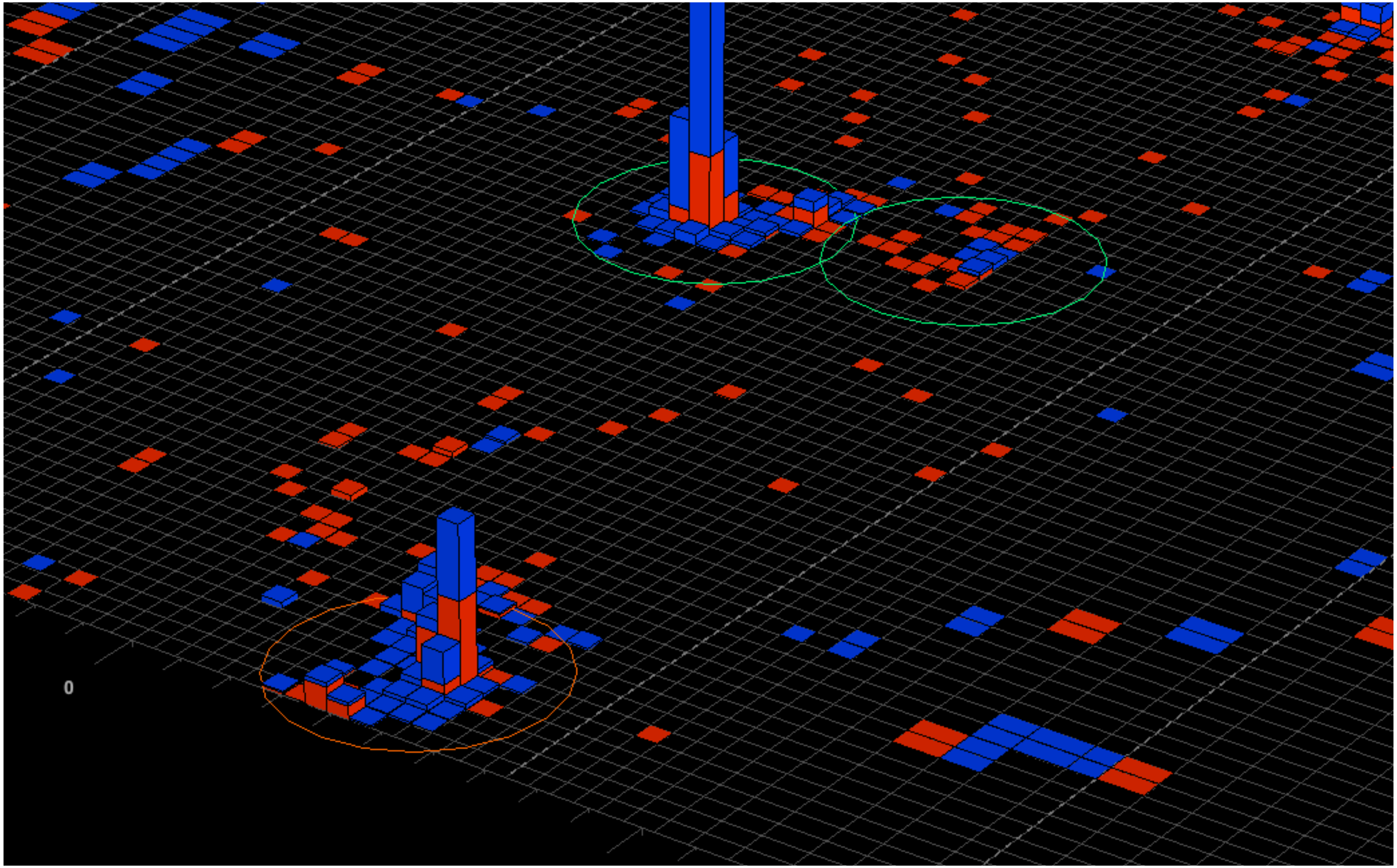


- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed

Jets with substructure

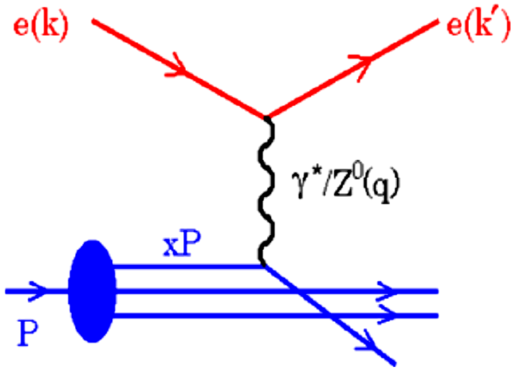


Jets with substructure



Reminder: parton density functions determine all LHC cross sections!

Proton structure probe



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

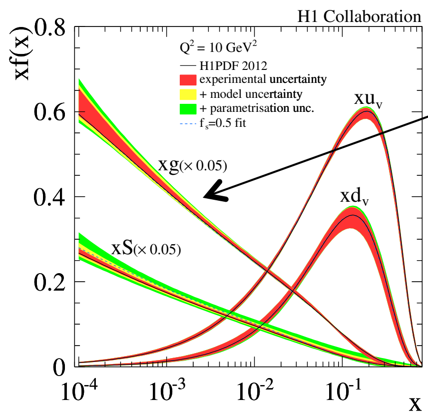
$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\ x)$.

Kinematics is determined by Q^2 and Bjorken x.
At leading order:

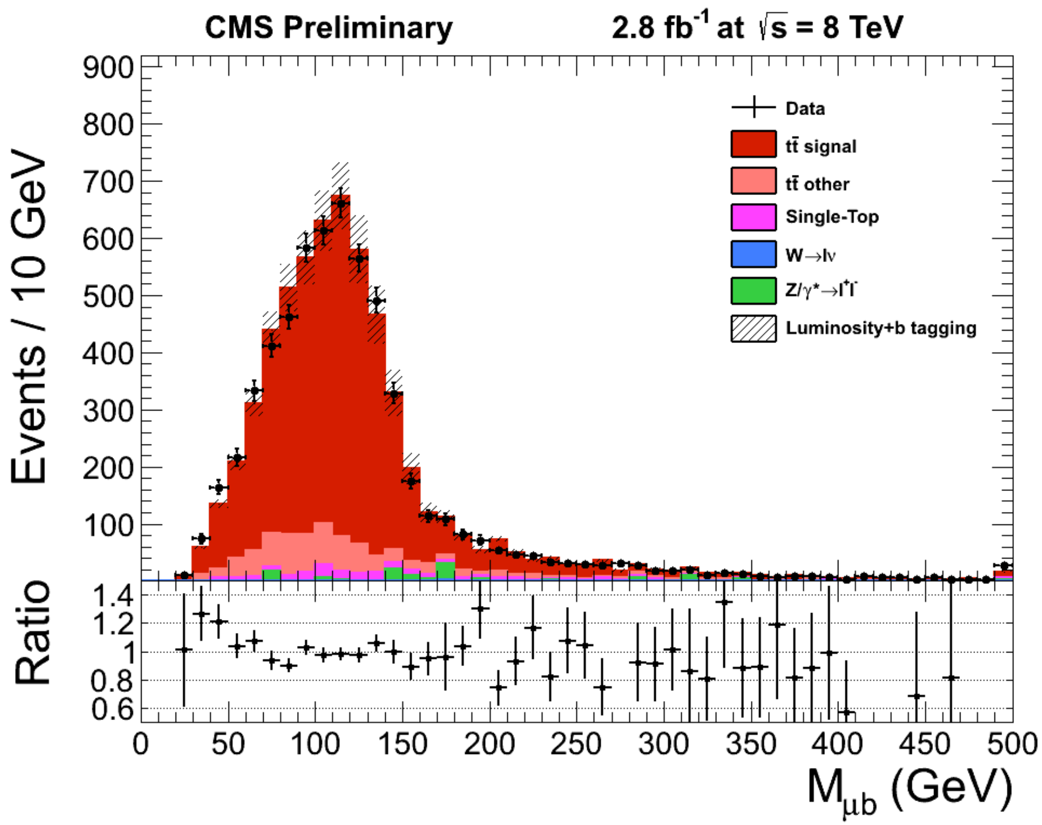
$$\begin{aligned}
F_2 &= x\sum e_q^2(q(x)+q(x)) \\
xF_3 &= x\sum 2e_q a_q(q(x)-q(x)) \\
\sigma_{CC}^+ &\sim x(u+c)+x(1-y)^2(d+s) \\
\sigma_{CC}^- &\sim x(u+c)+x(1-y)^2(d+s)
\end{aligned}$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



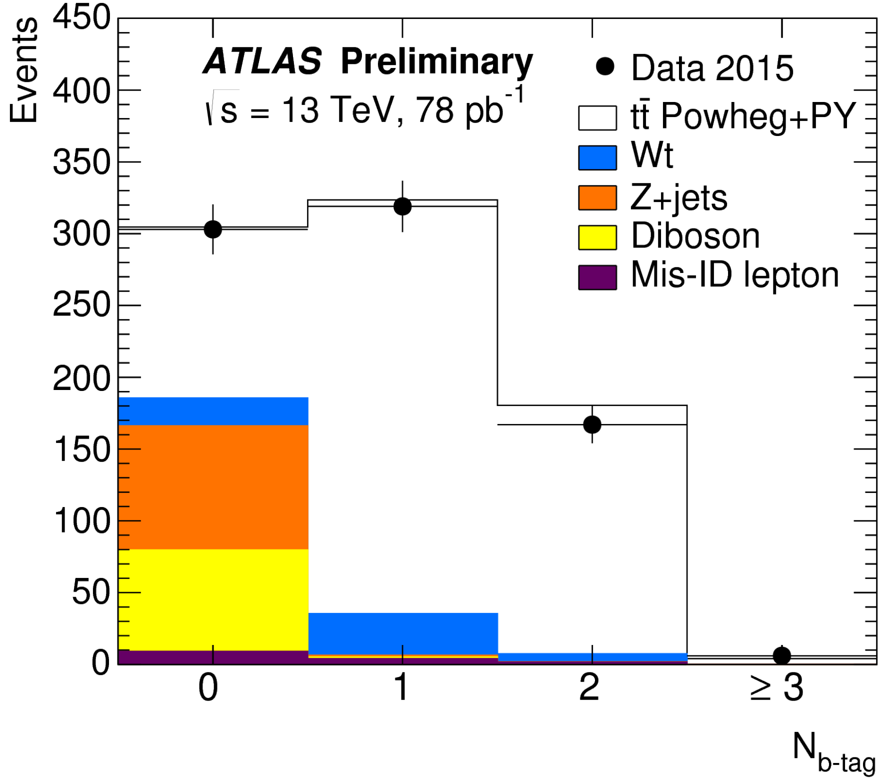
For most processes, LHC essentially is a gg collider

LHC: Top quark pair factory



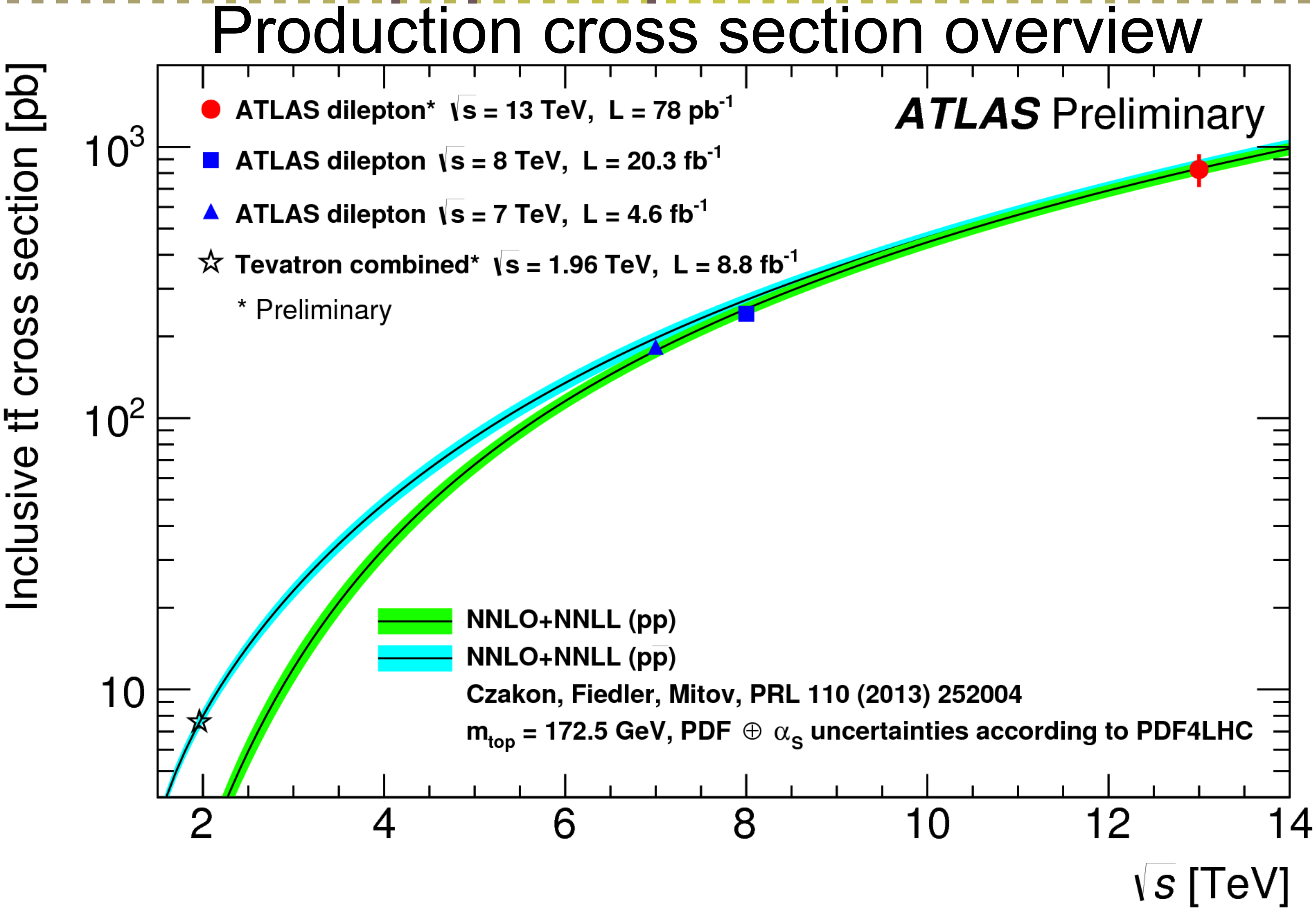
- Cross sections 8 TeV ~225 pb
- In combination with 20 /fb datasets:
  - LHC is a top factory
  - Very productive program of Standard Model precision top physics

LHC: Top quark pair factory



- Cross sections 13 TeV ~800 pb
- In combination with 80 / pb datasets:
  – LHC is a top factory
  – Very productive program of Standard Model precision top physics

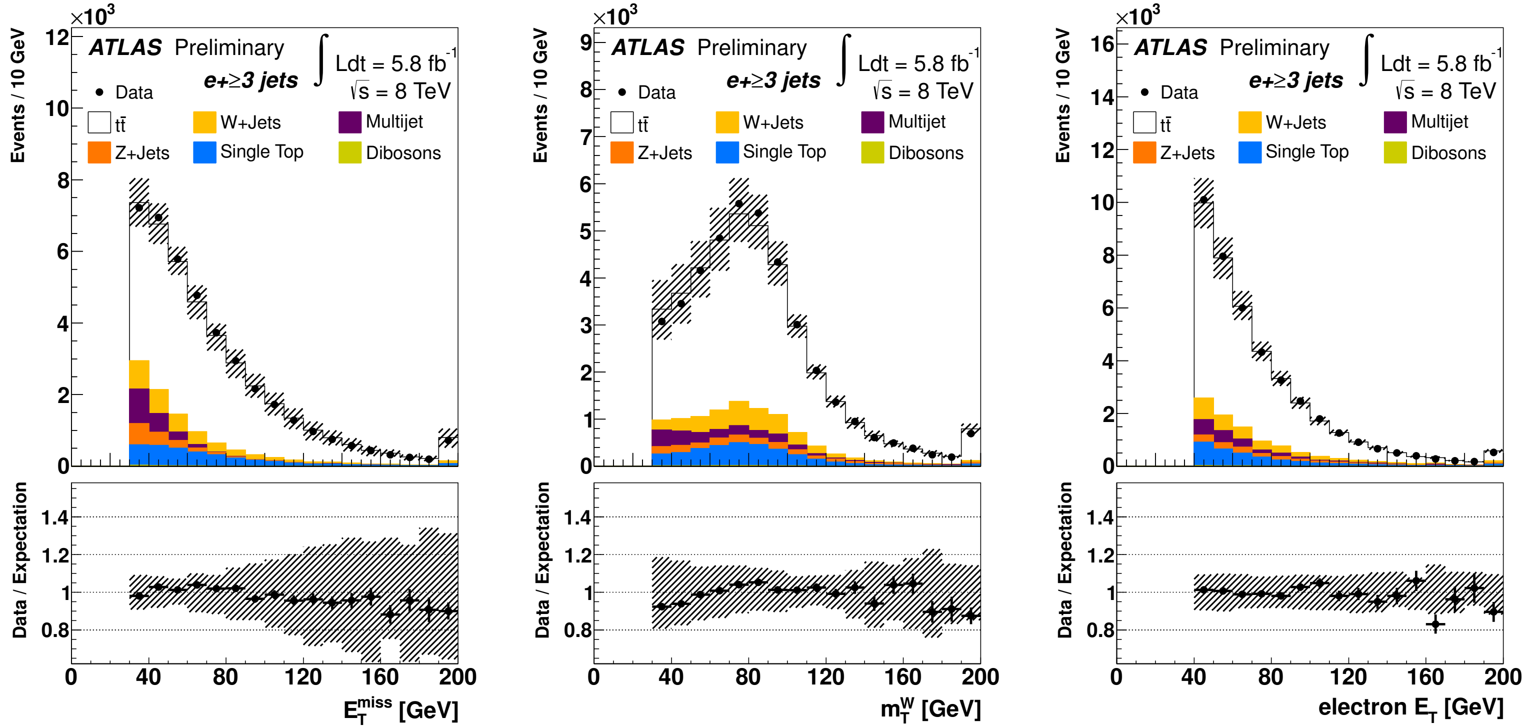
Top pair production



Top cross sections

- Good benchmark to explain basic strategies in top physics and see main backgrounds
- Chosen result: ATLAS lepton+jets cross section with kinematic variables
- This is an analysis that uses the kinematical quantities of events with one lepton and (at least) 3 jets, including one b-tagged jet, to derive the total number of top quark events in the sample
  – And from that the production cross section

Event quantities



	e+≥3 jets	μ+≥3 jets
$t\bar{t}$	31000^{+2900}_{-3100}	44000±4000
W+jets	5700±2400	9000±4000
Multijet	1900± 900	1100± 500
Z+jets	1400± 600	1200± 500
Single top	3260± 160	4610± 230
Dibosons	115± 6	158± 8
Total Expected	43000±4000	61000±6000
Data	40794	58872

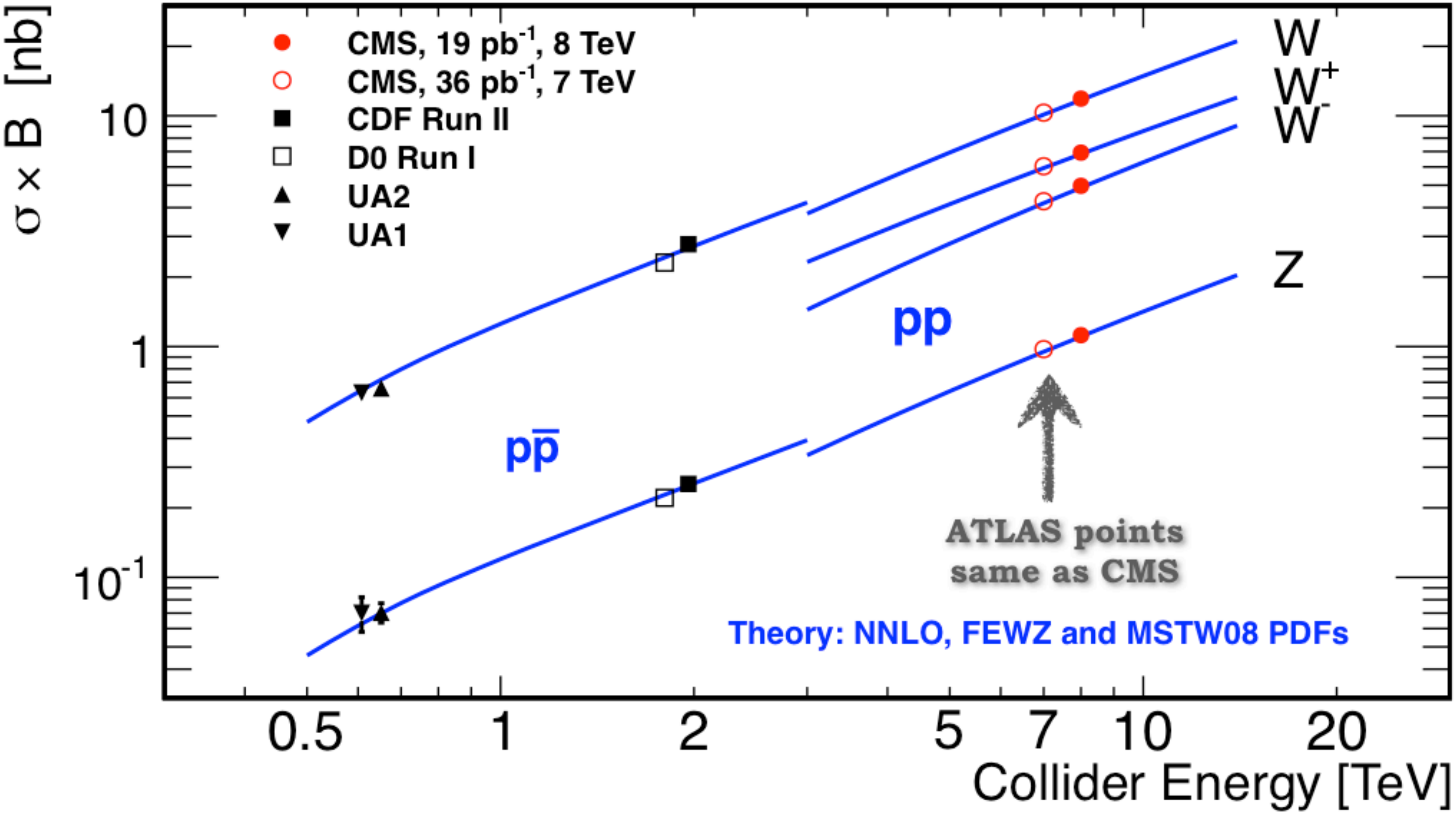
Expected from detailed MC simulation using full detector response (GEANT)

Events generated with full Standard Model matrix element at Next-to-leading order, and full modeling of hadronization of quarks/gluons

Simulation takes much time (typical: few min/event at least)

Events scaled to NNLO theory cross section predictions

EWK cross section overview



Question: why at LHC W^+ different than W^-?

Multijet background, aka ‘QCD’

‘Electron’s that are ‘QCD’

- Overlap track w/ photon
- Photon conversions
- b-quarks and c-quarks that decay to leptons
  - Rest of decay missed? Real leptons
- Jets with fluctuations in hadronization
  - Very few charged tracks
  - Very small hadronic energy fraction

‘Muons’ that are ‘QCD’

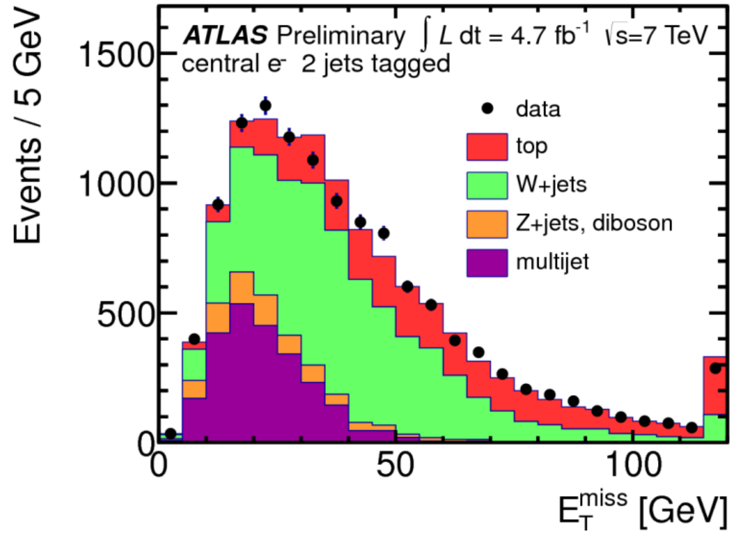
- Pions, kaons that decay in flight in tracking region
- b-quarks and c-quarks decaying to leptons
  - rest of decay missed? Real leptons
- Hadrons that did not shower in calorimeter?
- Punch-through hadrons

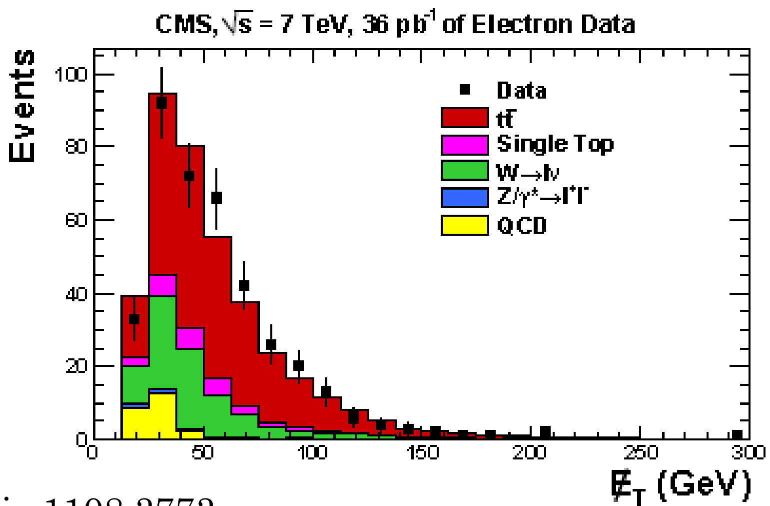
Simulation of fake electrons and muons using simulated QCD events is <u>both</u> **unreliable** and **impractical**

Data-driven methods

Many methods, all rely on isolating a control region enriched in fake leptons

- Select a sample of known lepton-like jets (looser version of your sample) and determine how often you see a muon or electron
  - Derive shapes from this and normalise to sideband (low Missing ET for example)
  - Good at modeling bad hadronization
- Or determine a sample of 'anti' electrons/ muons by inverting one of the selection cuts (typically the isolation requirement)
  - Very good at modeling complex variables
  - Good at modeling HF jets that fake isolated leptons





arXiv:1108.3773

Data-driven methods

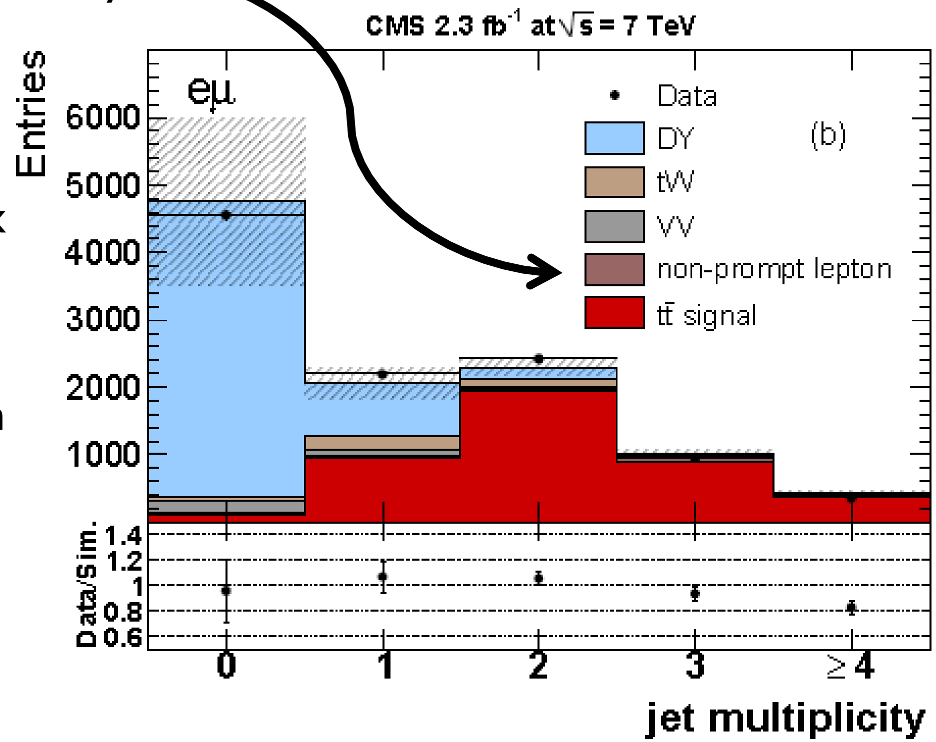
Matrix method:

Use two control regions with different, known, real/fake fraction and compare them to derive both fake rate and efficiency or vice versa

- Involves matrix inversion of 2x2 matrix
- needs well-understood sample composition of loose and tight sample
- Or needs known efficiency and known fake rate derived from other samples such as multijet and Z->ll resonance

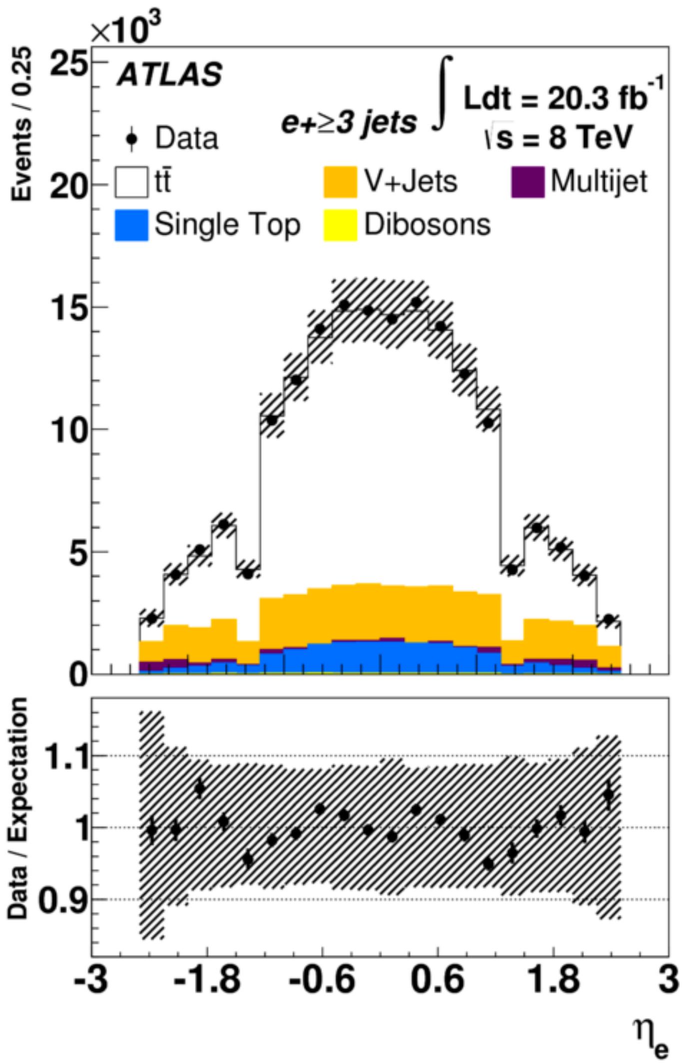
- Advantage: can completely determine composition of samples and with small uncertainties
  - But is complicated and involves many cross checks

Non-prompt background in CMS 7 TeV dilepton cross section analysis derived this way



Also commonly used in determination b-tag efficiency and fake rate from b-bbar events

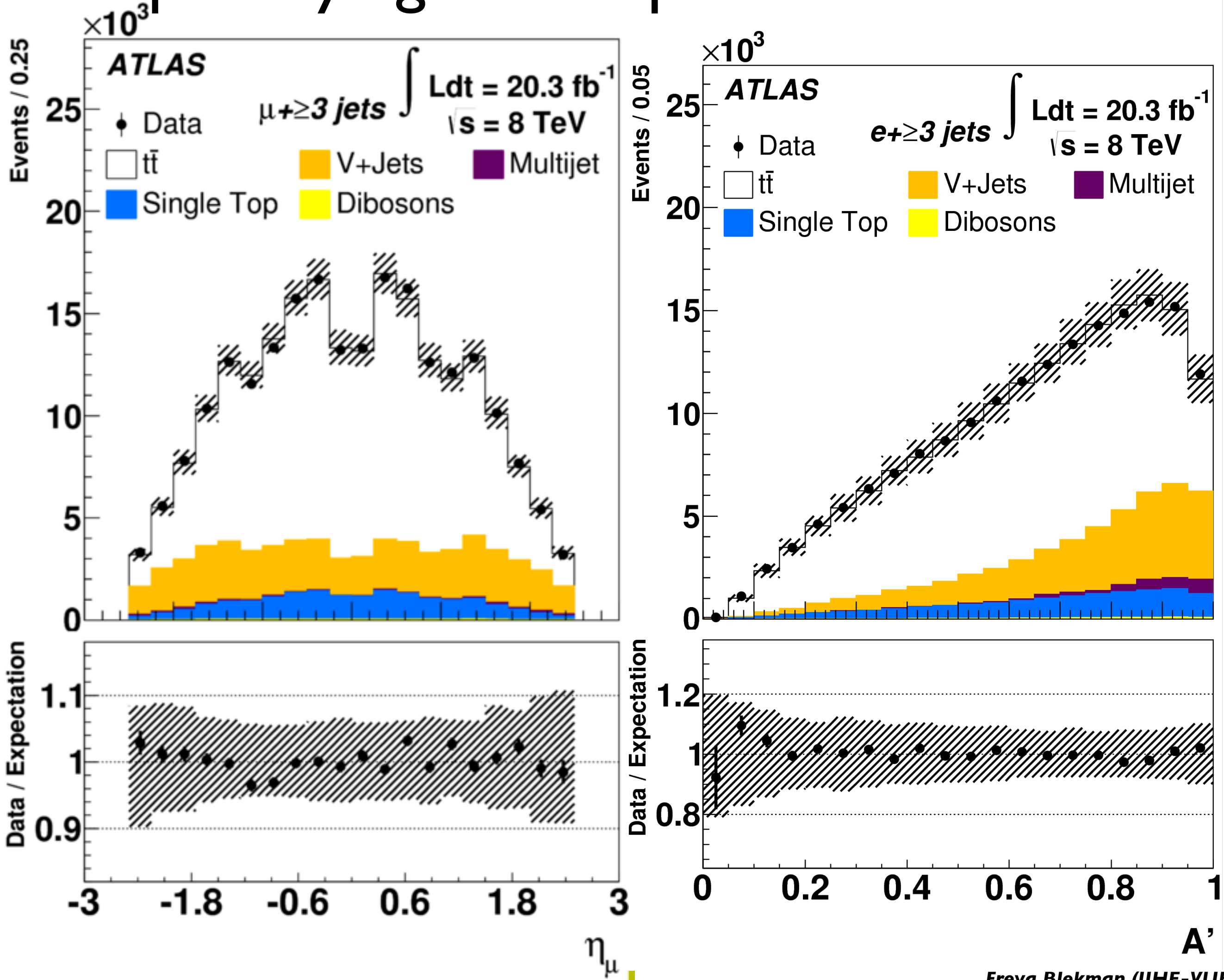
Back to ATLAS' cross section measurement



- Muon multijet contribution derived with matrix method
  - Used high MET (>100) region (few fakes) and low MET (<20) region to determine fake rate.
  - Low MET region of course contained W and Z bosons so those were subtracted using simulated contributions
- Electron multijet contribution derived from jet-enriched sample

Combined in likelyhood

- Likelihood in this case means single number per event quantifying how top-like the event is



- Statistical fit that varies backgrounds within their uncertainties used to determine remaining number of ttbar events, which is then used:

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\mathcal{L} \times BR \times \varepsilon_{\rm sig}}$$

- Efficiencies: determined from simulation with corrections from data

Systematic uncertainties

Uncertainty on inclusive $\sigma_{t\bar{t}}$	e+jets	μ+jets	ℓ+jets
Lepton reconstruction	$+2.7$ -2.6	$+2.1$ -1.9	$+1.7$ -1.6
Jet reconstruction and E_T^{miss}	$+3.3$ -3.9	$+2.6$ -3.2	$+2.8$ -3.4
b-tagging	$+2.1$ -1.9	$+2.2$ -1.9	$+2.1$ -1.9
Backgrounds	$+2.8$ -3.0	$+1.8$ -2.1	$+1.7$ -2.1
Monte Carlo generator	-2.2 $+2.2$	-3.3 $+3.3$	-2.7 $+2.7$
Parton shower and fragmentation	$+2.0$ -2.0	$+2.6$ -2.6	$+2.3$ -2.3
Initial- and final-state radiation	-4.1 $+4.1$	-1.8 $+1.8$	-3.0 $+3.0$
Parton distribution functions	$+6.2$ -6.0	$+5.6$ -5.9	$+5.9$ -5.9
Total	$+9.7$ -9.8	$+8.4$ -8.7	$+8.6$ -8.9
Uncertainty on fiducial $\sigma_{t\bar{t}}$	**e+jets**	**μ+jets**	**ℓ+jets**
Monte Carlo generator	-2.1 $+2.1$	-3.5 $+3.5$	-2.8 -2.8
Parton shower and fragmentation	-2.6 $+2.6$	-3.1 $+3.1$	-2.9 $+2.9$
Initial- and final-state radiation	$+0.4$ -0.4	$+0.2$ -0.2	$+0.3$ -0.3
Total	$+8.9$ -9.0	$+8.5$ -8.8	$+8.3$ -8.6

- Each of these numbers involves rerunning the analysis taking into account known uncertainties on the lepton reconstruction, etc.
- Some, like the ‘MC modelling’ uncertainty, contain many effects such as ISR/FSR model uncertainty, parton density functions, parton shower models, uncertainties of the event generator used for the simulation
- More examples of systematic studies/uncertainties in next lectures

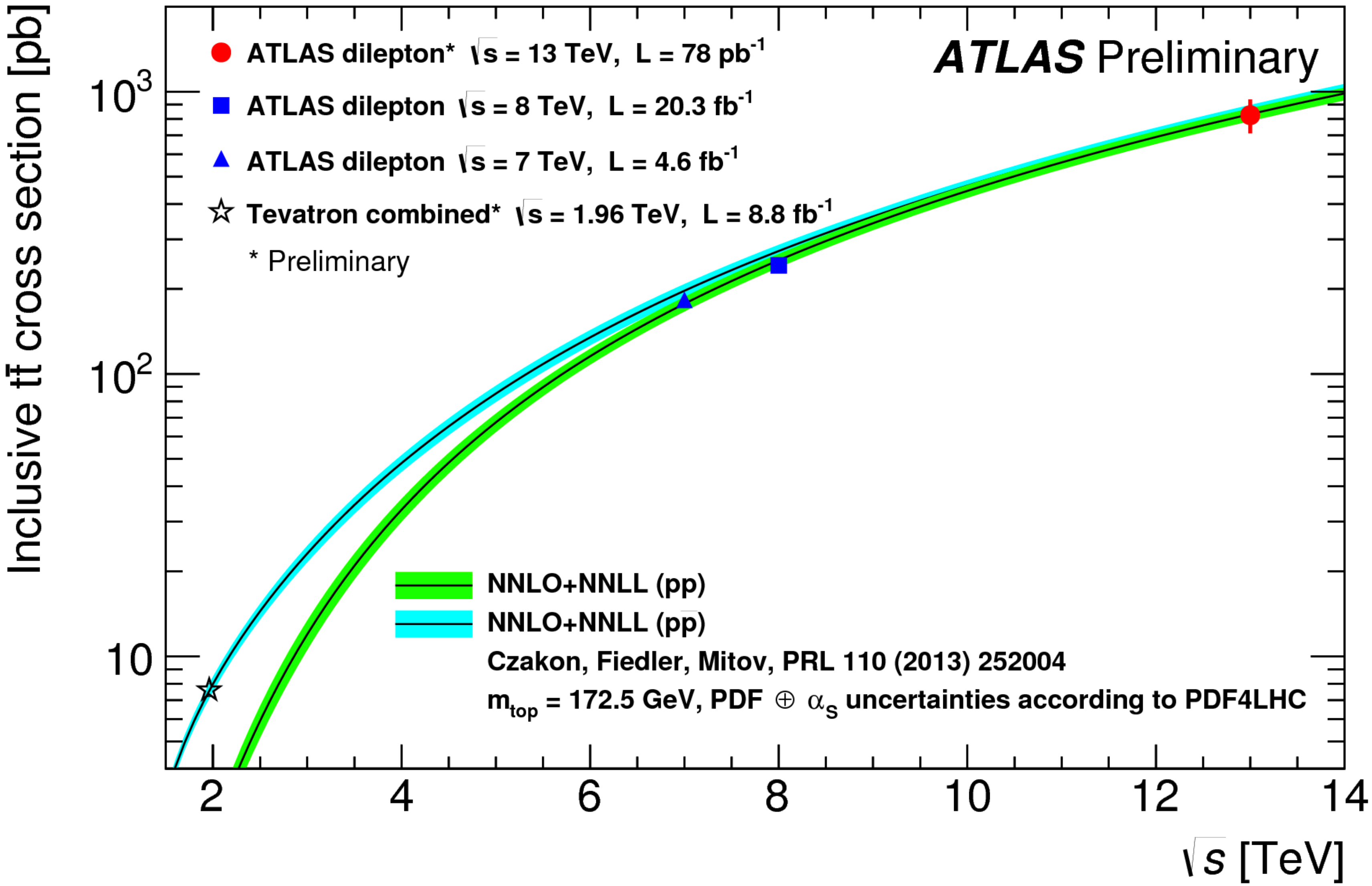
Final cross section

- Final cross sections traditionally (in top physics) are split up to have several uncertainties:

$$260 \pm 1(\text{stat.})^{+22}_{-23}(\text{syst.}) \pm 8(\text{lumi.}) \pm 4(\text{beam})\ \text{pb}$$

- The analysis determined the cross section at 8 TeV, which of course also has theory predictions. Some examples:
  – (approximate) Next-to-next-to-leading order assuming QCD production of generic heavy quarks: 238±10% pb (HATHOR, arXiv:1007:1327)
  – Full next-to-next-to-leading order: 246±3%±2.6 pb (arXiv:1303.6254)

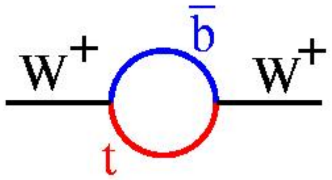
And in the end…



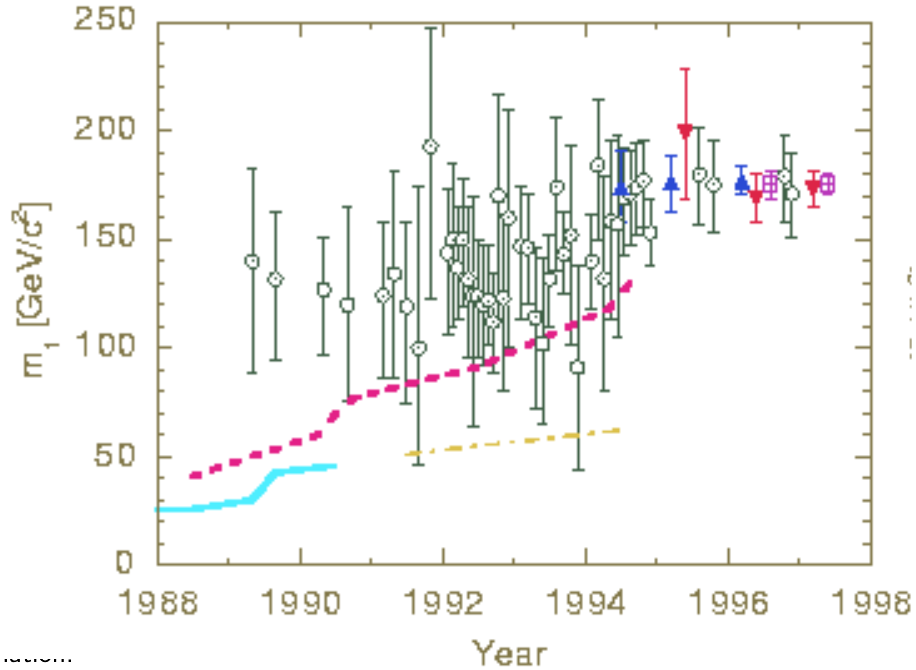
Top properties

History of the top quark

- 1989: Indirect constraints on top from precision measurements at LEP

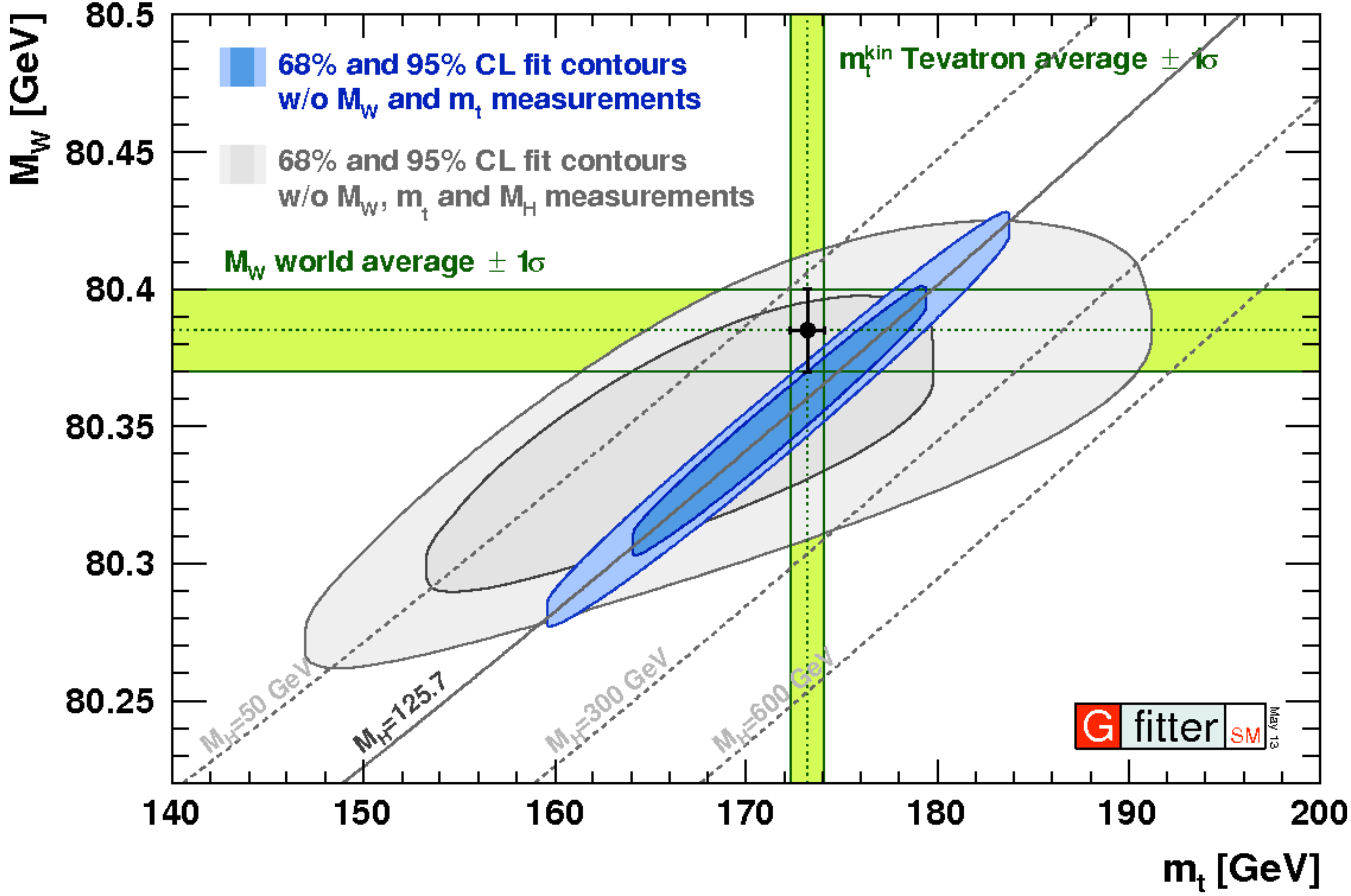


- 1995: Observation of Top-quark at the TeVatron collider at Fermilab
- Historic perspective indirect -> direct measurements -> precision



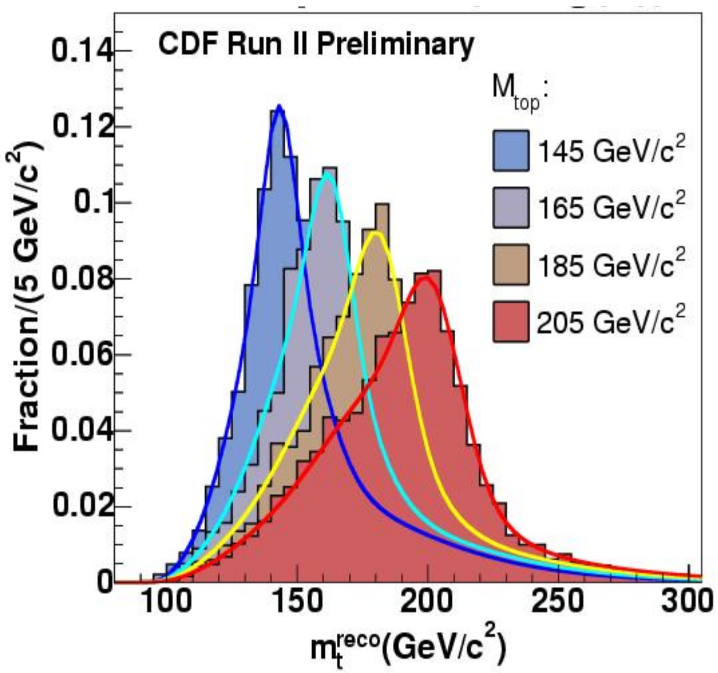
VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.07 ± 0.52 ± 0.72	**OUR EVALUATION**			See comments in the header above.
174.5 ± 0.6 ± 2.3	[1] AAD	12I	ATLS	$\ell + \not{E}_T + \geq 4$ jets (≥ 1 b), MT
172.85 ± 0.71 ± 0.85	[2] AALTONEN	12AI	CDF	$\ell + \not{E}_T + \geq 4$j (0,1,2$b$) template
172.7 ± 9.3 ± 3.7	[3] AALTONEN	12AL	CDF	$\tau_h + \not{E}_T$ +4j ($\geq 1b$)
172.5 ± 1.4 ± 1.5	[4] AALTONEN	12G	CDF	6–8 jets with ≥ 1 b
173.9 ± 1.9 ± 1.6	[5] ABAZOV	12AB	D0	$\ell\ell + \not{E}_T + \geq 2$j ($\nu$WT+MWT)
172.5 ± 0.4 ± 1.5	[6] CHATRCHYAN	12BA	CMS	$\ell\ell + \not{E}_T + \geq 2$j ($\geq 1b$), AMWT
173.49 ± 0.43 ± 0.98	[7] CHATRCHYAN	12BP	CMS	$\ell + \not{E}_T + \geq 4$j ($\geq 2b$)
172.3 ± 2.4 ± 1.0	[8] AALTONEN	11AK	CDF	$\not{E}_T + \geq 4$ jets (≥ 1 b-tag)
172.1 ± 1.1 ± 0.9	[9] AALTONEN	11E	CDF	ℓ + jets and dilepton
174.94 ± 0.83 ± 1.24	[10] ABAZOV	11P	D0	$\ell + \not{E}_T$ + 4 jets (≥ 1 b-tag)
173.0 ± 1.2	[11] AALTONEN	10AE	CDF	$\ell + \not{E}_T$ + 4 jets (≥ 1 b-tag), ME method
170.7 ± 6.3 ± 2.6	[12] AALTONEN	10D	CDF	$\ell + \not{E}_T$ + 4 jets (b-tag)

Top quark mass in Standard Model



Template method

- Isolate a sample rich in top events
  - Use some form of b-quark identification
- Select the most likely combination of jets, leptons and missing transverse energy
- Have templates of top signal at different masses and of background
- For each event, determine probability signal or background
  - Fit which mass is most probable
  - Modern analyses also use different templates for the di-jet W candidates



DISADVANTAGE:
Only use one possible permutation of jets,leptons, missing energy

Matrix element method

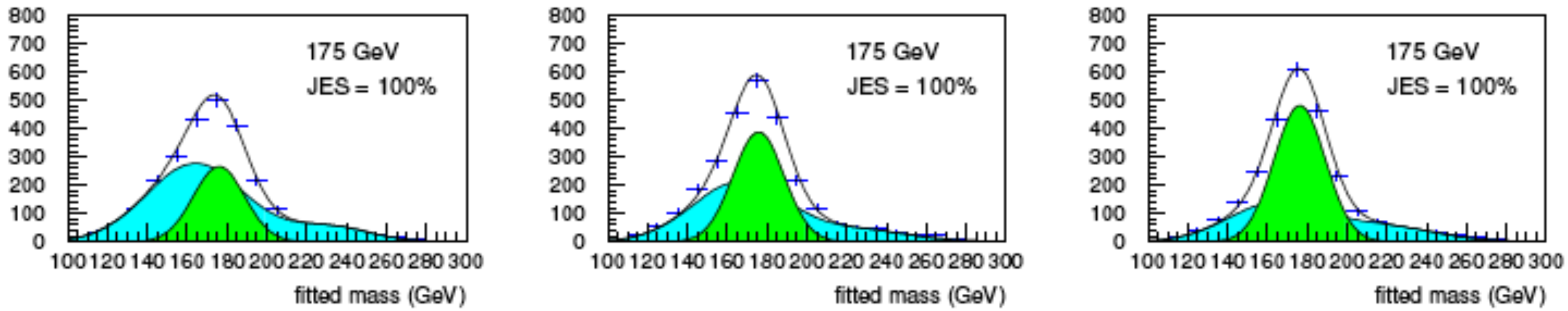
$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \times \sum_{\text{perm.},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$$

- Method first used for top physics by DØ in Tevatron Run I
- Use LO matrix element
  'Standard' integral (20D)
- put in all known information
  - Eight jet angles
  - Lepton 3-momentum
  - Conservation of energy and momentum (4x)

- Do Monte Carlo integration
  - |M(top)| for range of top masses
  - $|M(BG)|^2$ not dependent of top mass
- Get signal probability per event
  - used in likelihood fit

DISADVANTAGE:
Very computing intensive

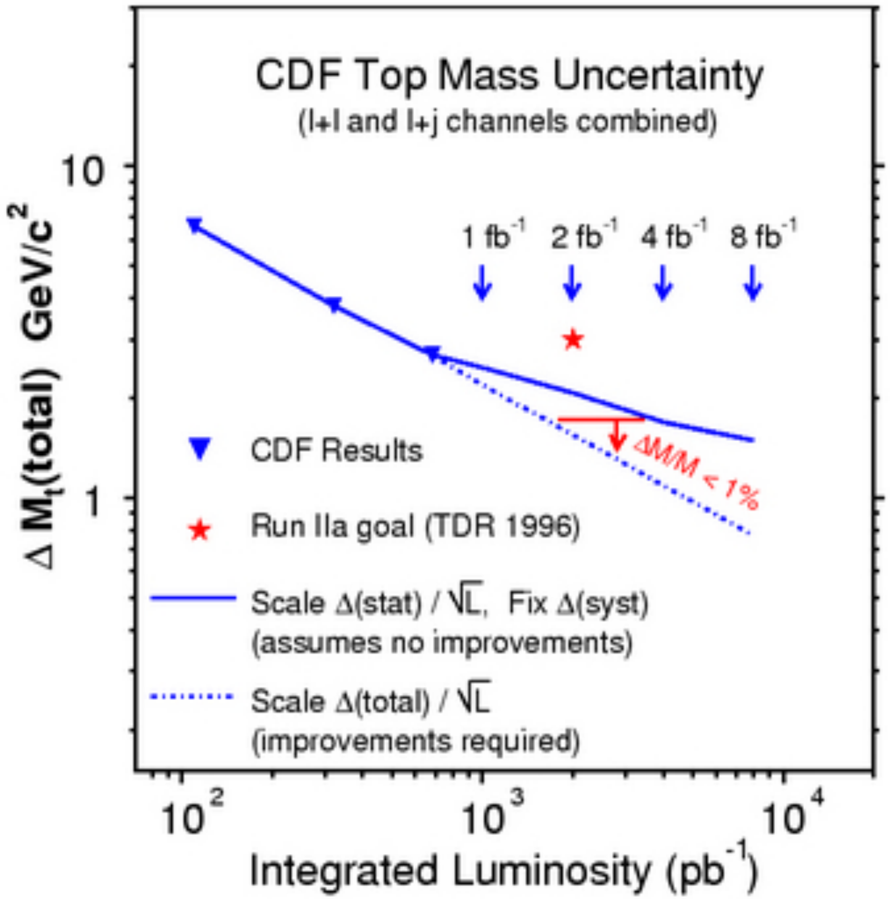
Ideogram method



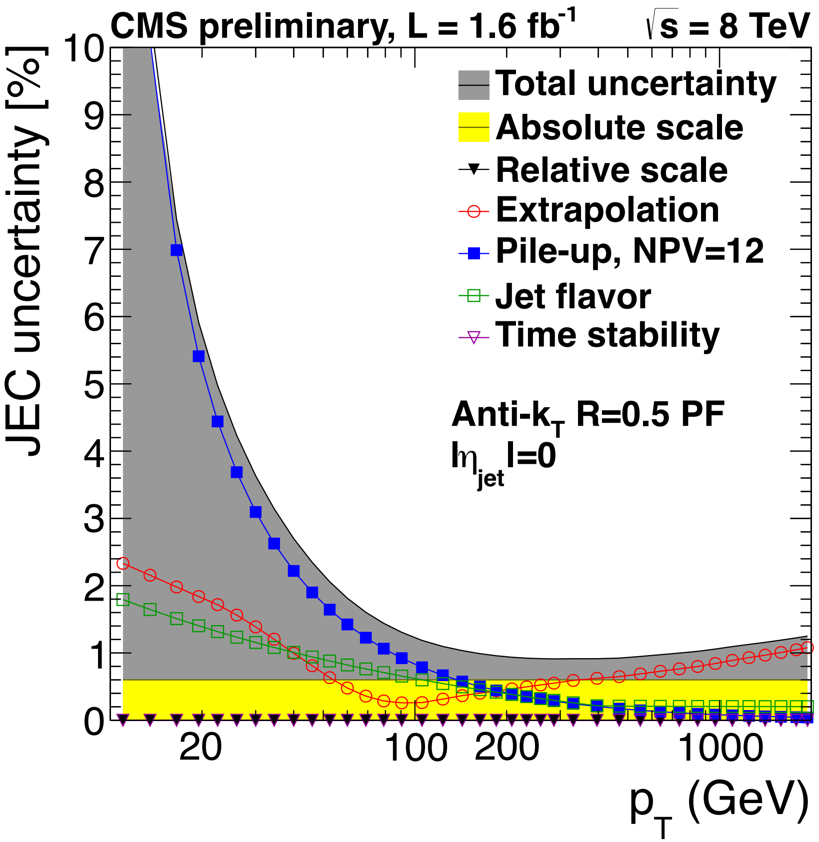
- Already used in LEP era
- Compromise:
  - Use all different permutations in weighted probability
  - Also makes use of topological information
- Takes into account resolutions as observed in simulation
- Include b quark identification
- Include mis-tags

"In situ" jet energy calibration

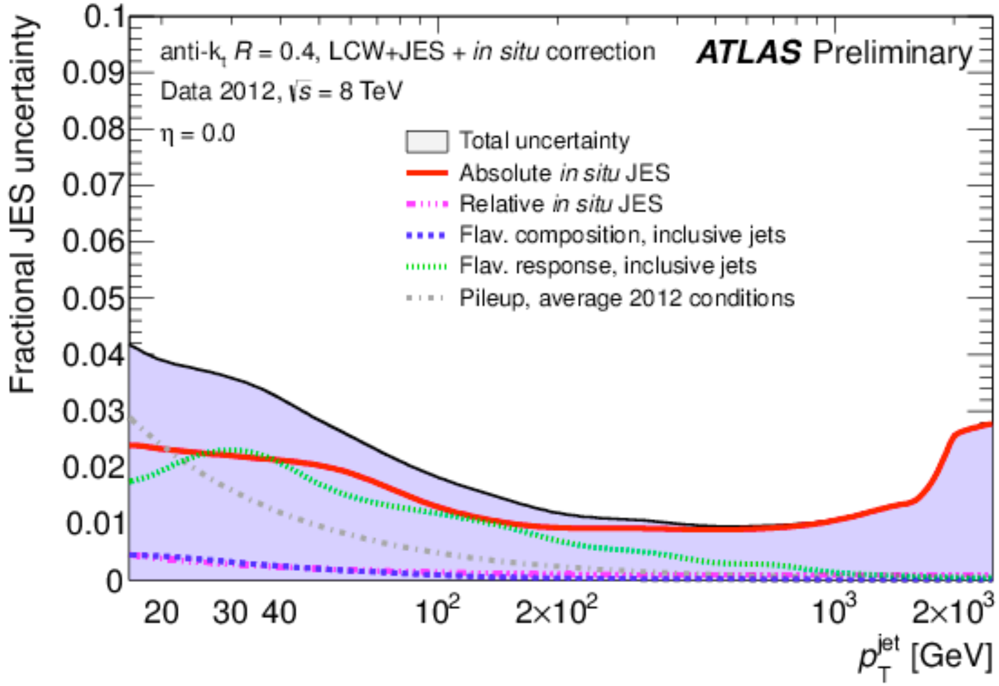
- Tevatron top mass measurements use *in situ* jet energy calibration
  - = Fit energy scale of jets to W mass simultaneously with top mass
- Impressive decrease uncertainties wrt expected!
- Not always necessary at LHC as leading systematic uncertainties can be different



JES no longer only leading syst. Uncertainty?

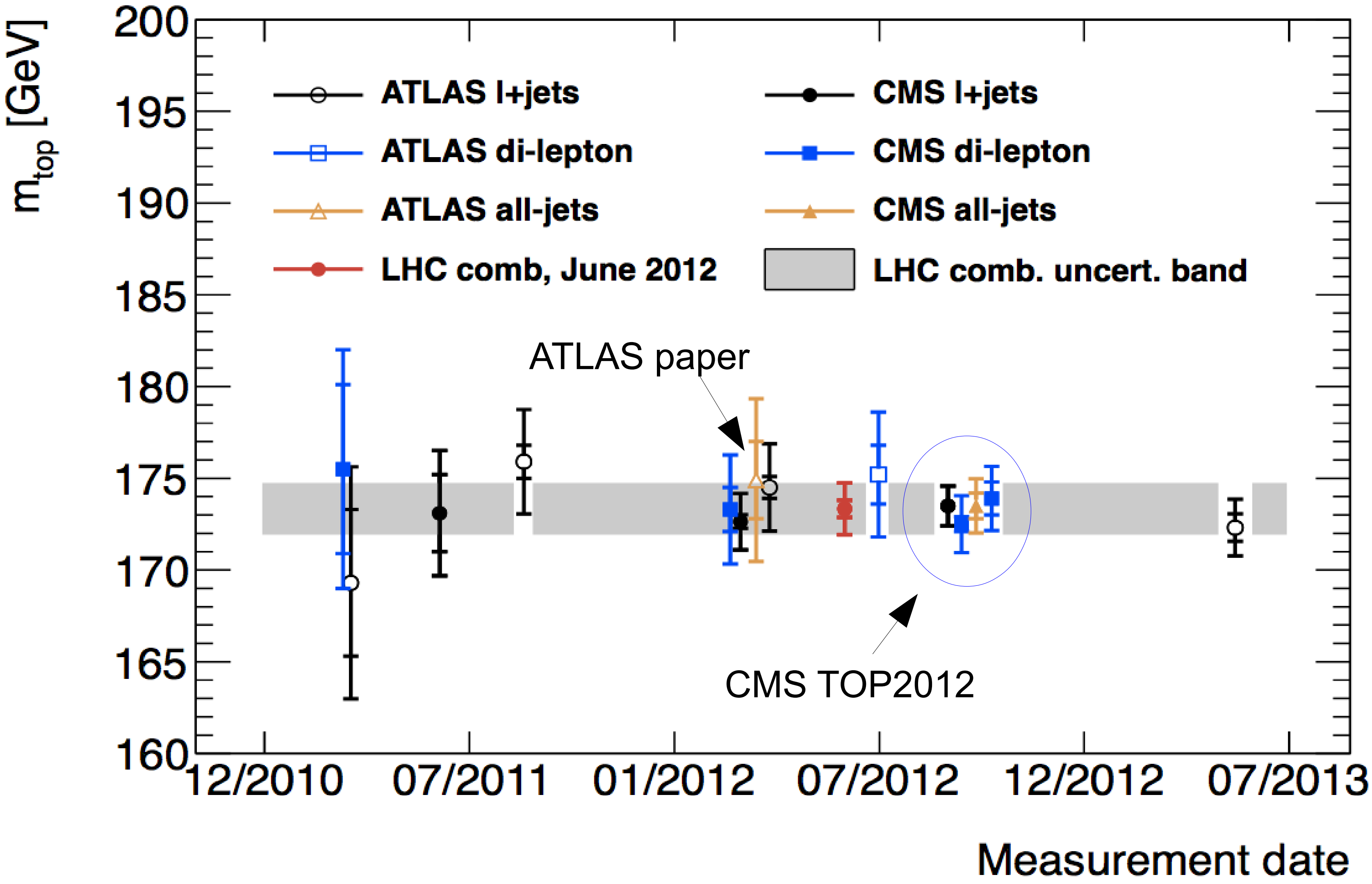


- But of course still crucial for accurate measurement

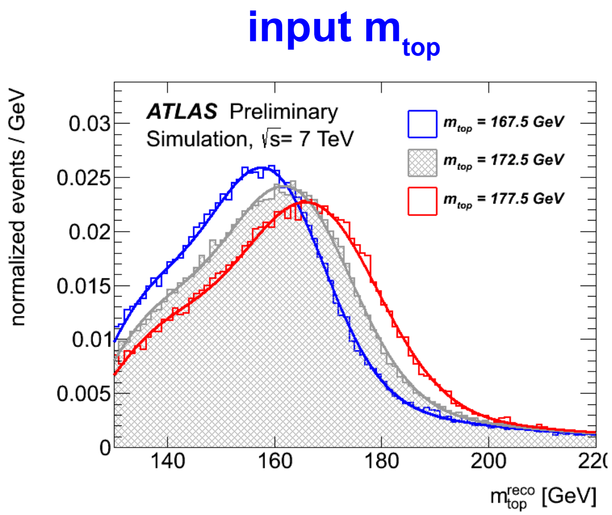


So let's look at some measurements

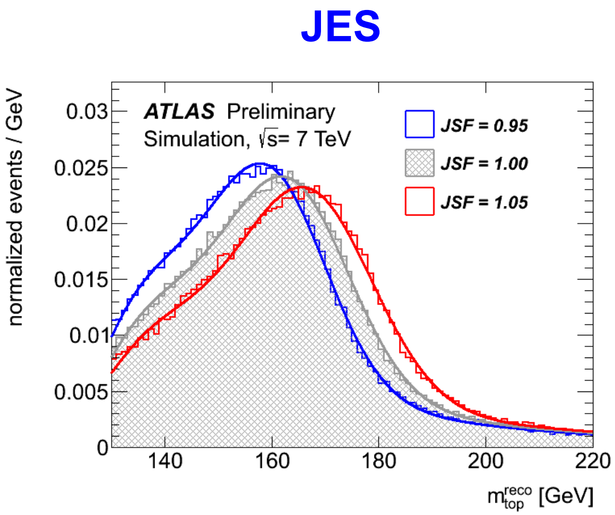
LHC history of mtop:



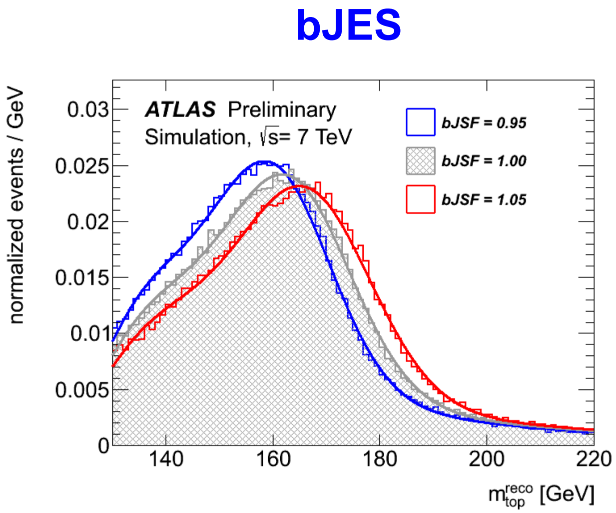
ATLAS 3D mass



Good sensitivity to the underlying top quark mass.



Large dependence on the jet energy scale → large systematics!

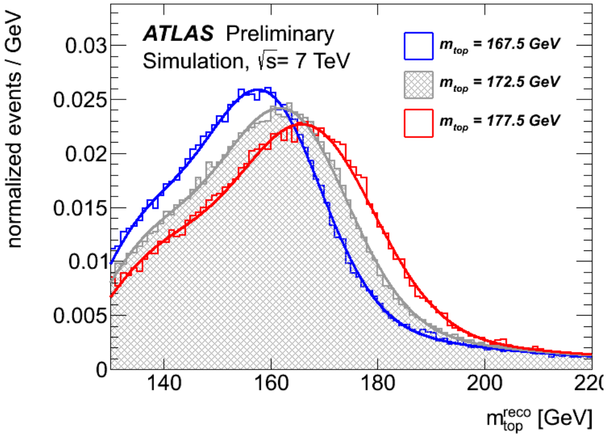


Large dependence on the b-jet energy scale → large systematics!

- Determine top mass while simultaneously constraining jet energy scale for light and b jets

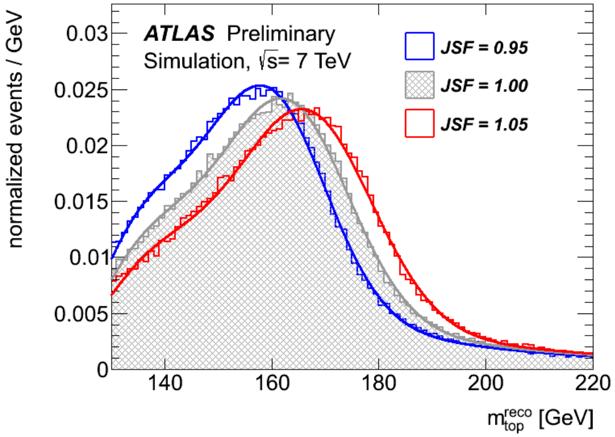
ATLAS 3D mass

input m_{top}



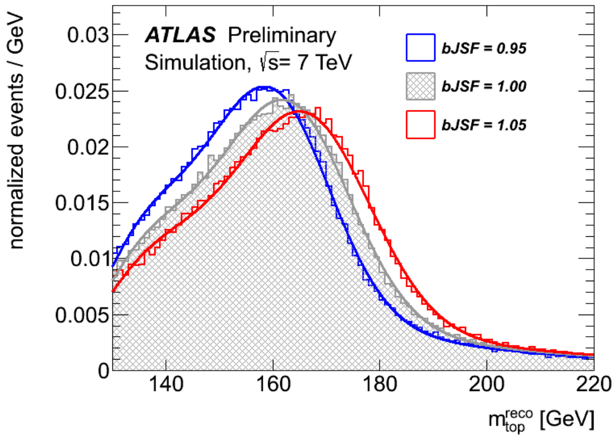
Good sensitivity to the underlying top quark mass.

JES



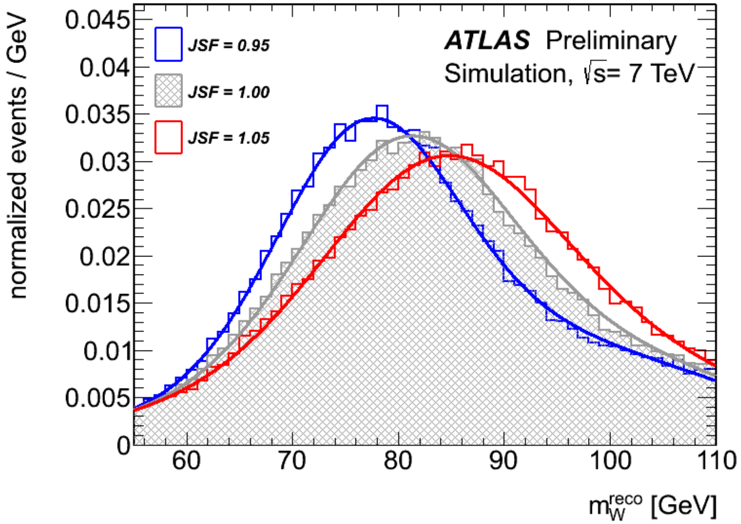
Large dependence on the jet energy scale → large systematics!

bJES



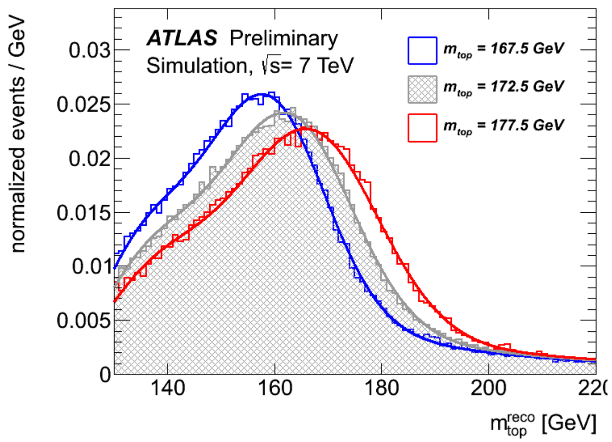
Large dependence on the b-jet energy scale → large systematics!

- Constrain JES using W mass instead of top mass



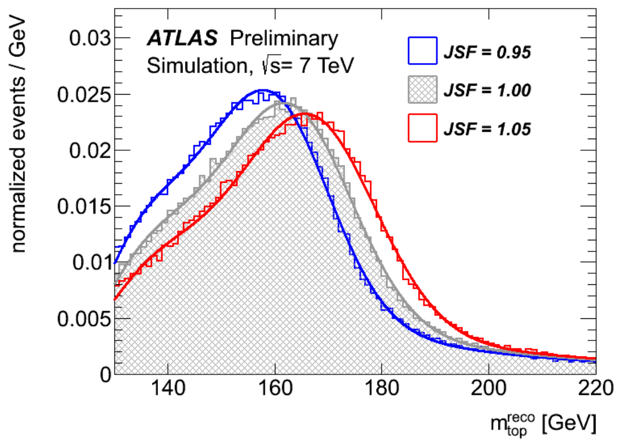
ATLAS 3D mass

input m_{top}



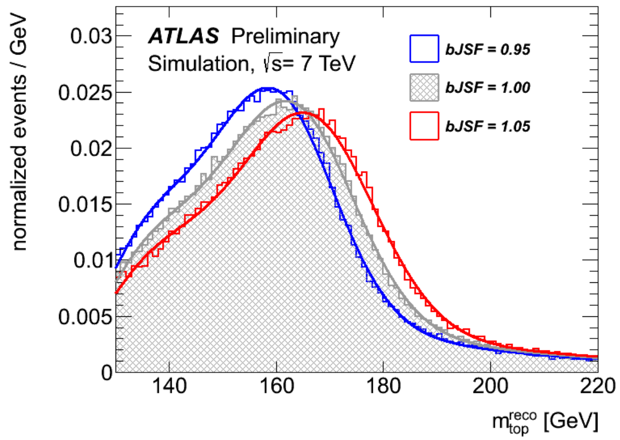
Good sensitivity to the underlying top quark mass.

JES



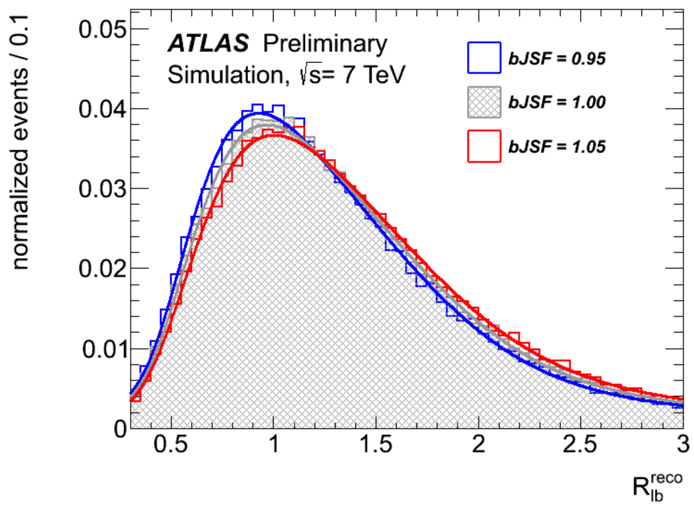
Large dependence on the jet energy scale → large systematics!

bJES

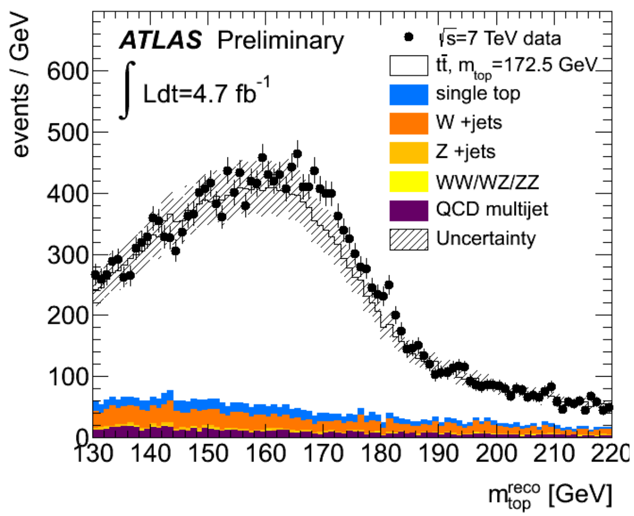


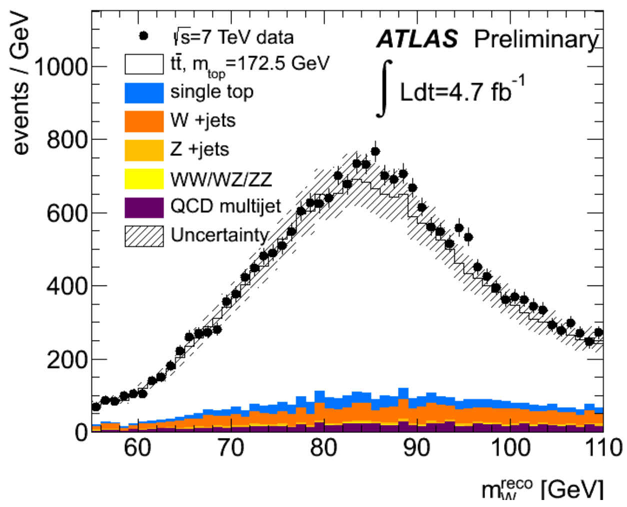
Large dependence on the b-jet energy scale → large systematics!

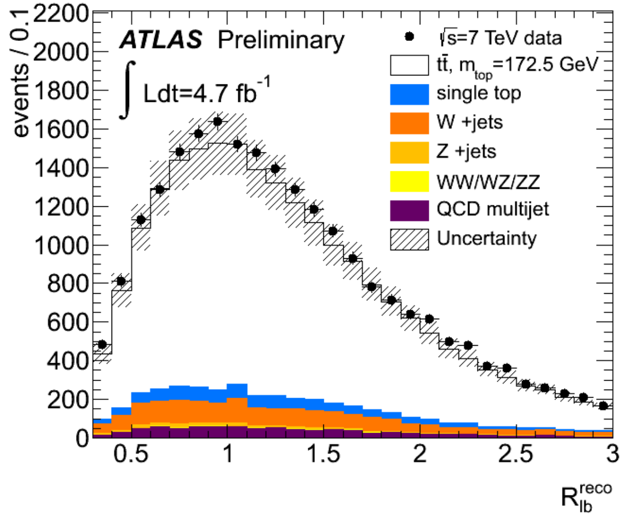
- Constrain JES for b jets using ration bJES/light JES



With Data, before fit

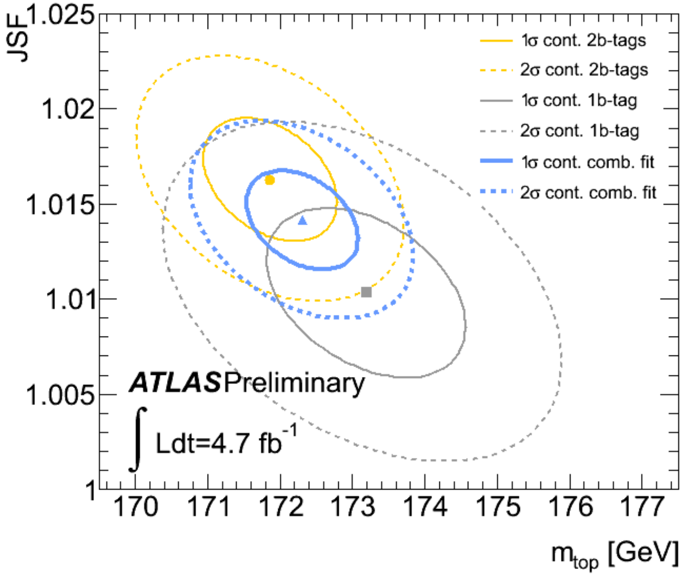


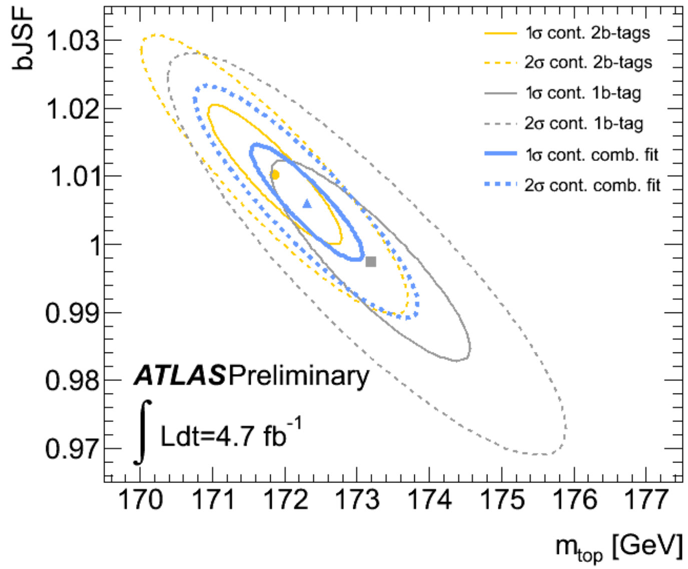




- All this information combined in 3D template fit

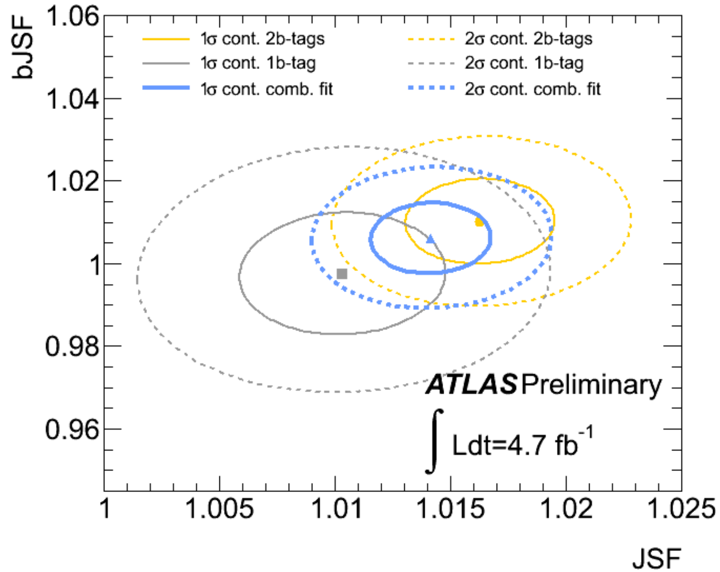
Repeat in 1 b-tag/2 b-tag/combined



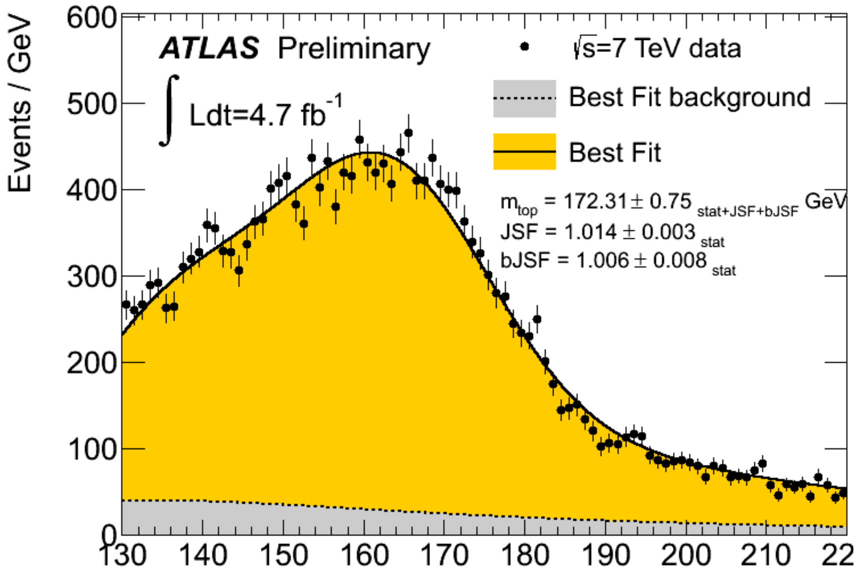


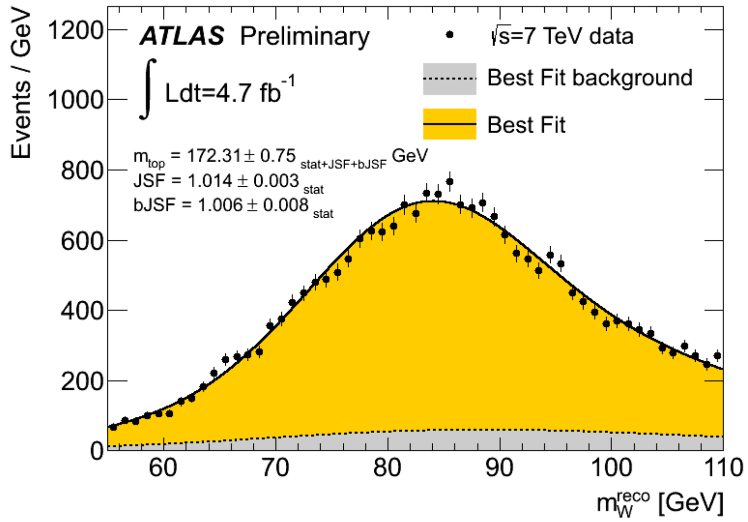
- Fits are consistent
- JES and bJES almost uncorrelated

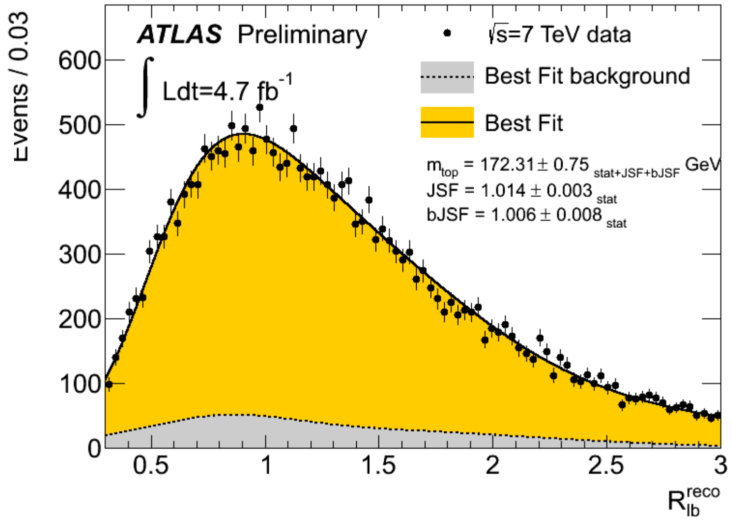
- (stat uncertainties only)



Post-fit







- After applying fit consistent picture in all three variables
- And m_{top}= 172.31 ±0.75 ±1.35 GeV

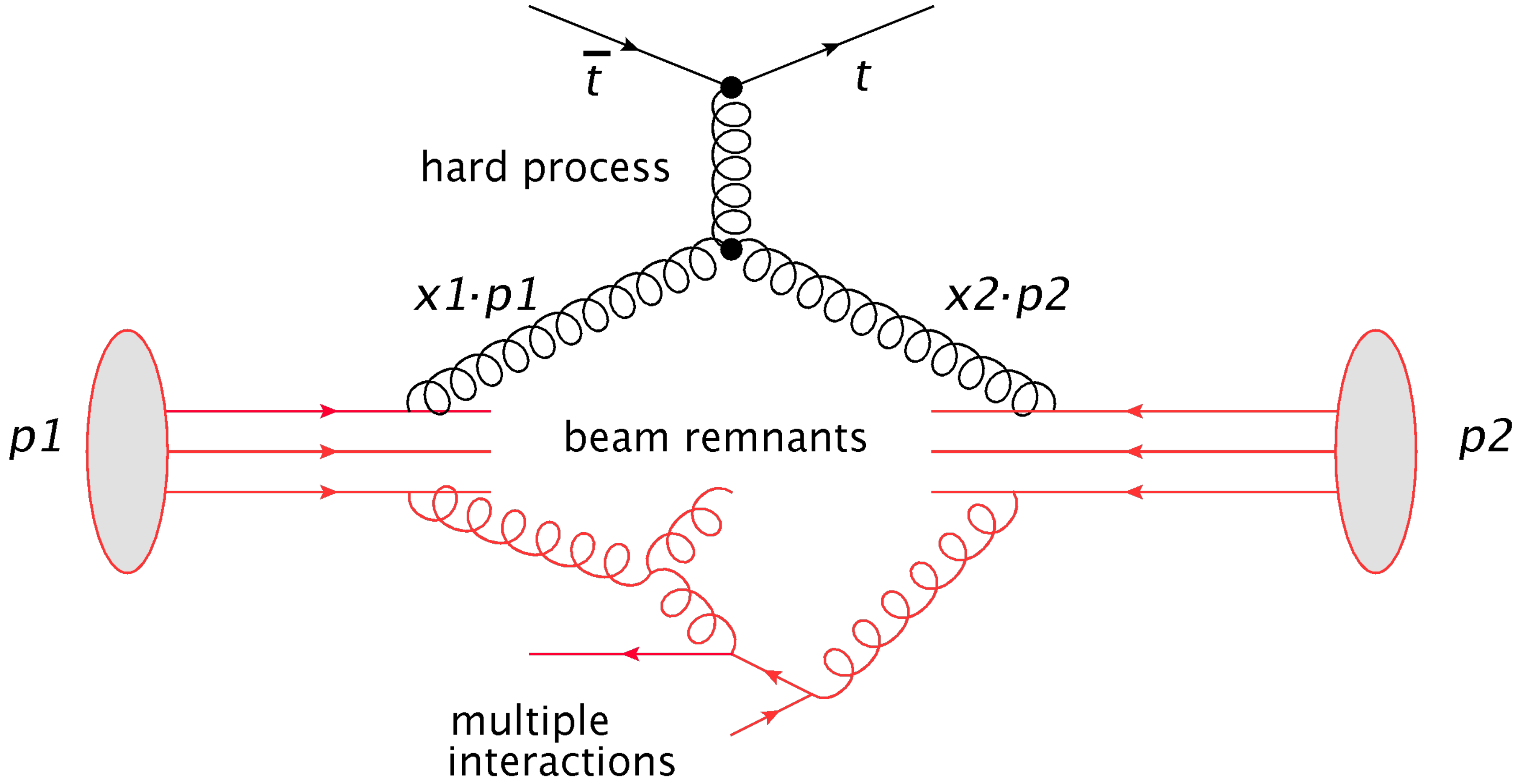
JES, stat

Other systematic uncertainties

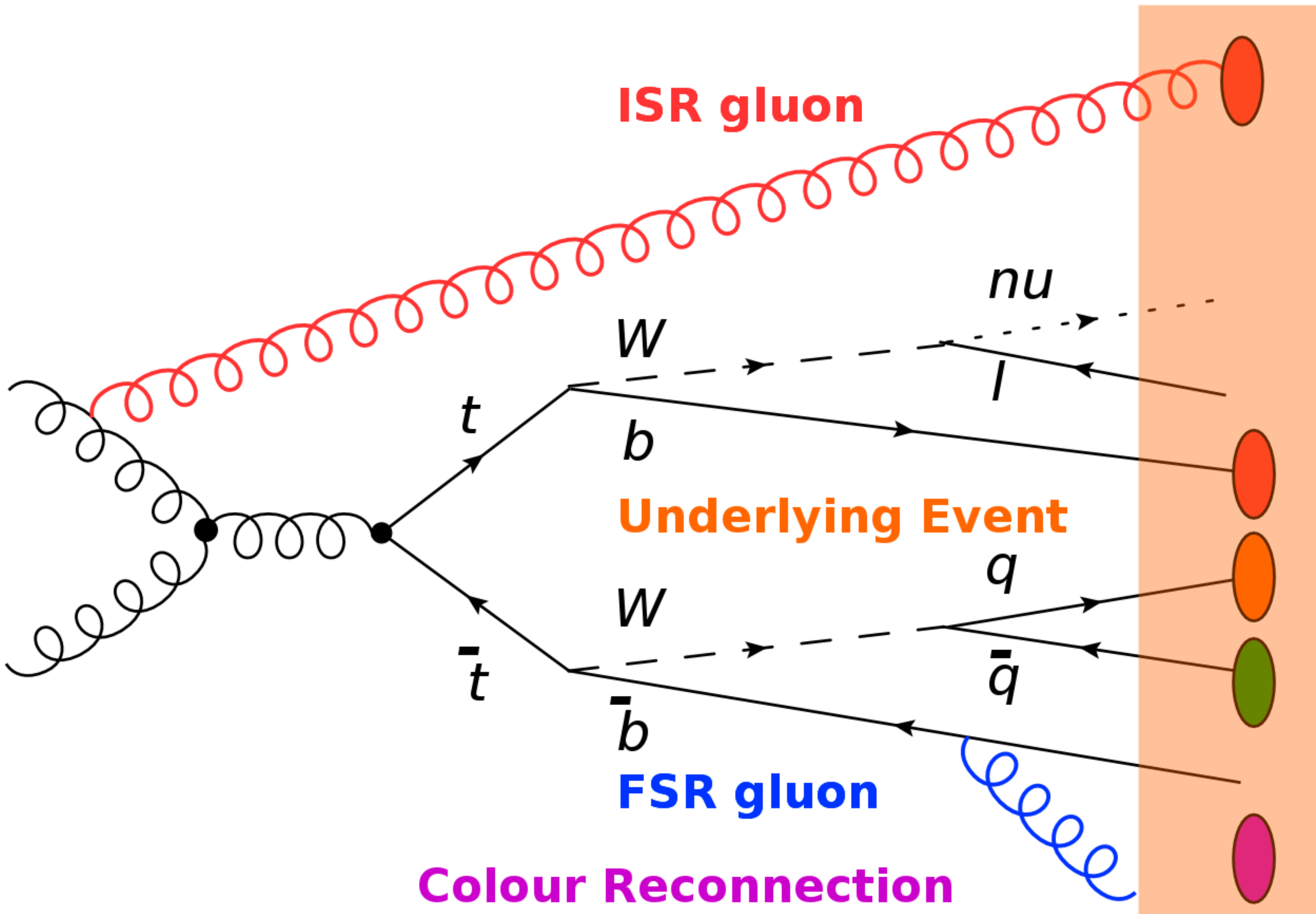
Systematic uncertainties

	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

Underlying event



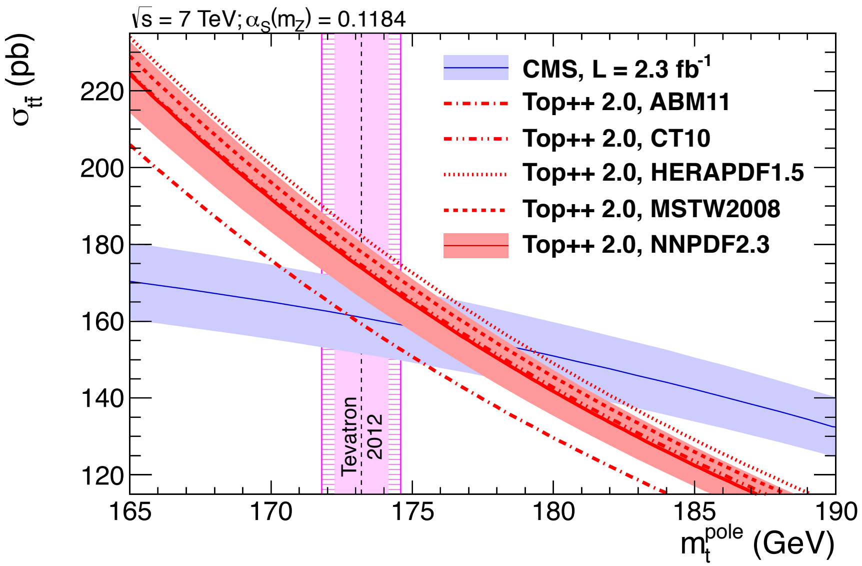
Other generator uncertainties

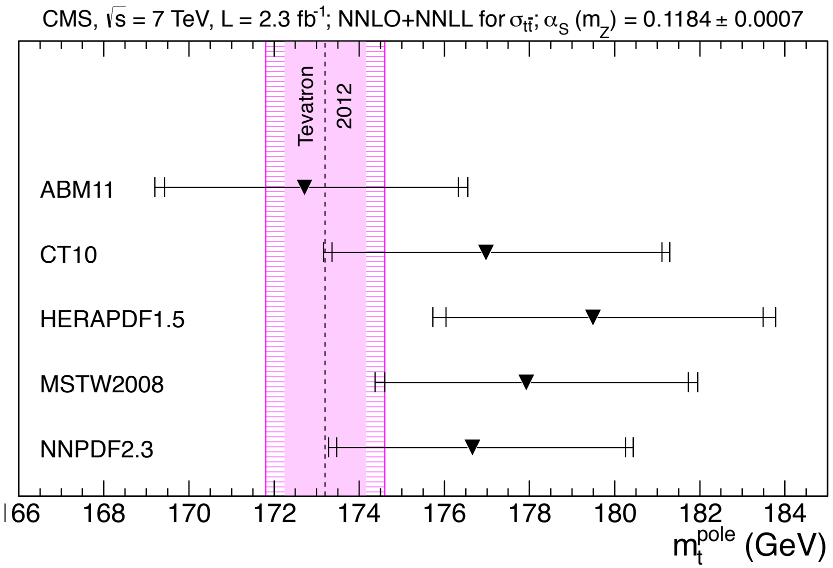


What top mass, really?

- When measurements are so accurate question is what one really measures
  - The top quark mass is a parameter of the SM
    - Mass is usually defined as a pole mass or $\overline{\mathrm{MS}}$ mass
    - Definition is confusing, we typically use pole mass when dealing with mass/yukawa couplings, while $\overline{\mathrm{MS}}$ is used for prediction cross sections.
    - There is a transformation from one scheme to the other, but this relies on order of calculation and strong coupling constant.
- The measured mass effectively is a number we use as input to a MC generator

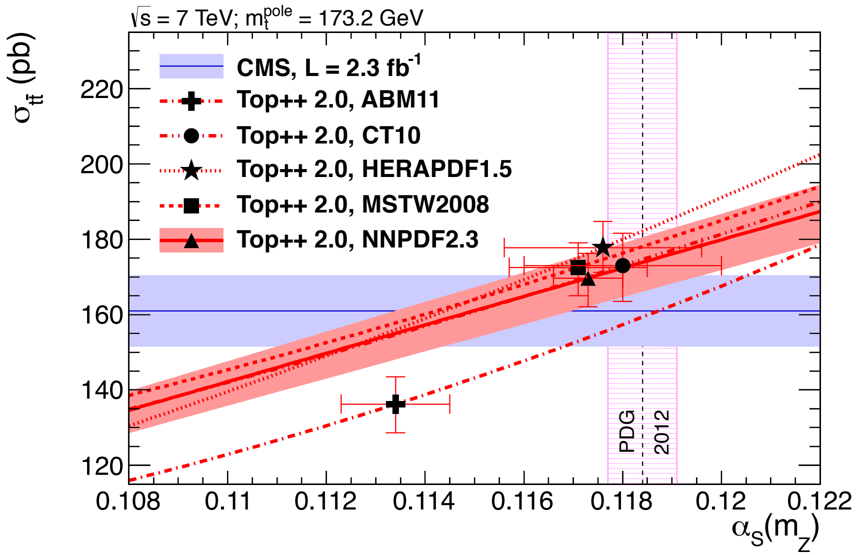
Derive top mass from cross section





- Comparison of most accurate ttbar cross section measurement and do transformation mass
  - Measure xsec for different mTop
  - And α_S, best NNLO calculation
  - $M_t^{pole} = 176.7\ ^{+3.8}_{-3.4}$ GeV

Or use cross section to find α_s

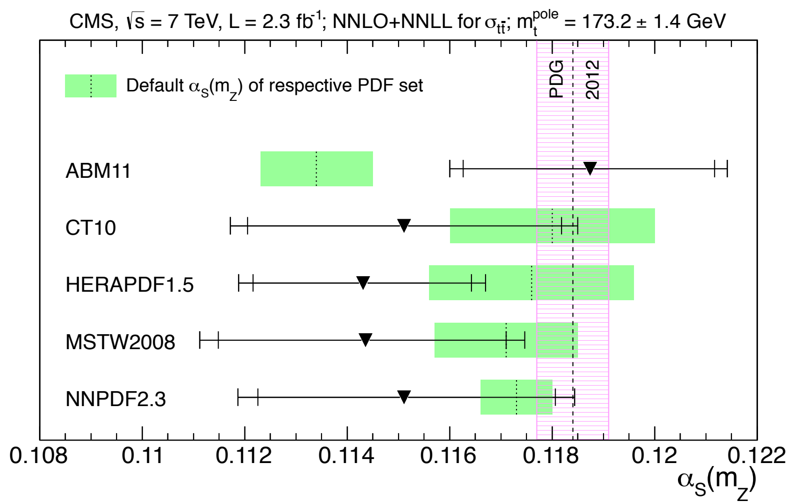


- Use precise pole mass measurement and compare to cross section

- Derive α_s using NNLO theoretical cross section predictions

$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

- Strong pdf dependence!



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Final word definitely not said

Summary

Top quark mass

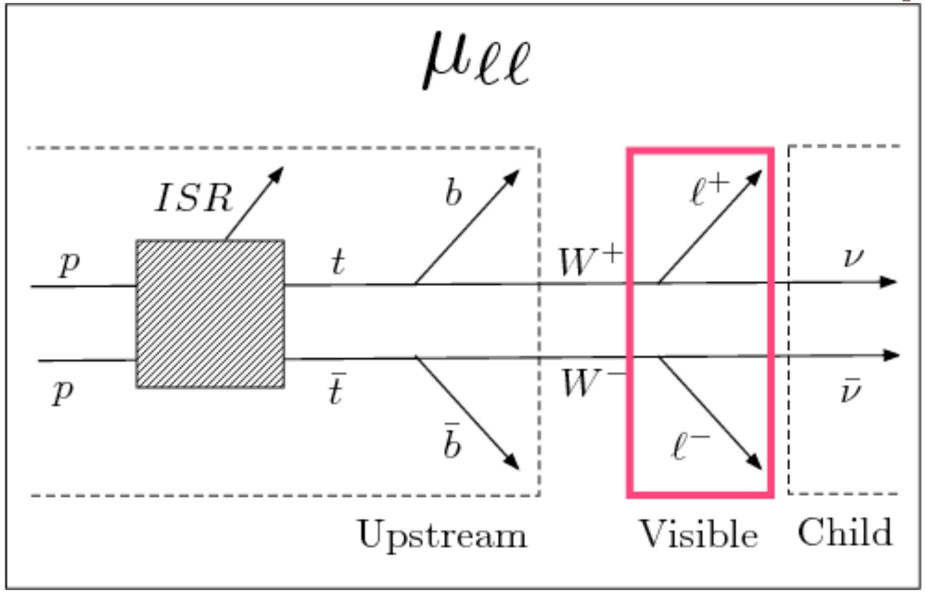
- On-shell scheme (pole mass) at NNLO in QCD

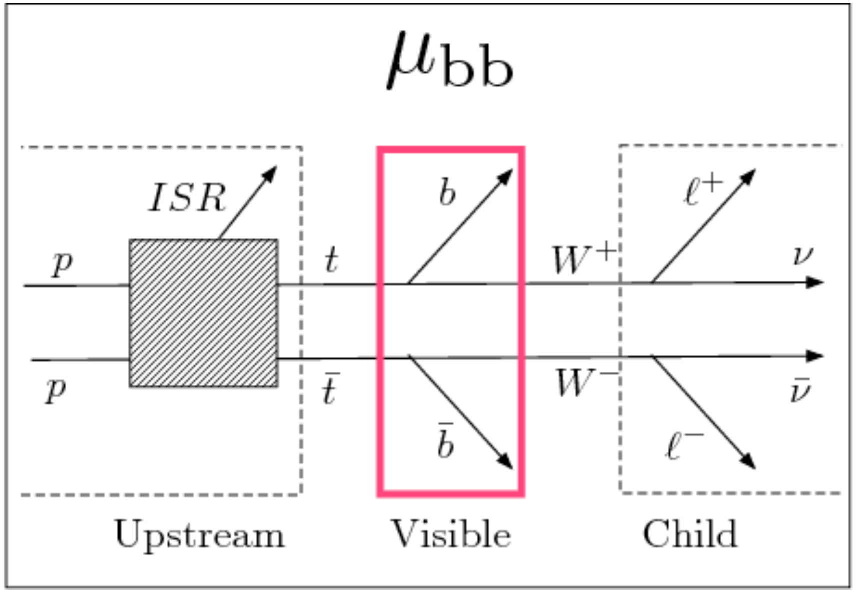
$$m_t = 173.18 \pm 0.94 \pm \mathcal{O}(\text{few})\,\text{GeV}$$

- Running mass ($\overline{\mathrm{MS}}$ scheme) at NNLO in QCD

$$m_t(m_t) = 163.3 \pm 2.7\text{GeV}$$

Or measure m_{top} in other ways?

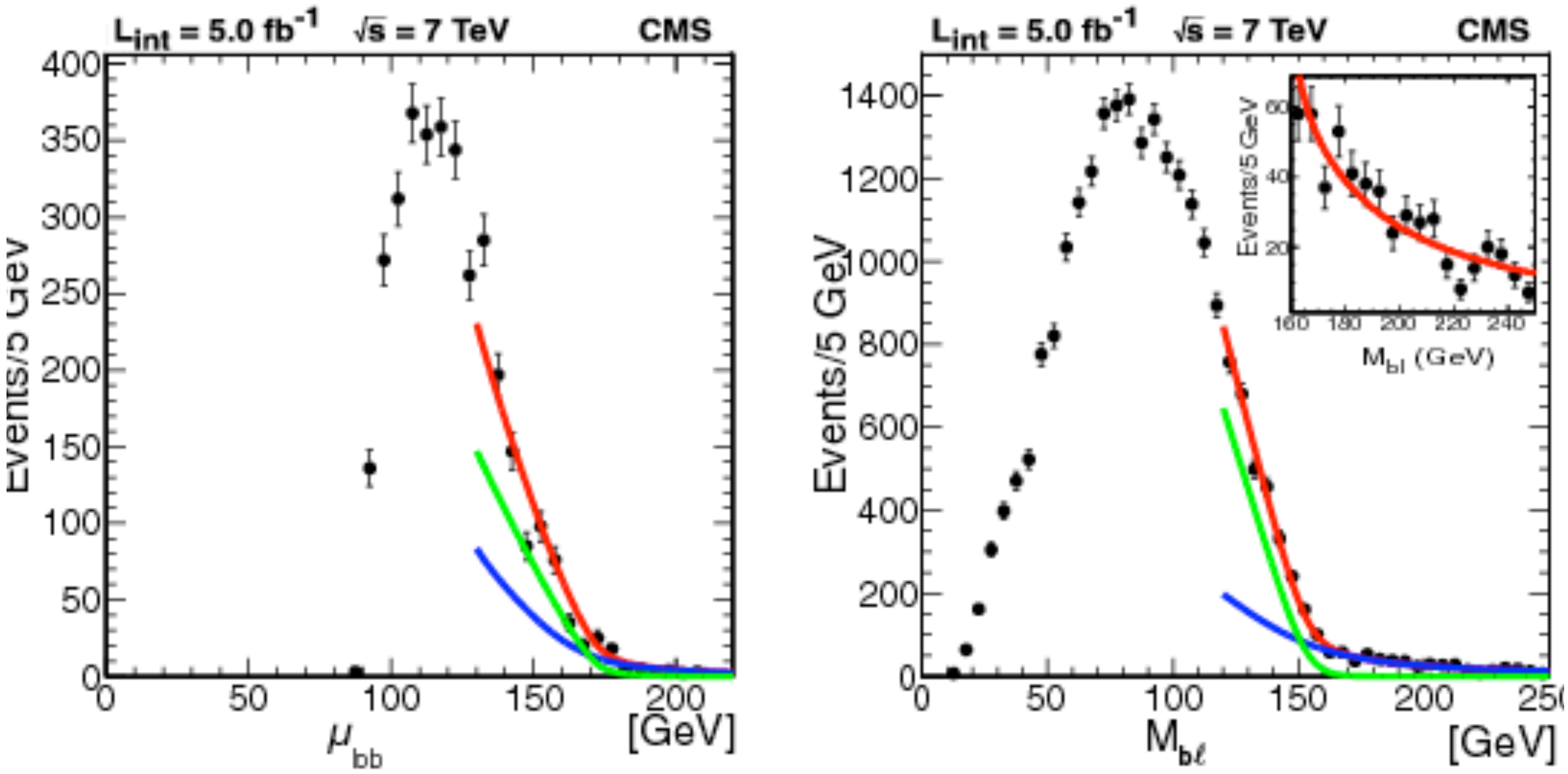




- In di-lepton events the di-lepton mass has a direct kinematic correlation to the top mass
  - Or with possible new physics particles if applied to cascade decays
- Measuring 'endpoint' of m(ll) distribution accurately means measuring the top quark mass accurately
- Basis of CMS endpoint measurement (arXiv:1304.5783)

Detailed fit with backgrounds included

- Small Background contribution derived from data



Advantage: very different syst. uncertainties

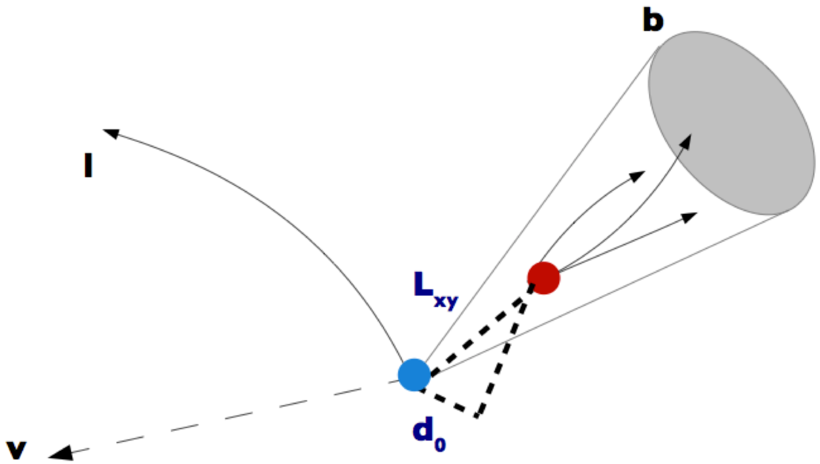
Source	δM_t (GeV)
Jet energy scale	$^{+1.3}_{-1.8}$
Jet energy resolution	± 0.5
Lepton energy scale	$^{+0.3}_{-0.4}$
Fit range	± 0.6
Background shape	± 0.5
Jet and lepton efficiencies	$^{+0.1}_{-0.2}$
Pileup	<0.1
QCD effects	± 0.6
Total	$^{+1.7}_{-2.1}$

- Jet energy scale still there, but few theory/ modeling uncertainties

$$M_t = 173.9 \pm 0.9\ (\text{stat.})^{+1.7}_{-2.1}\ (\text{syst.})\ \text{GeV}.$$

- Not the best measurement in the world, but still competitive!

Lifetime method

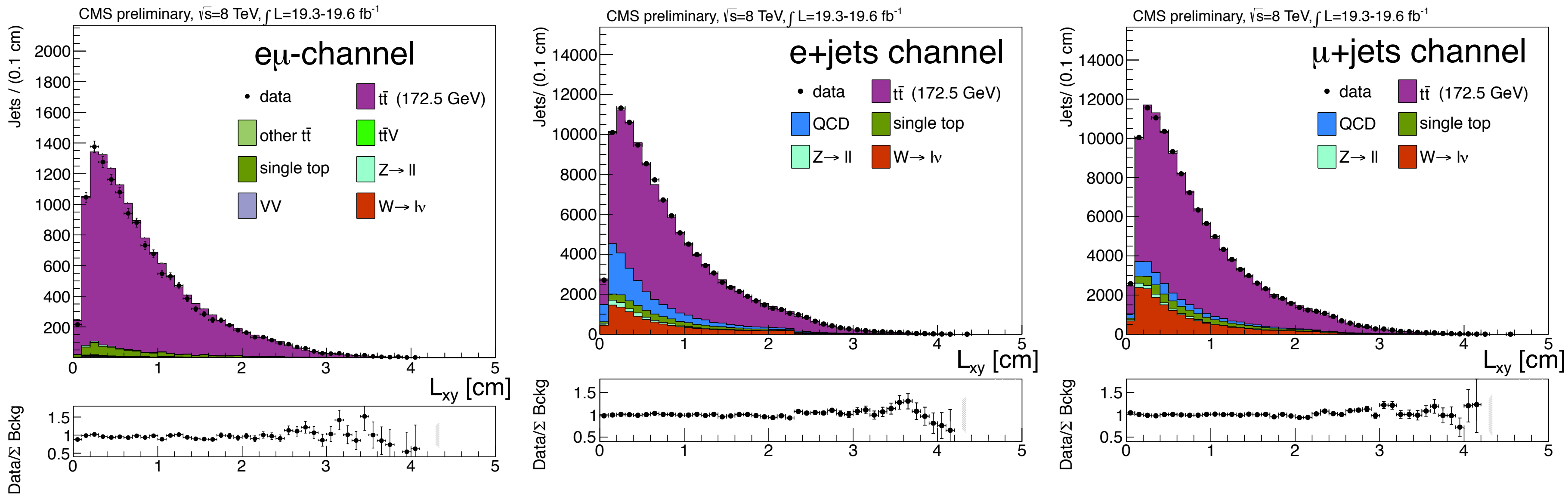


- Boost of b quark correlated with top mass

- Decay length of secondary vertex can be used to measure top mass
  - Also possible: momentum of soft leptons from b-quarks
  - Technique pioneered by CDF

(CMS PAS TOP-12-030)

Examine decay length in dilepton and l+jets

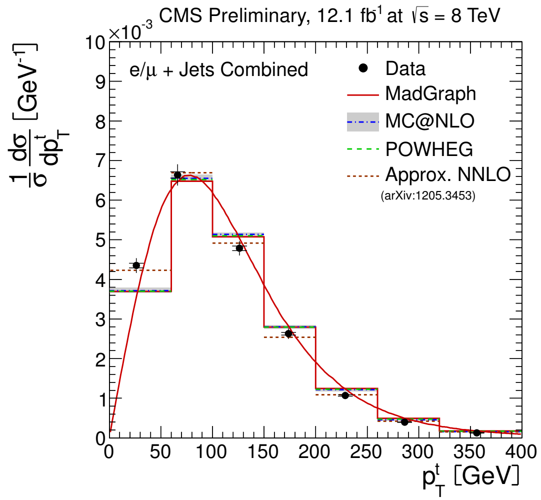


$\widehat{L_{xy}} = 0.682 \pm 0.004\ cm$	$\widehat{L_{xy}} = 0.6536 \pm 0.0013\ cm$	$\widehat{L_{xy}} = 0.6690 \pm 0.0013\ cm$
$m_t^{MC} = 173.7 \pm 2.0$ GeV	$m_t^{MC} = 172.8 \pm 1.0$ GeV	$m_t^{MC} = 173.2 \pm 1.0$ GeV

Again – different systematic uncertainties

		μ+jets	e+jets	$e\mu$
Experimental	Jet energy scale	0.30 ± 0.01	0.30 ± 0.01	0.30 ± 0.01
	Multijet normalization (ℓ+jets)	0.50 ± 0.01	0.67 ± 0.01	-
	W+jets normalization (ℓ+jets)	1.42 ± 0.01	1.33 ± 0.01	-
	DY normalization ($\ell\ell$)	-	-	0.38 ± 0.06
	Other backgrounds normalization	0.05 ± 0.01	0.05 ± 0.01	0.15 ± 0.07
	W+jets background shapes (ℓ+jets)	0.40 ± 0.01	0.20 ± 0.01	-
	Single top background shapes	0.20 ± 0.01	0.20 ± 0.01	0.30 ± 0.06
	DY background shapes ($\ell\ell$)	-	-	0.04 ± 0.06
	Calibration	0.42 ± 0.01	0.50 ± 0.01	0.21 ± 0.01
Theory	Q^2-scale	0.47 ± 0.13	0.20 ± 0.03	0.11 ± 0.08
	ME-PS matching scale	0.73 ± 0.01	0.87 ± 0.03	0.44 ± 0.08
	PDF	0.26 ± 0.15	0.26 ± 0.15	0.26 ± 0.15
	Hadronization model	0.95 ± 0.13	0.95 ± 0.13	0.67 ± 0.10
	B-hadron composition	0.39 ± 0.01	0.39 ± 0.01	0.39 ± 0.01
	B-hadron lifetime	0.29 ± 0.18	0.29 ± 0.18	0.29 ± 0.18
	Top quark p_T modeling	3.27 ± 0.48	3.07 ± 0.45	2.36 ± 0.35
	Underlying event	0.27 ± 0.51	0.25 ± 0.48	0.19 ± 0.37
	Colour reconnection	0.36 ± 0.51	0.34 ± 0.48	0.26 ± 0.37

- Leading systematic: p_T^{top} modeling



Final results

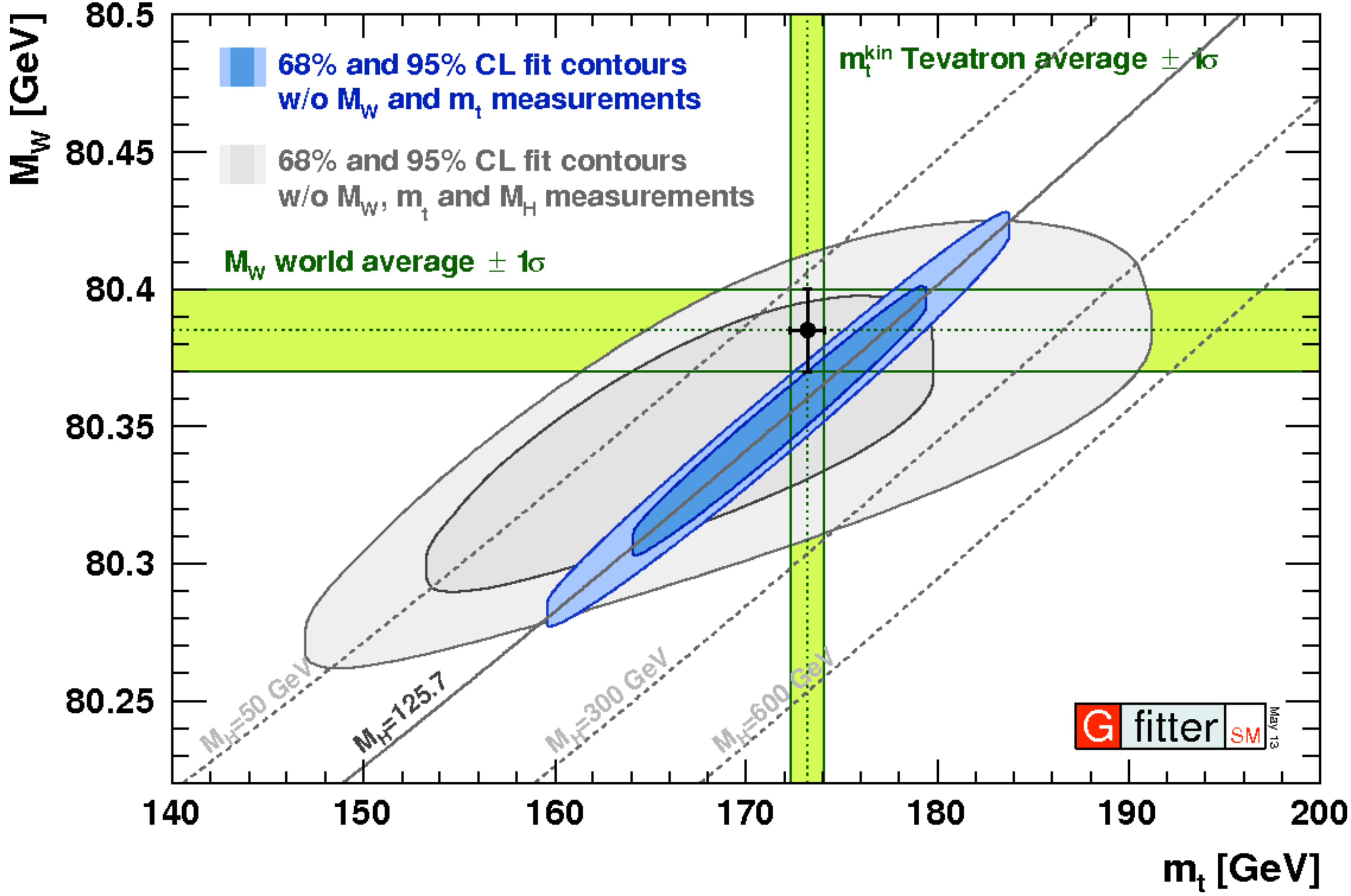
Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

Combination of all channels

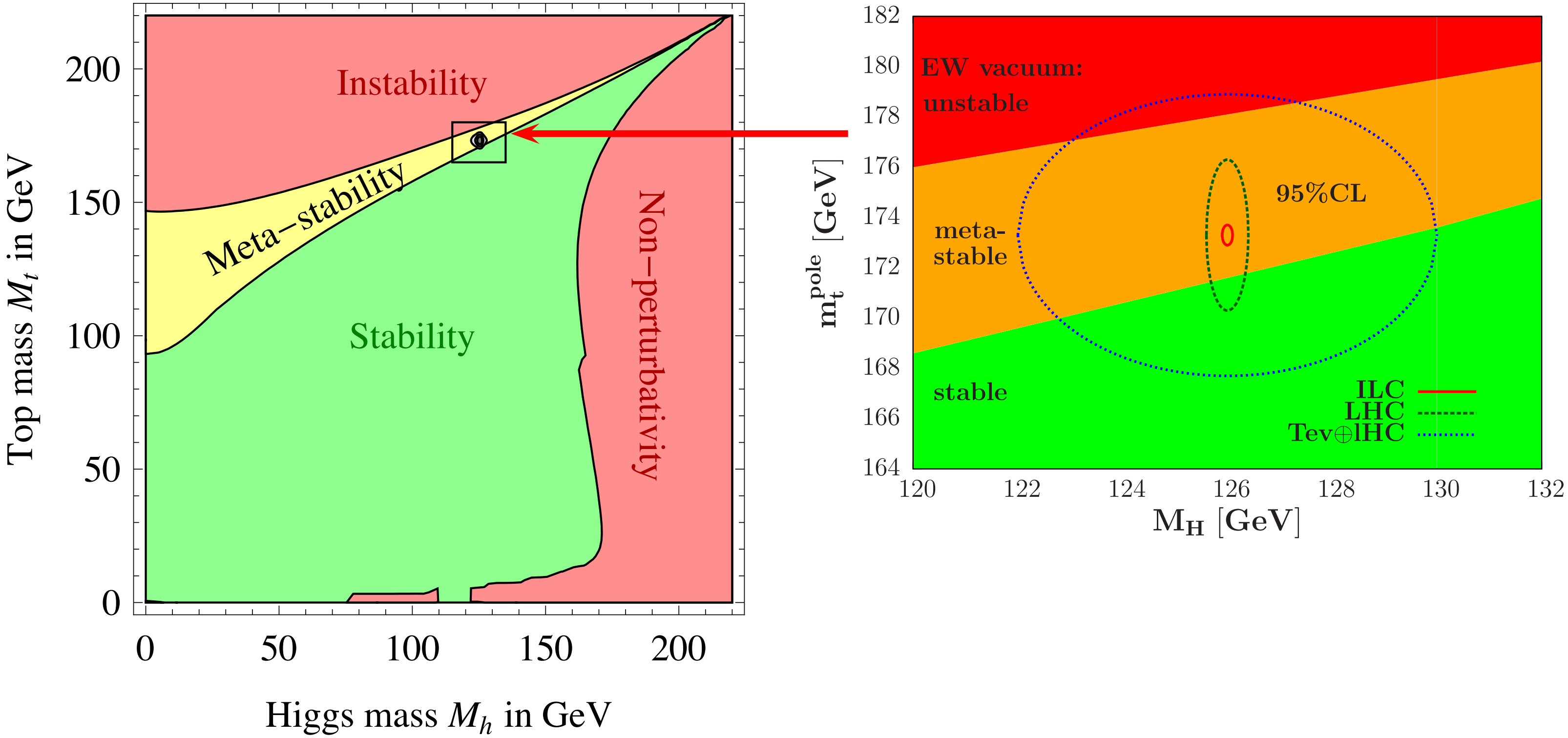
$$m_t^{MC} = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T^{top}}$$

src: Stijn Blyweert @EPS-HEP 2013

Top quark mass in Standard Model



The top mass vs stability of the universe



- Constraints from the SM can also be used to assess stability of physics laws
  – Example: arXiv:1205.6497

End of lecture one – questions?

Break

Outline

- Part 2: SM and top physics, the portal to physics searches
    - Measuring top properties
    - Searches for physics beyond the standard model using tops

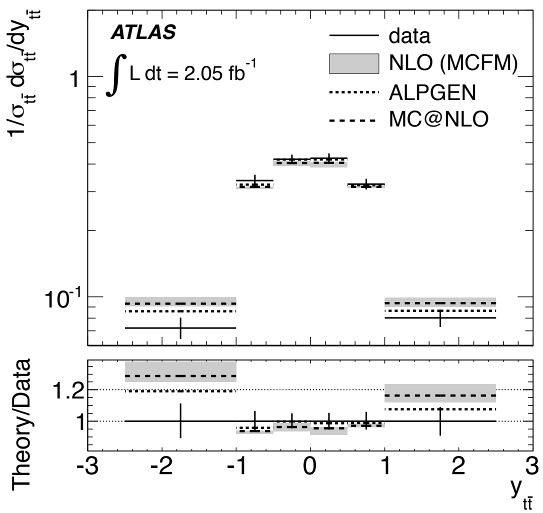
Top quark and new physics

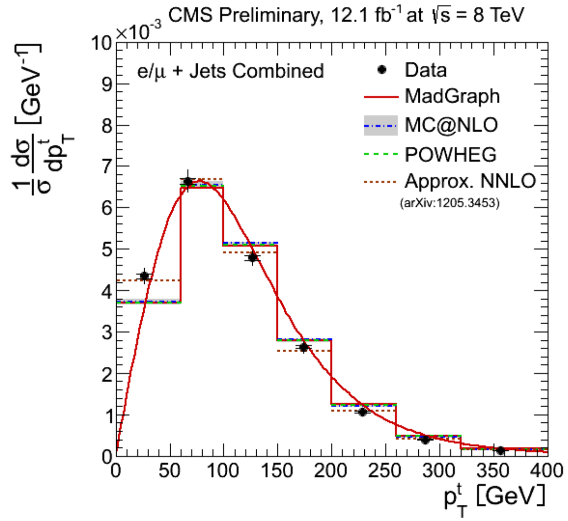
- Precise SM measurements
  - Heaviest known elementary particle (large Yukawa coupling)
    - Constraints on Higgs mass
    - Unique window on bare quarks due to short lifetime
  - Probe for QCD at scale >gauge bosons
- A window to new physics
  - New physics - many models couple preferentially to top
  - New particles may decay to top
  - Non-standard couplings
- In many new physics scenarios (e.g. SUSY) top is dominant BG
- Great tool to calibrate detector
  - Jet energy scale, b-jet efficiency

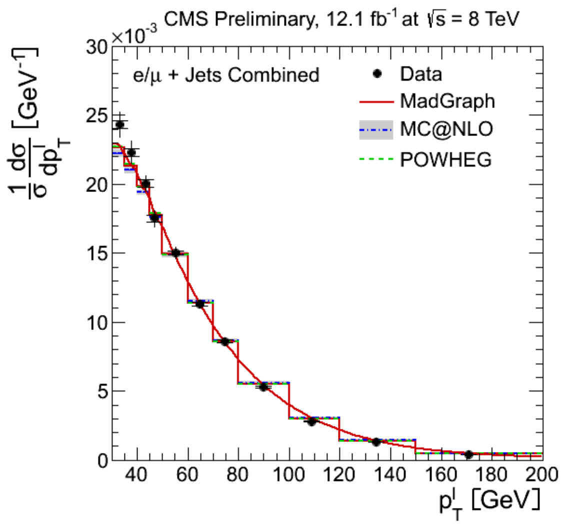
<u>Top pair production rate</u>
Top mass
Single top production rate
$B(t \to Wb)$
$|V_{tb}|$
W helicity
Top polarization
Anomalous couplings
Spin correlations
Rare decays
Top width
…

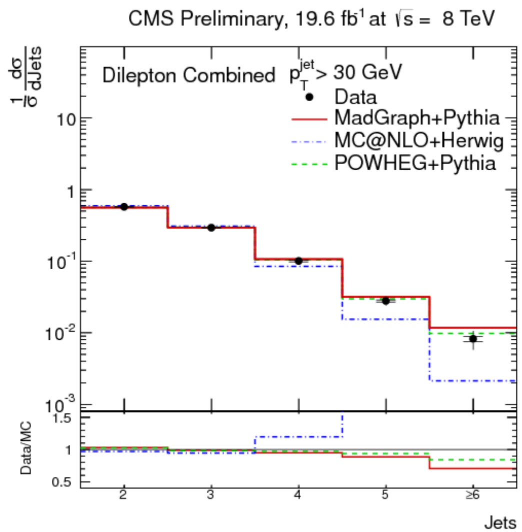
Properties of top pair production

- Very large LHC samples allow differential cross section measurements
- Most bins limited by systematic uncertainties
- Many differential kinematics examined
- Active interaction with generator and pdf community
- Improvement of models of great benefit to community for next LHC run – particularly for searches

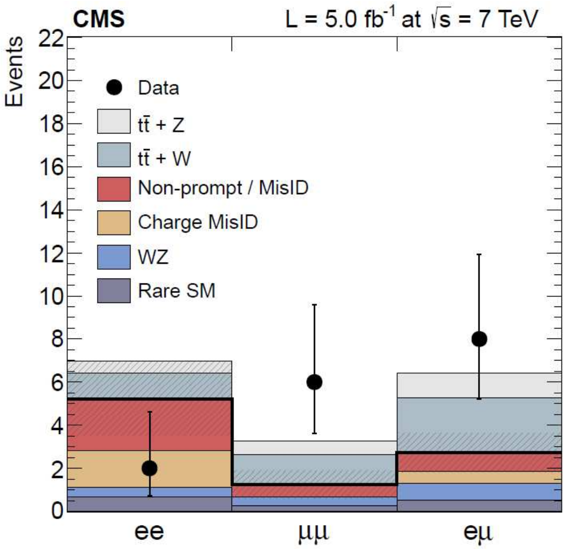


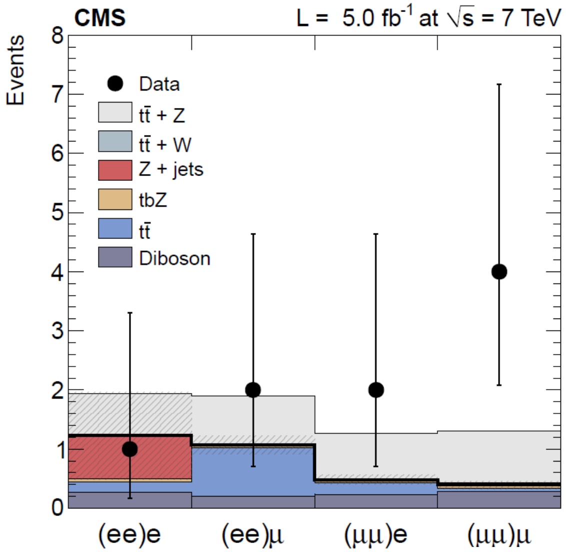


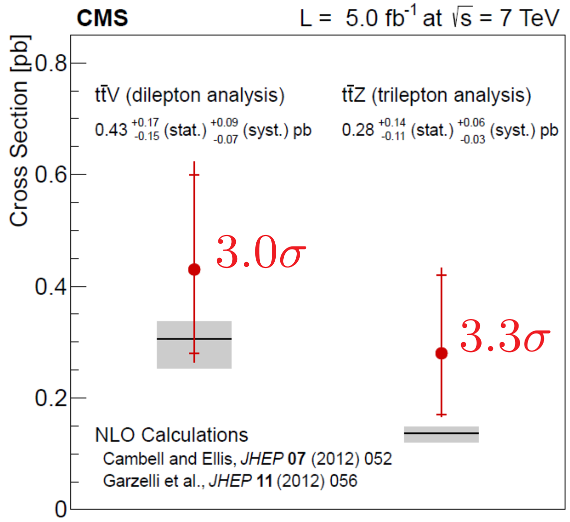


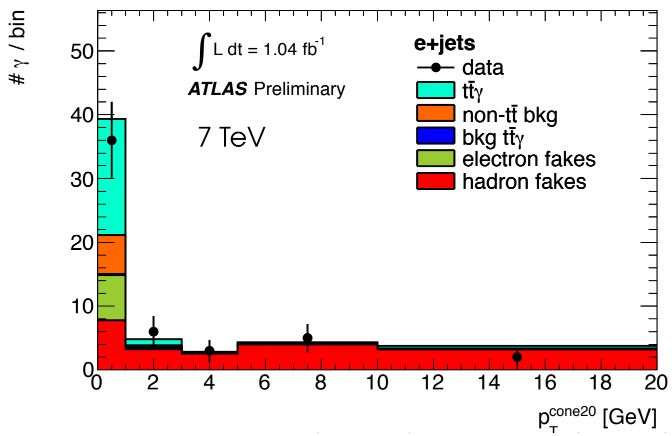


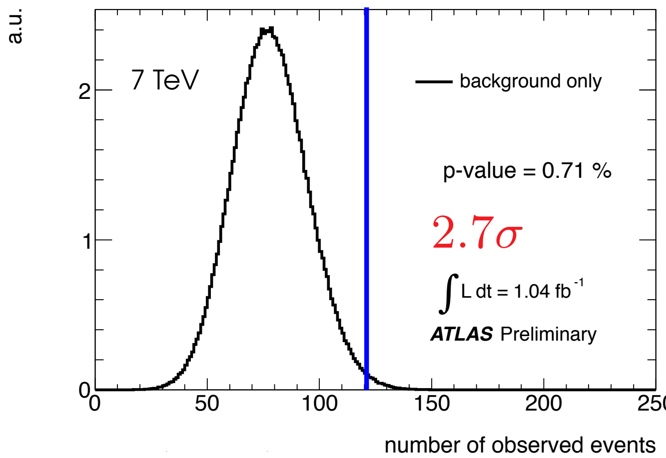
SM production of ttbar+Z/photon/W





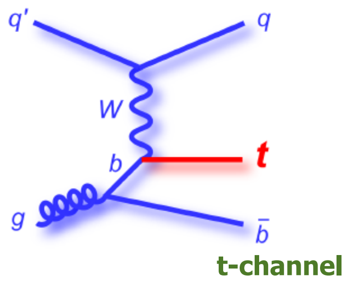


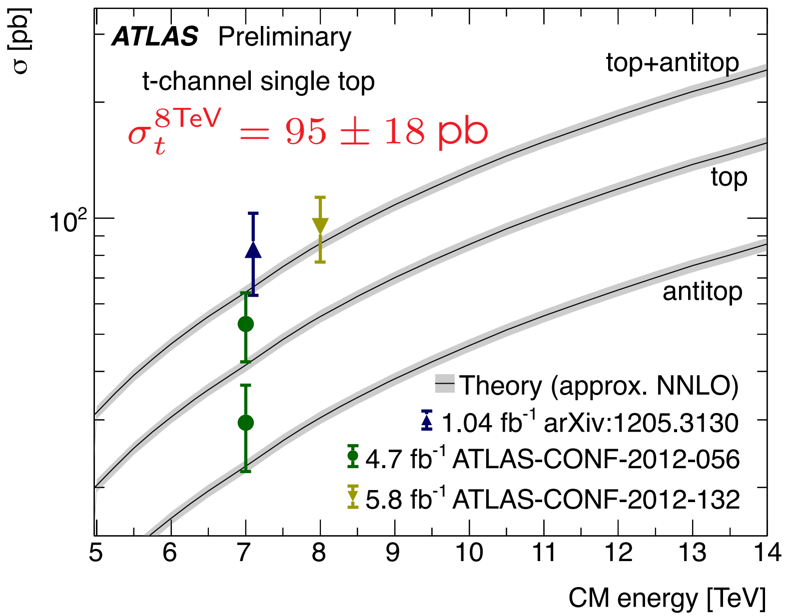




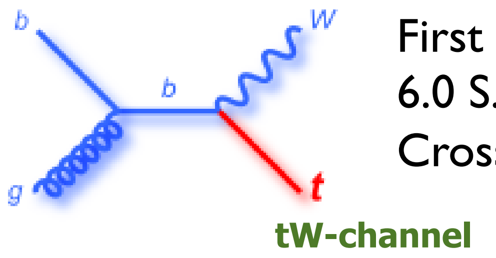
Single top production

- Single top in t-channel

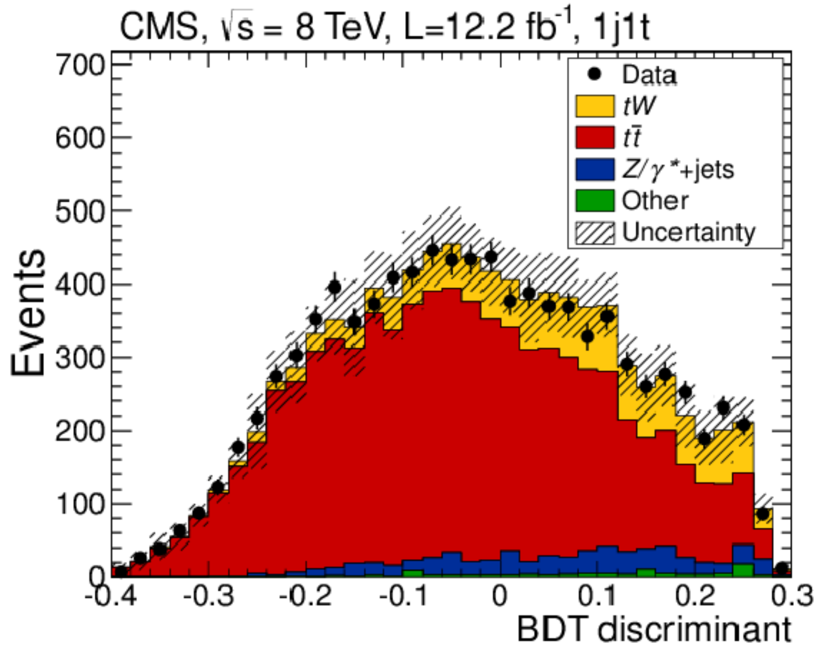




- Single top in tW-channel

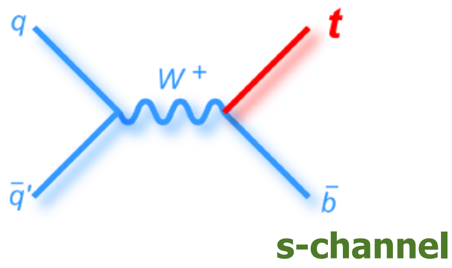


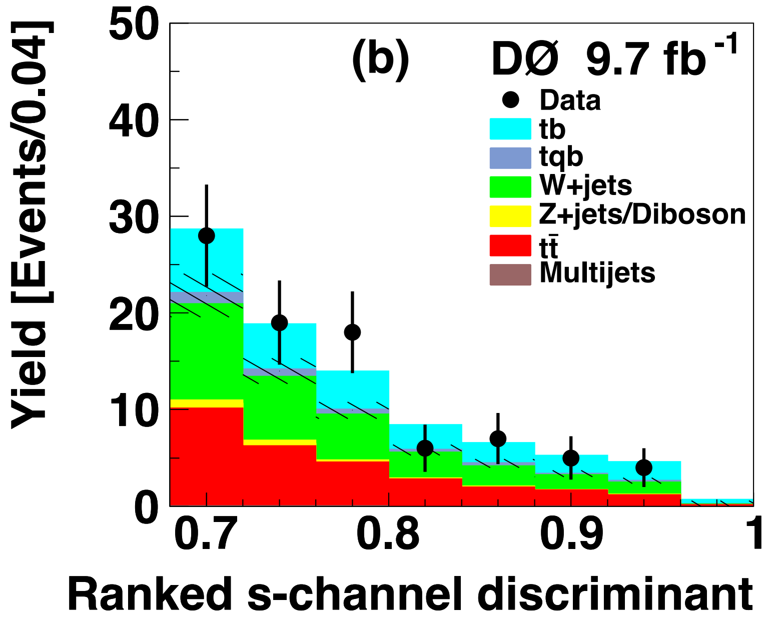
First observation
6.0 S.D. significance!
Cross section: 23.4±5.4 pb

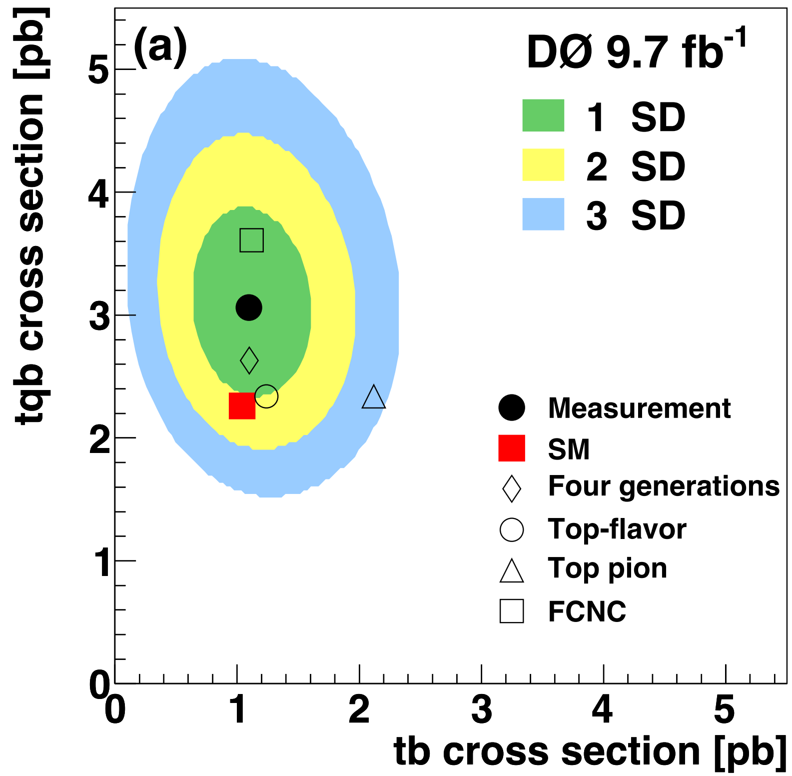


Single top in s-channel

- Tevatron legacy?
- Cross section: $1.10^{+0.33}_{-0.31}$ pb
- (A)NNLO: 1.06±0.04 pb
- Significance: 3.7 S.D.!!!





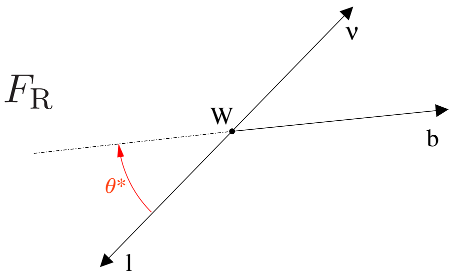


W helicity in top quark decay

- Helicity of W bosons very well-defined in standard model
- No hadronisation: coupling of top quark to W directly propagated to angular distributions of leptons in ttbar events

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)\,F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2\,F_{\rm L} + \frac{3}{8}\left(1+\cos\theta^*\right)^2\,F_{\rm R}$$

$$A_\pm = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)} \qquad z = \pm(1-2^{2/3})$$

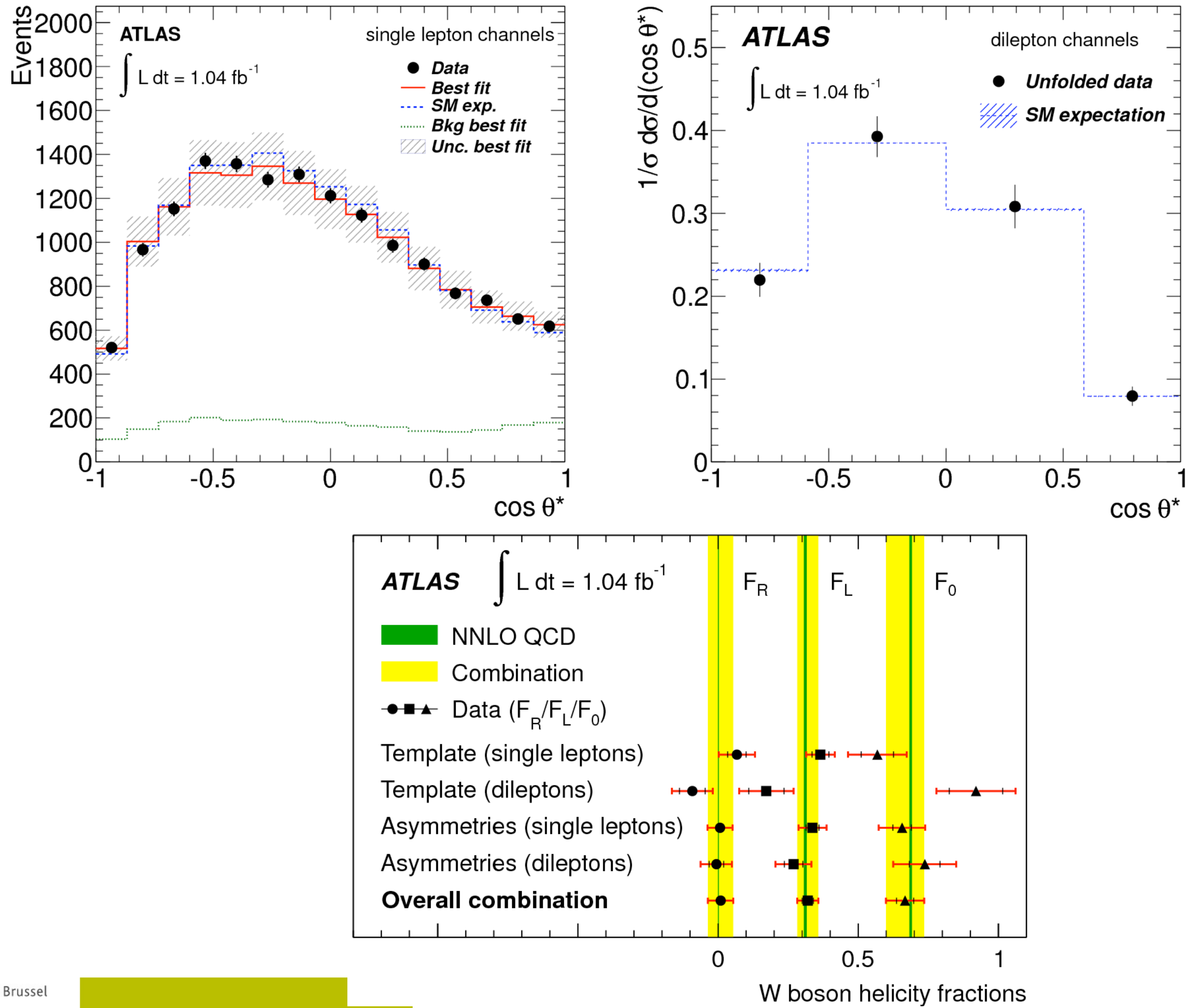


- Sensitive variable: Angle between down-type fermion in W rest frame and W momentum in top rest frame: cos(θ*)

- Measurements determine fractions of longitudinally, left, and right-handed W bosons

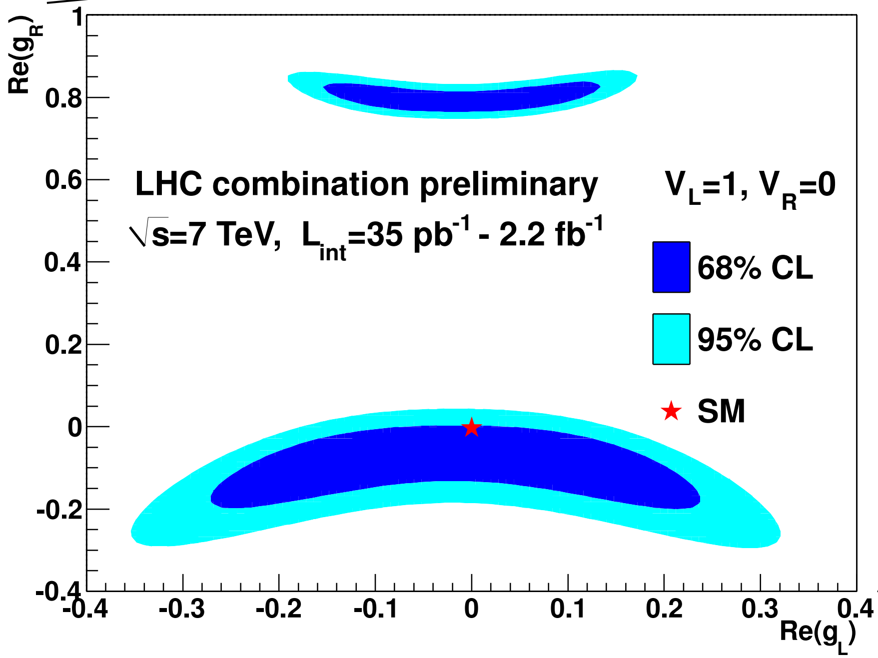
in SM (LO):
$F_0=0.6902$
$F_L=0.3089$
$F_R=0.0009$

Fitting the data



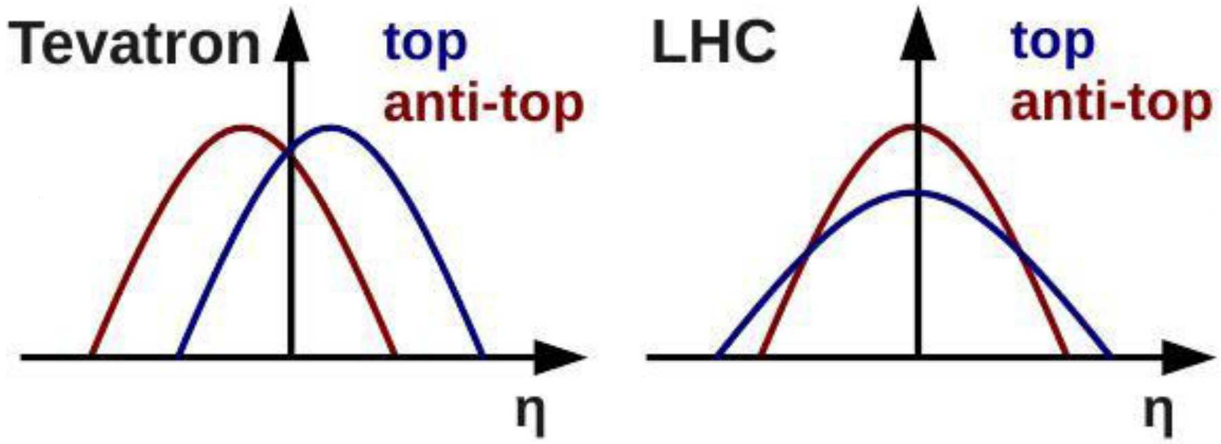
Interpret in effective lagrangean

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} + \mathrm{h.c.}$$



- Combination of ATLAS and equivalent CMS measurement used to constrain anomalous couplings at tWb vertex
- Very consistent with SM

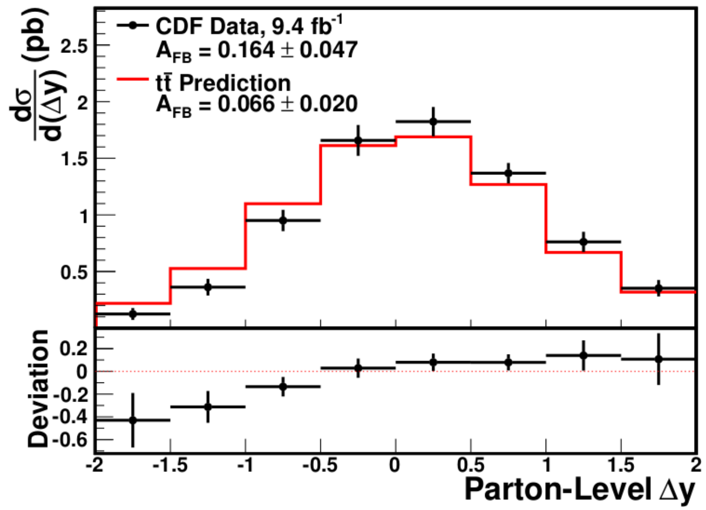
Top asymmetries: forward-backward



- New physics in production can alter angular distributions

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

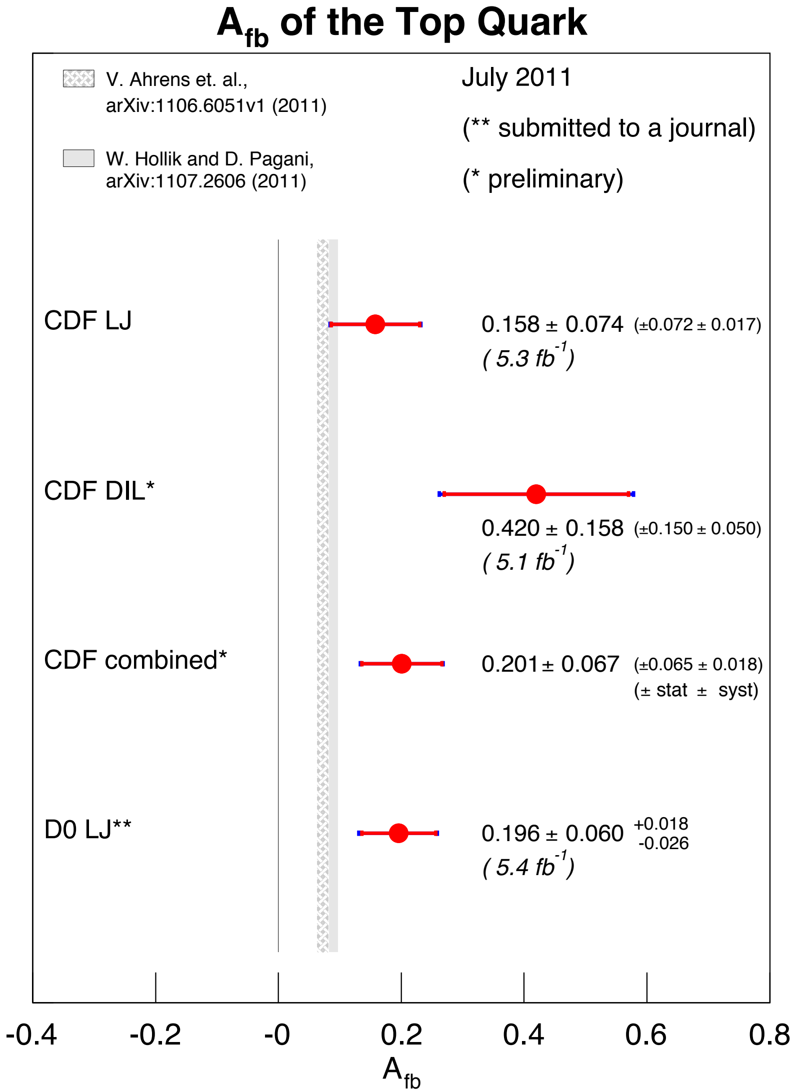
with $\Delta y = y_t - y_{\bar{t}}$

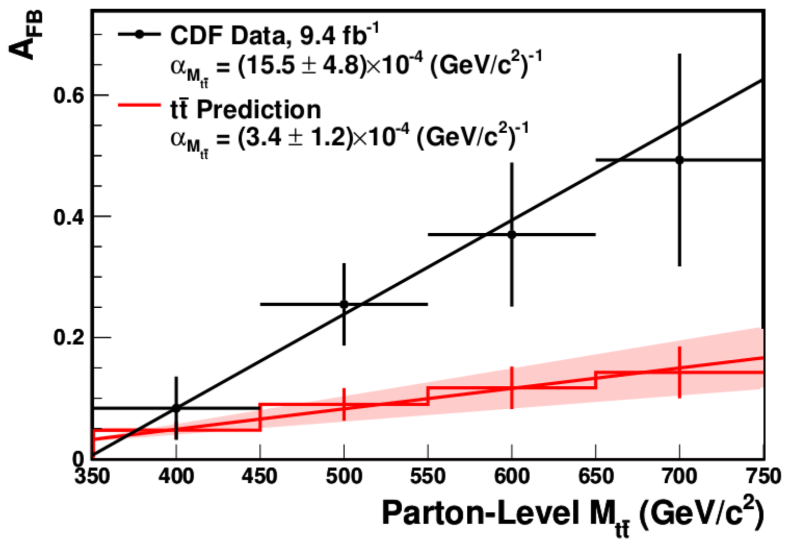


- At Tevatron:

  2.5 S.D. deviation from SM

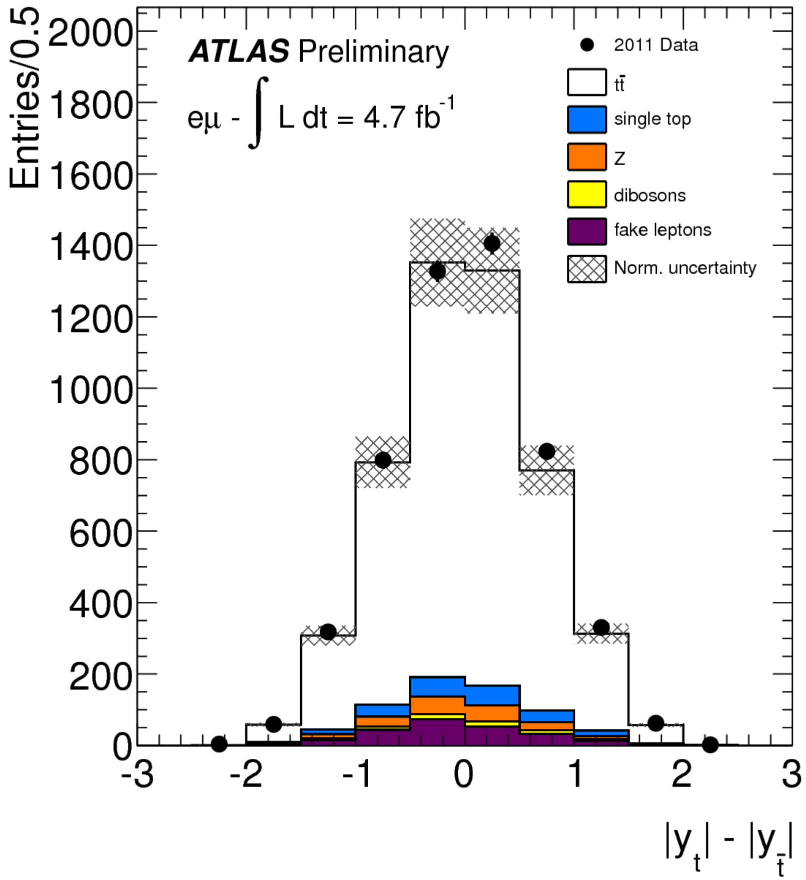
AFB details

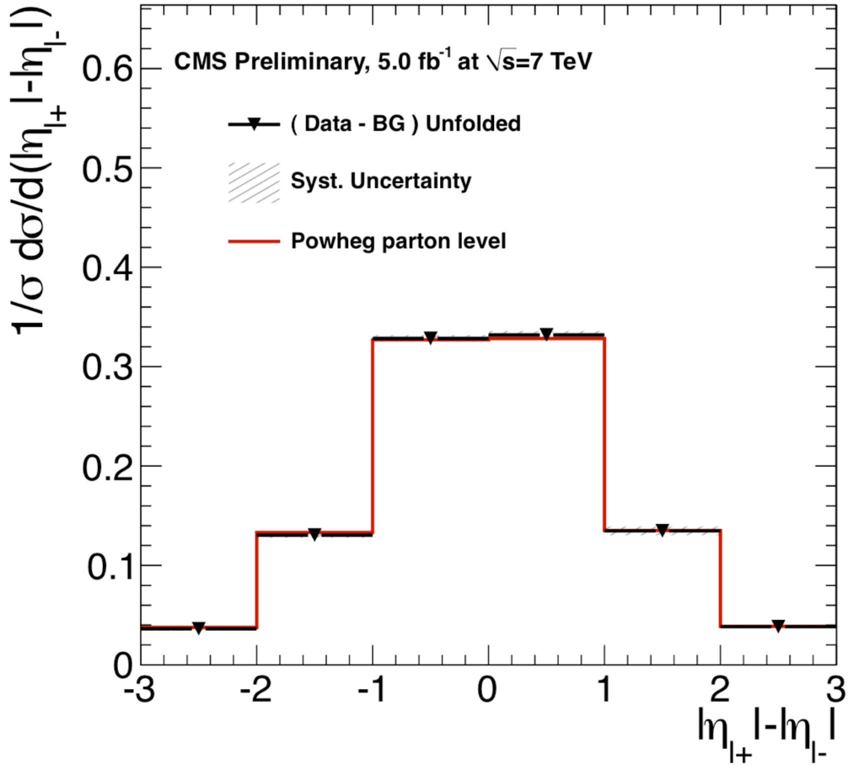




- AFB deviations largest at high m(ttbar)
- No effect at the LHC!!!

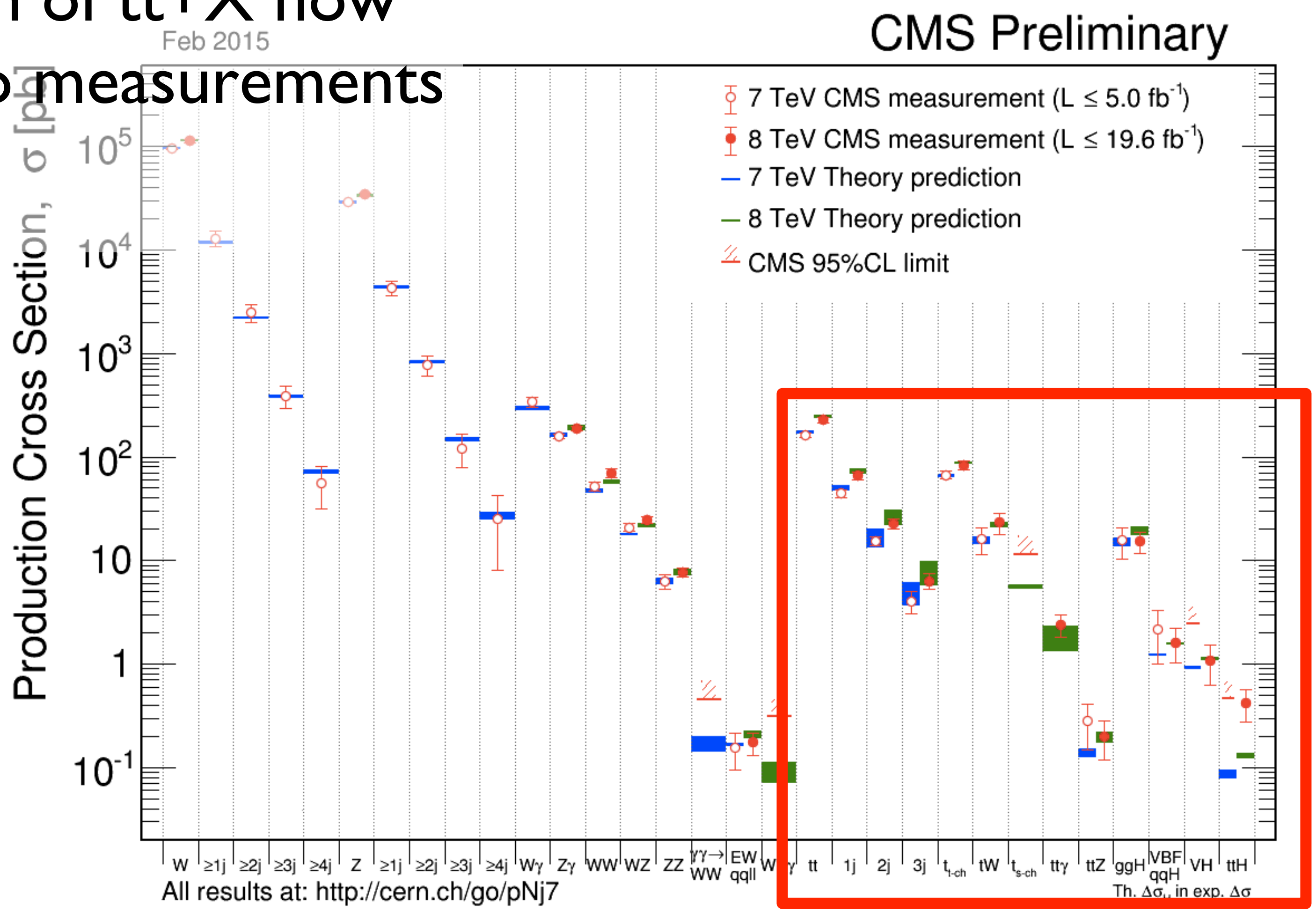
Asymmetry at the LHC?



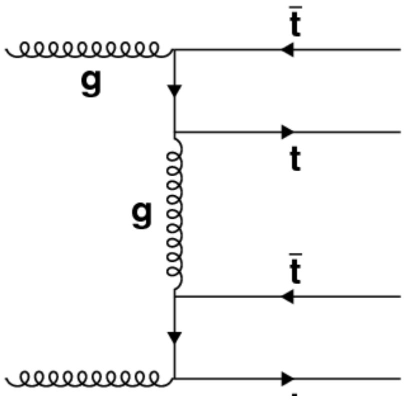


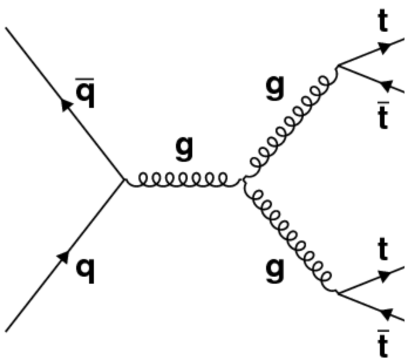
Top physics: rare decays

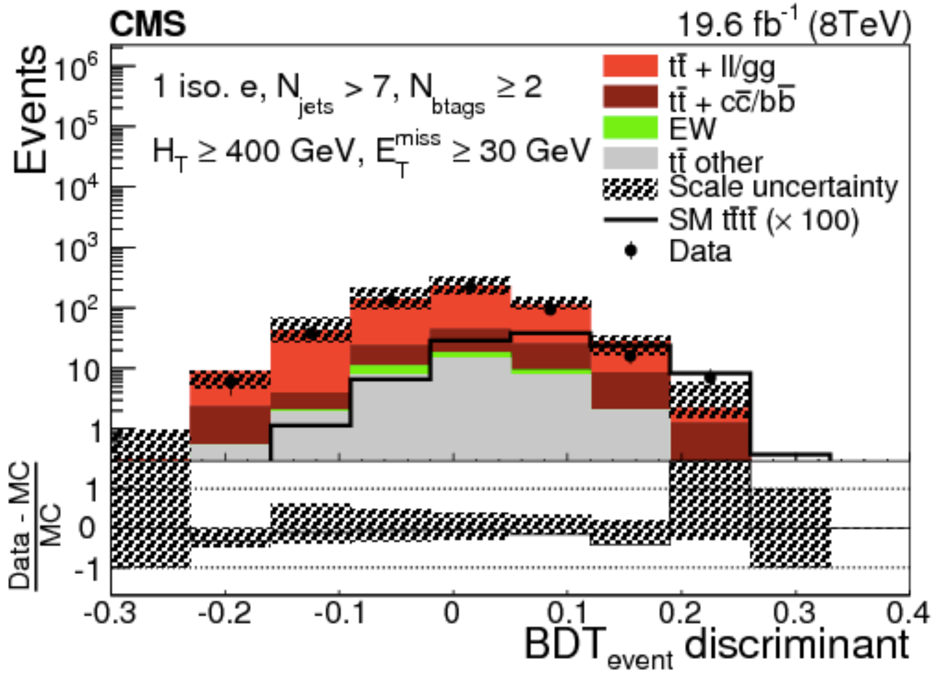
- Production of tt+X now used to do measurements to test SM



Next: undiscovered ttbar+X final states

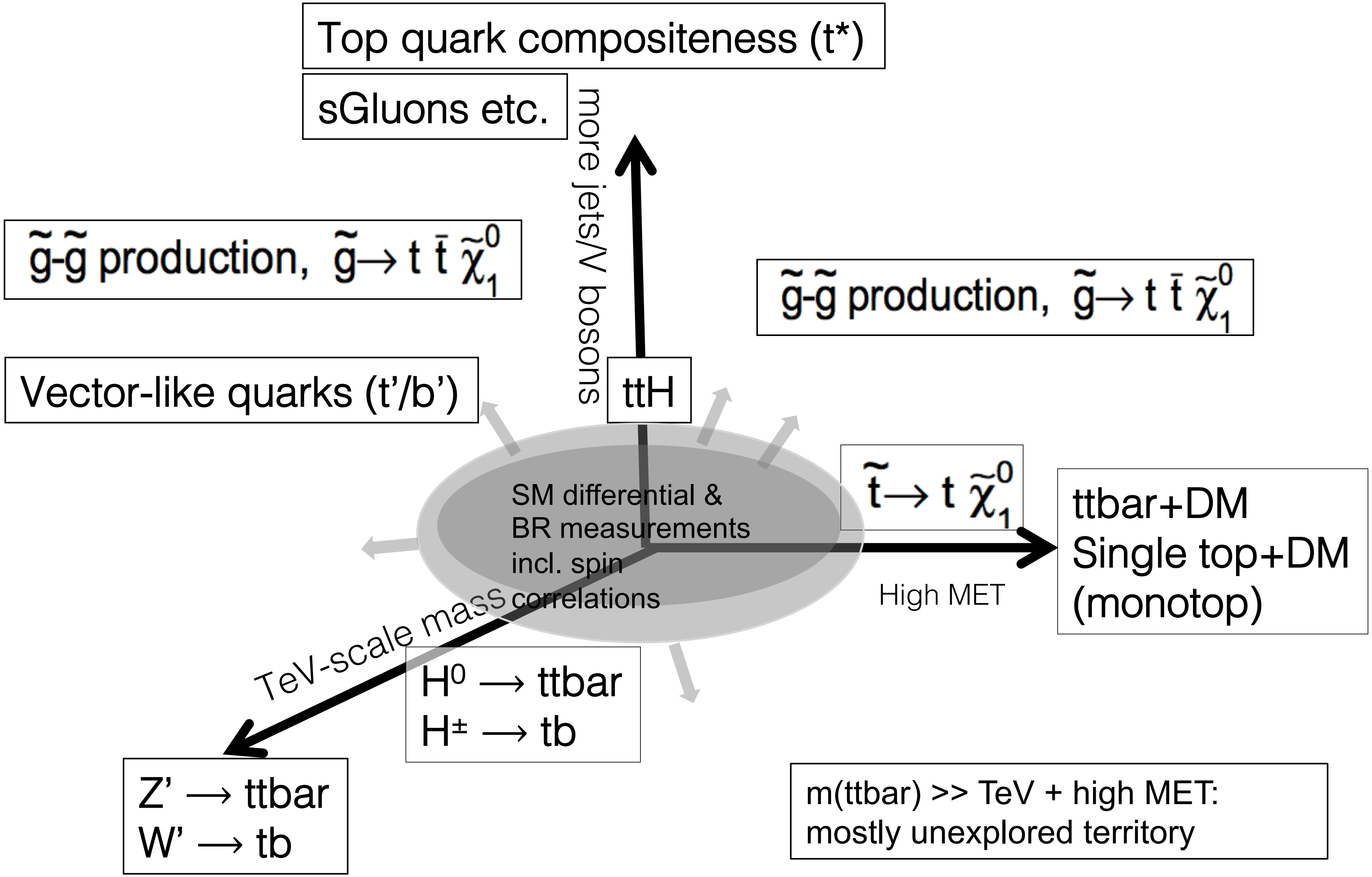




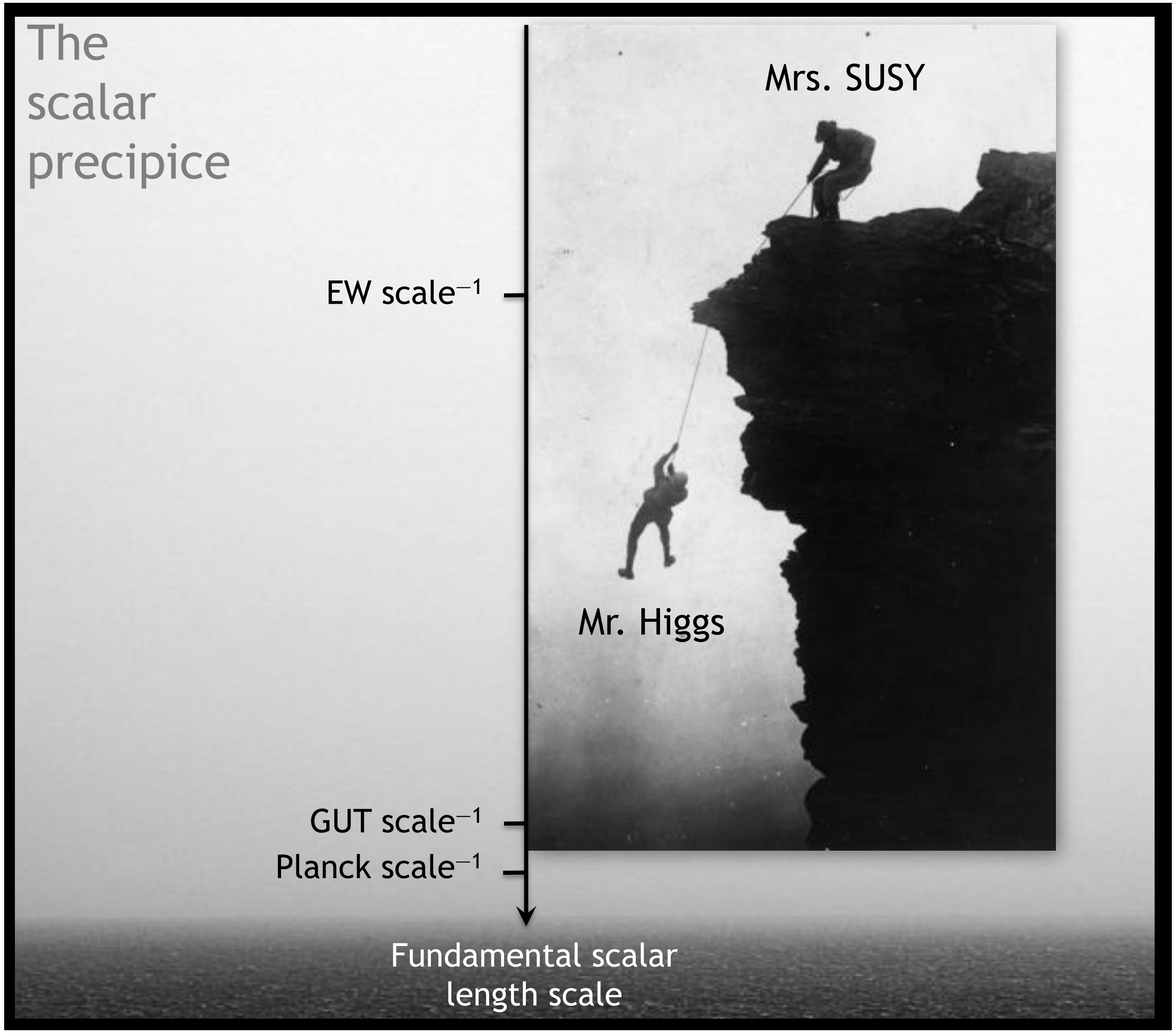


Production of tttt in SM: 1 fb!
Limits now at xsec<32 fb
Very sensitive to QCD-BSM

Src: TOP-13-012: JHEP 11 (2014) 154

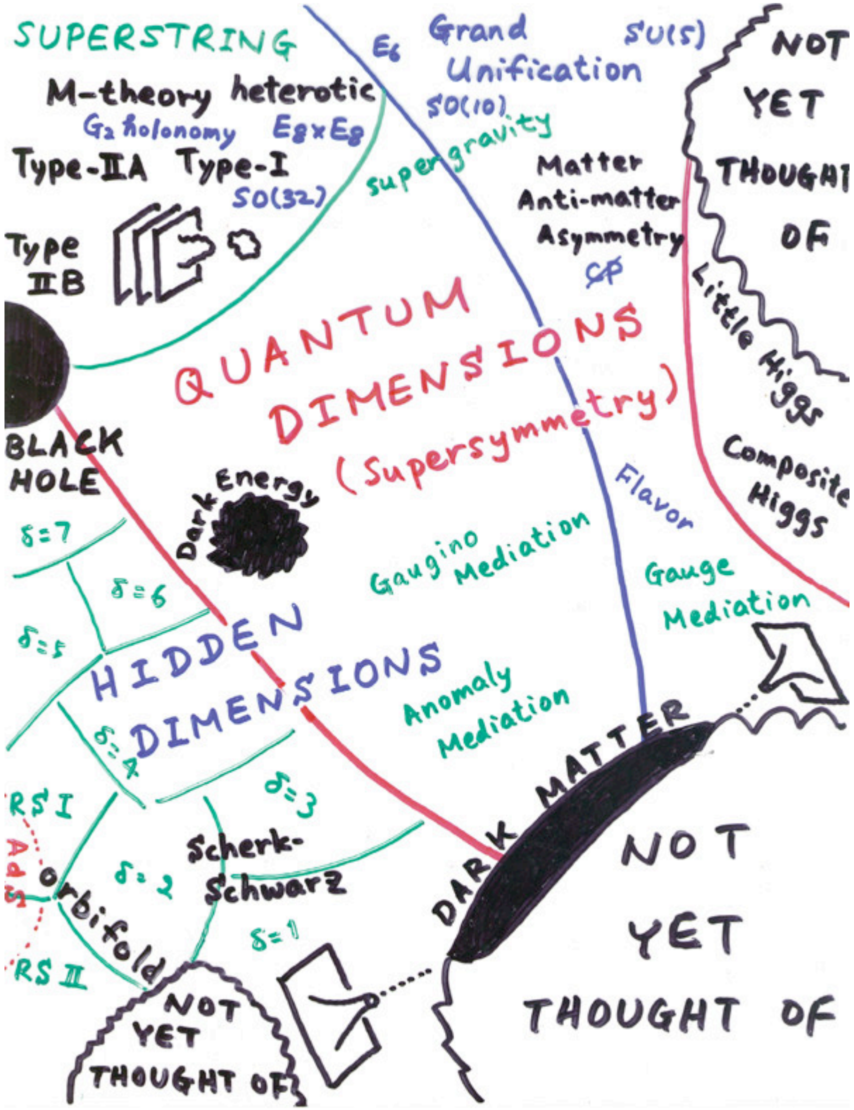

Top quark compositeness (t*)
sGluons etc.
more jets/V bosons
$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_1^0$
$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_1^0$
Vector-like quarks (t'/b')
ttH
$\tilde{t} \to t\,\tilde{\chi}_1^0$
SM differential &
BR measurements
incl. spin
correlations
ttbar+DM
Single top+DM
(monotop)
High MET
TeV-scale mass
$H^0 \longrightarrow$ ttbar
$H^\pm \longrightarrow$ tb
Z' $\longrightarrow$ ttbar
W' $\longrightarrow$ tb
m(ttbar) >> TeV + high MET:
mostly unexplored territory

The scalar precipice



17 SM parameters do not constrain creativity

- SUSY in all it's variations
  - GMSB
  - MSSM, CMSSM etc
- New strong interactions?
  - Technicolor; excited quarks; compositeness; new "contact" interactions
- Exotica:
  - Weird stuff: leptoquarks?
  - New "forces"?
  - New resonances (W-Z-like)
  - More generations?
    - Fourth generation (b'/t')
  - Gravity descending at the TeV scale?
  - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- SUSY-inspired exotica:
  - Long-lived massive (new) particles?
- Some true inspirations: "hidden valleys"?



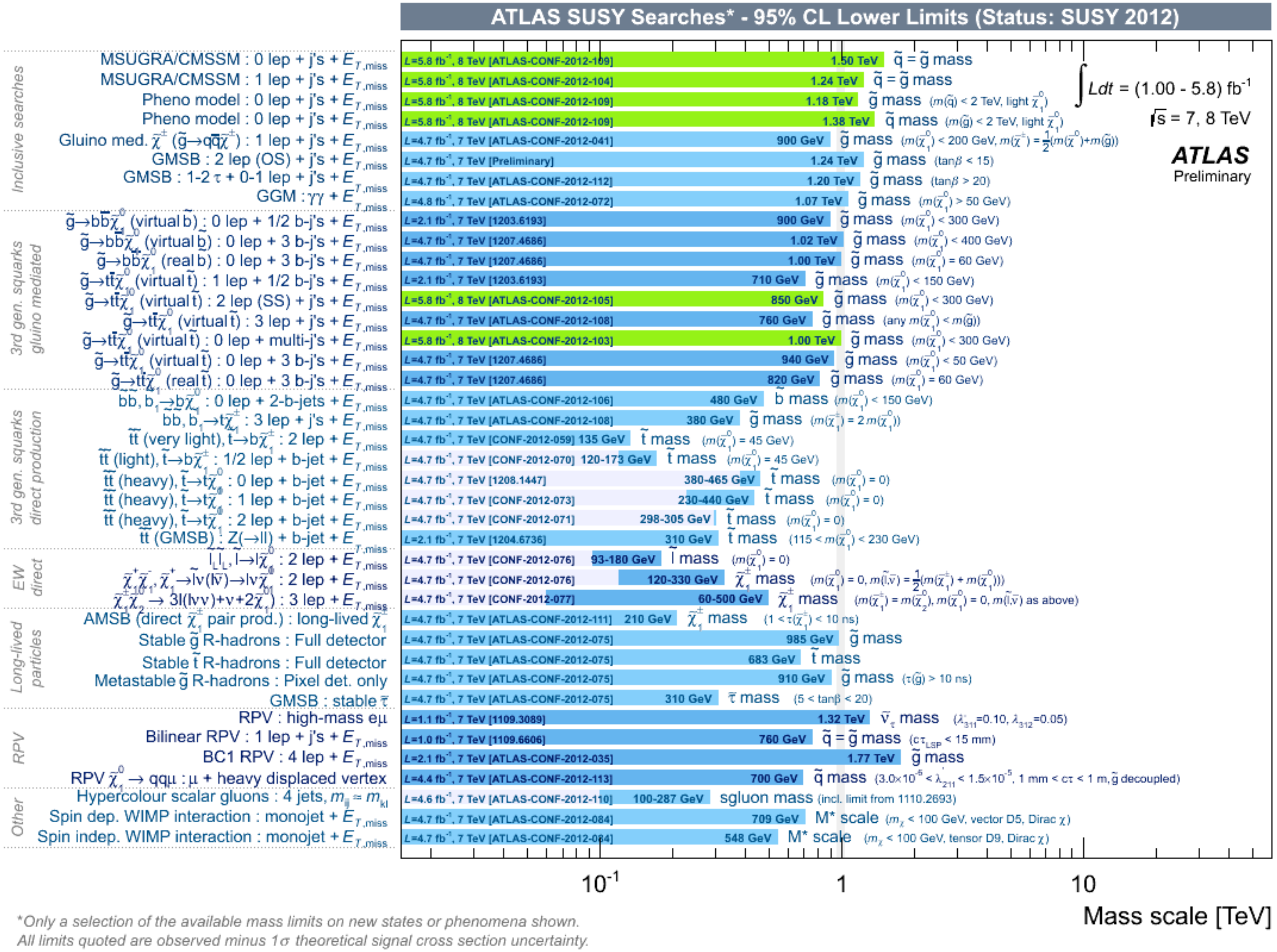
H. Murayama

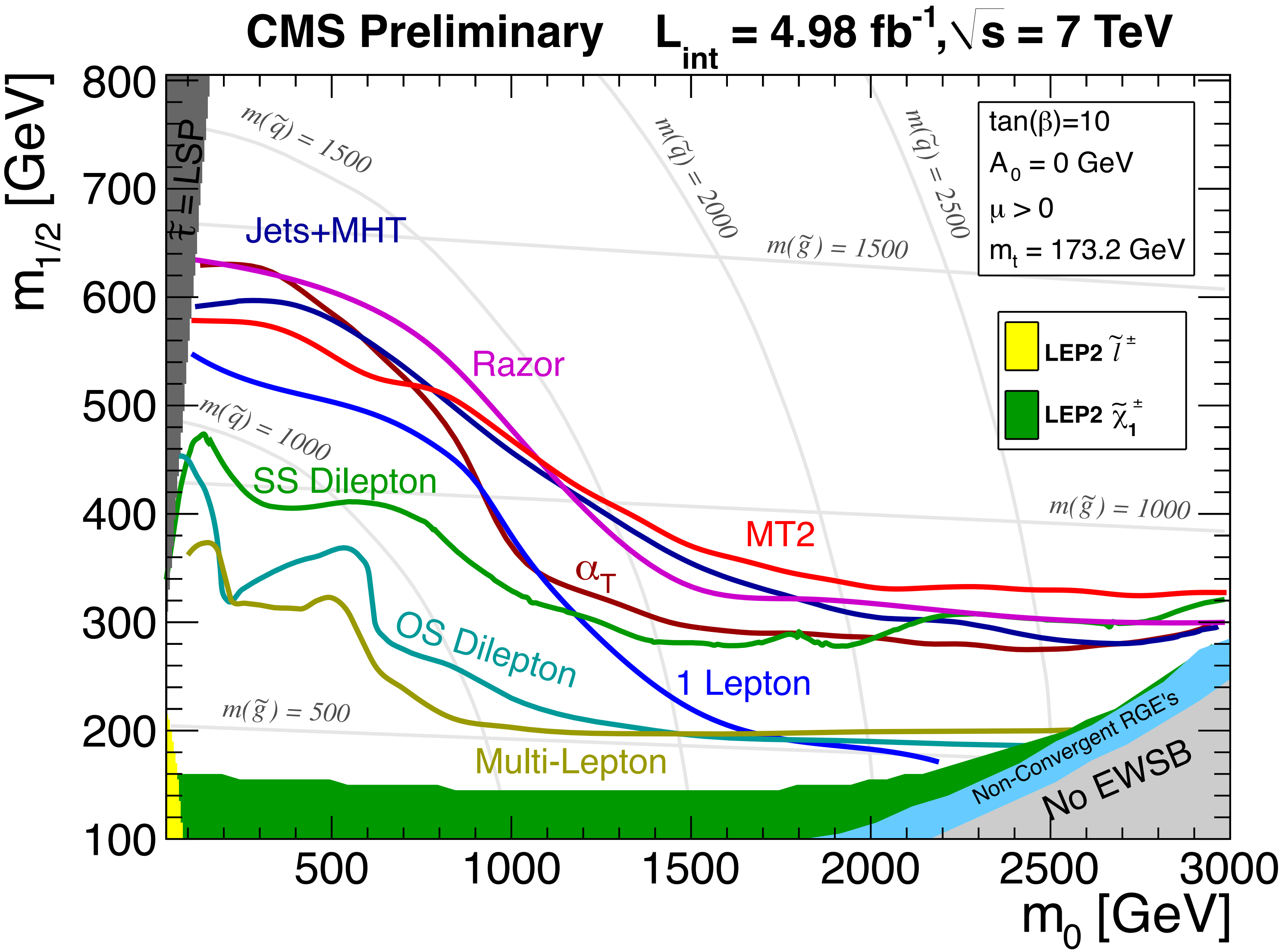
Which BSM model is 'right'?

- There is no right / wrong as far as hypothetical models are concerned (my subjective opinion)
  - Go to next major search conference (or the office of your local phenomenologist) to hear the exact opposite… for each model

- Hopefully the LHC will soon point us in the right direction
- Until then: better keep all options open

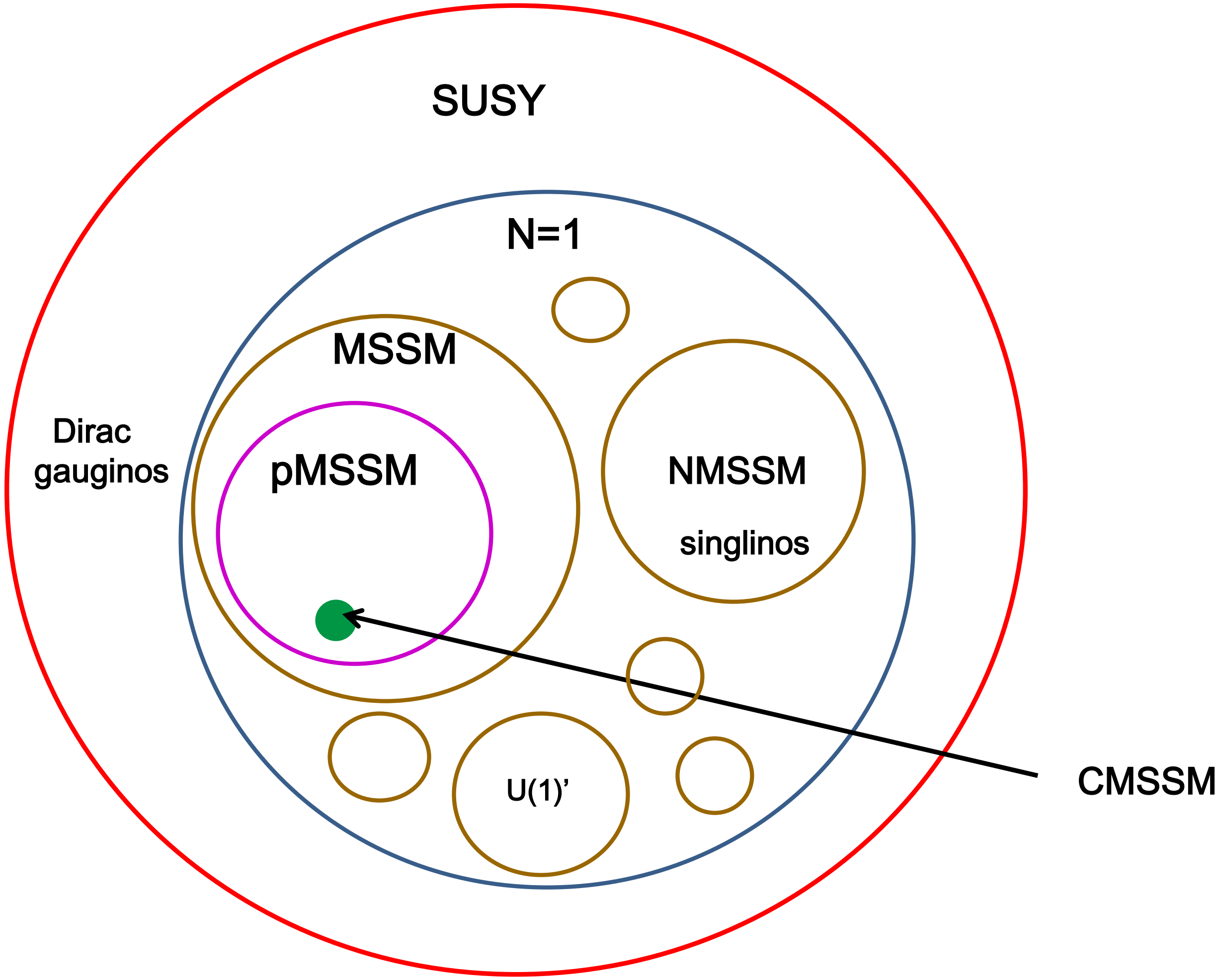
and that is exactly what the collaborations are doing…


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)
∫Ldt = (1.00 - 5.8) fb⁻¹
√s = 7, 8 TeV
ATLAS
Preliminary
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + E_T,miss — 1.50 TeV q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + E_T,miss — 1.24 TeV q̃ = g̃ mass
Pheno model : 0 lep + j's + E_T,miss — 1.18 TeV g̃ mass
Pheno model : 0 lep + j's + E_T,miss — 1.38 TeV q̃ mass
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + E_T,miss — 900 GeV g̃ mass
GMSB : 2 lep (OS) + j's + E_T,miss — 1.24 TeV g̃ mass (tanβ < 15)
GMSB : 1-2 τ + 0-1 lep + j's + E_T,miss — 1.20 TeV g̃ mass (tanβ > 20)
GGM : γγ + E_T,miss — 1.07 TeV g̃ mass
3rd gen. squarks gluino mediated
g̃→bb̄χ̃⁰₁ (virtual b̃) : 0 lep + 1/2 b-j's + E_T,miss — 900 GeV g̃ mass
g̃→bb̄χ̃⁰₁ (virtual b̃) : 0 lep + 3 b-j's + E_T,miss — 1.02 TeV g̃ mass
g̃→bb̃χ̃⁰₁ (real b̃) : 0 lep + 3 b-j's + E_T,miss — 1.00 TeV g̃ mass
g̃→tt̄χ̃⁰₁ (virtual t̃) : 1 lep + 1/2 b-j's + E_T,miss — 710 GeV g̃ mass
g̃→tt̄χ̃⁰₁ (virtual t̃) : 2 lep (SS) + j's + E_T,miss — 850 GeV g̃ mass
g̃→tt̄χ̃⁰₁ (virtual t̃) : 3 lep + j's + E_T,miss — 760 GeV g̃ mass
g̃→tt̄χ̃⁰₁ (virtual t̃) : 0 lep + multi-j's + E_T,miss — 1.00 TeV g̃ mass
g̃→tt̄χ̃⁰₁ (virtual t̃) : 0 lep + 3 b-j's + E_T,miss — 940 GeV g̃ mass
g̃→tt̄χ̃⁰₁ (real t̃) : 0 lep + 3 b-j's + E_T,miss — 820 GeV g̃ mass
3rd gen. squarks direct production
bb, b̃₁→bχ̃⁰₁ : 0 lep + 2-b-jets + E_T,miss — 480 GeV b̃ mass
bb, b̃₁→tχ̃±₁ : 3 lep + j's + E_T,miss — 380 GeV g̃ mass
tt (very light), t̃→bχ̃±₁ : 2 lep + E_T,miss — 135 GeV t̃ mass
tt (light), t̃→bχ̃±₁ : 1/2 lep + b-jet + E_T,miss — 120-173 GeV t̃ mass
tt (heavy), t̃→tχ̃⁰₁ : 0 lep + b-jet + E_T,miss — 380-465 GeV t̃ mass
tt (heavy), t̃→tχ̃⁰₁ : 1 lep + b-jet + E_T,miss — 230-440 GeV t̃ mass
tt (heavy), t̃→tχ̃⁰₁ : 2 lep + b-jet + E_T,miss — 298-305 GeV t̃ mass
tt (GMSB) : Z(→ll) + b-jet + E_T,miss — 310 GeV t̃ mass
EW direct
l̃_L l̃_L, l̃→lχ̃⁰₁ : 2 lep + E_T,miss — 93-180 GeV l̃ mass
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→l̃ν(lν̃)→lνχ̃⁰₁ : 2 lep + E_T,miss — 120-330 GeV χ̃±₁ mass
χ̃±₁χ̃⁰₂ → 3l(lνν)+ν+2χ̃⁰₁ : 3 lep + E_T,miss — 60-500 GeV χ̃±₁ mass
Long-lived particles
AMSB (direct χ̃±₁ pair prod.) : long-lived χ̃±₁ — 210 GeV χ̃±₁ mass
Stable g̃ R-hadrons : Full detector — 985 GeV g̃ mass
Stable t̃ R-hadrons : Full detector — 683 GeV t̃ mass
Metastable g̃ R-hadrons : Pixel det. only — 910 GeV g̃ mass
GMSB : stable τ̃ — 310 GeV τ̃ mass
RPV
RPV : high-mass eμ — 1.32 TeV ν̃_τ mass
Bilinear RPV : 1 lep + j's + E_T,miss — 760 GeV q̃ = g̃ mass
BC1 RPV : 4 lep + E_T,miss — 1.77 TeV g̃ mass
RPV χ̃⁰₁ → qqμ : μ + heavy displaced vertex — 700 GeV q̃ mass
Other
Hypercolour scalar gluons : 4 jets, m_ij ≈ m_kl — 100-287 GeV sgluon mass
Spin dep. WIMP interaction : monojet + E_T,miss — 709 GeV M* scale
Spin indep. WIMP interaction : monojet + E_T,miss — 548 GeV M* scale
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



CMS Preliminary L_int = 4.98 fb^-1, √s = 7 TeV
m_1/2 [GeV]
m_0 [GeV]
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000
τ̃ = LSP
m(q̃) = 1500
m(q̃) = 2000
m(q̃) = 2500
m(g̃) = 1500
m(q̃) = 1000
m(g̃) = 1000
m(g̃) = 500
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 l̃^±
LEP2 χ̃_1^±
Jets+MHT
Razor
SS Dilepton
MT2
α_T
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB

MSSM vs SUSY



Experiments are getting creative

- Trying to hit many ~~birds~~ models with one ~~stone~~ analysis

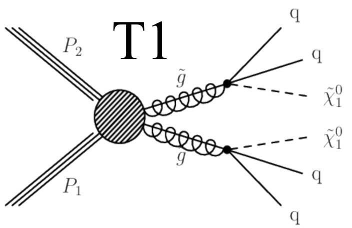
- Tension between cMSSM and experimental evidence growing – time to look at alternatives
  - But so many available in SUSY sector alone…

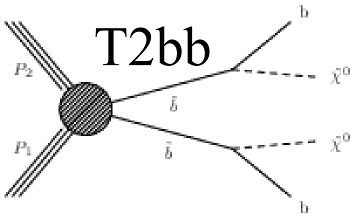
- Trying to interpret searches in generic models
  - Effective field theory, Simplified Model Spectra, MadAnalysis, Rivet, etc, etc

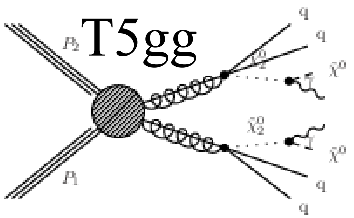
Simplified models: example

- Only consider limited set of hypothetical particles and decay chains
  - Of course not 100% perfect but field theory motivates that cross sections for most LHC new phenomena are driven by kinematic phase space (mass vs available energy, branching ratios)
- Main parameters of simplified model are exactly this:
  - Reinterpret existing analyses as upper limits on models where only the mass and branching ratio are free
- ATLAS and CMS are both pursuing this analysis strategy

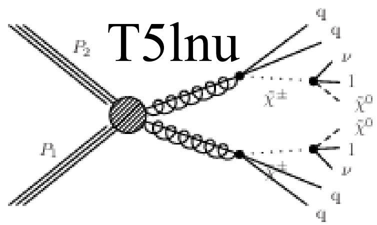
Example: CMS model list

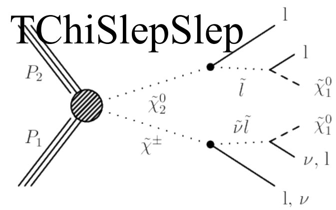




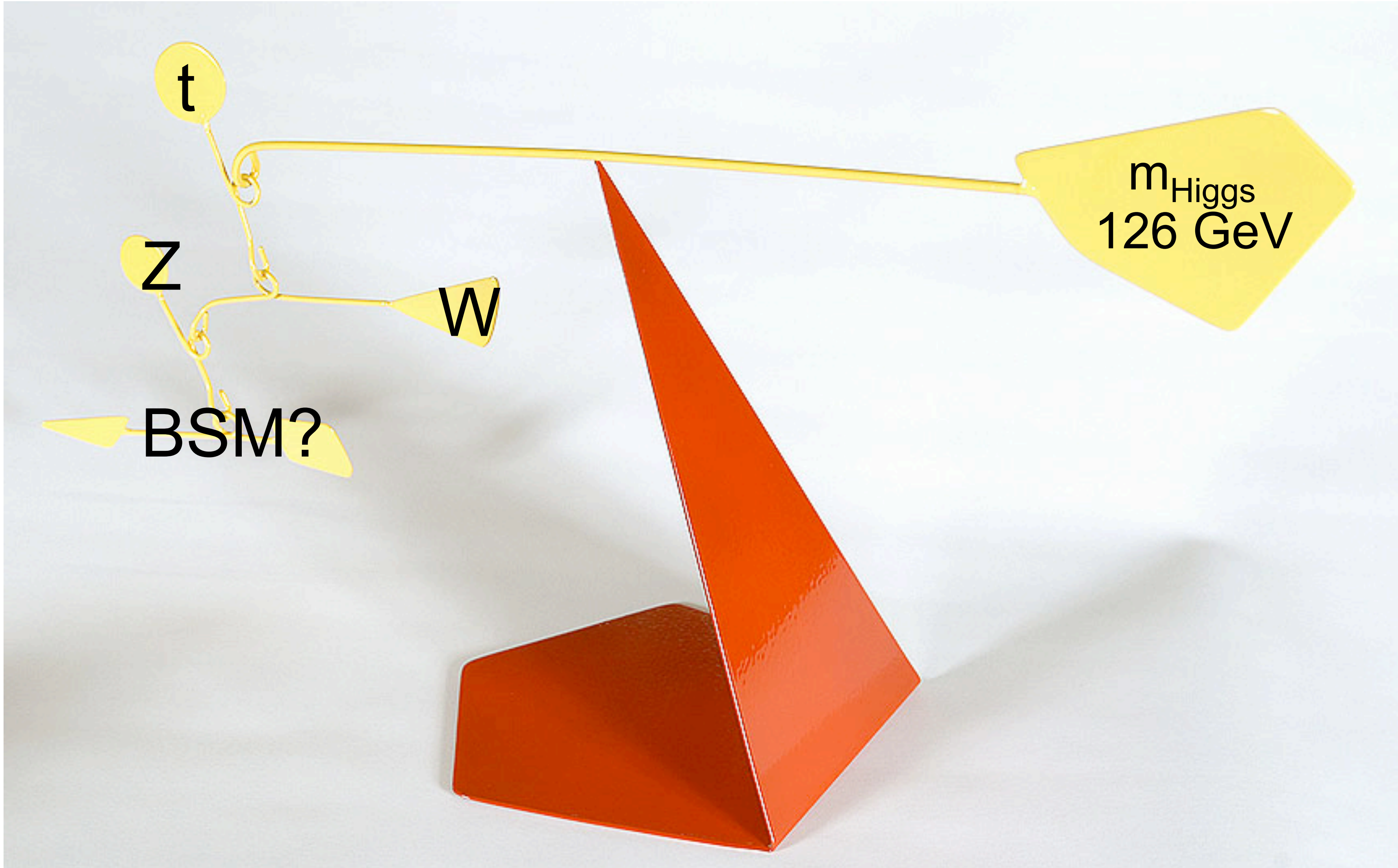


model name	prod. mode	decay	visibility
T1	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^0$	hadronic
T2	$\tilde{q}\,\tilde{q}^*$	$\tilde{q} \to q\tilde{\chi}^0$	hadronic
T5zz	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to q\bar{q}Z\tilde{\chi}^0$	hadronic di-leptons multi-leptons
T3w	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^0$ $\tilde{g} \to q\bar{q}\tilde{\chi}^\pm$, $\tilde{\chi}^\pm \to W^\pm\tilde{\chi}^0$	single lepton
T5lnu	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^\pm\ \tilde{\chi}^\pm \to \ell\nu\tilde{\chi}^0$	di-leptons
T3lh	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^0$ $\tilde{g} \to q\bar{q}\ell^+\ell^-\tilde{\chi}^0$	di-leptons
T2bb	$\tilde{b}\,\tilde{b}^*$	$\tilde{b} \to b\,\tilde{\chi}^0$	hadronic
T2tt	$\tilde{t}\,\tilde{t}^*$	$\tilde{t} \to t\,\tilde{\chi}^0$	hadronic
T1bbbb	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to b\,\bar{b}\,\tilde{\chi}^0$	hadronic
T1tttt	$\tilde{g}\,\tilde{g}$	$\tilde{g} \to t\,\bar{t}\,\tilde{\chi}^0$	hadronic(b) single-leptons(b) di-leptons(b) inclusive(b)
TChiSlepSlep	$\tilde{\chi}^\pm\tilde{\chi}^0_2$	$\tilde{\chi}^0_2 \to \ell^\pm\tilde{\ell}^\mp$, $\tilde{\ell} \to \ell\tilde{\chi}^0$ $\tilde{\chi}^\pm \to \nu\tilde{\ell}$, $\tilde{\ell} \to \ell\tilde{\chi}^0$	multi-leptons
TChiwz	$\tilde{\chi}^\pm\tilde{\chi}^0_2$	$\tilde{\chi}^\pm \to W^\pm\tilde{\chi}^0$, $\tilde{\chi}^0_2 \to Z\tilde{\chi}^0$	multi-leptons
TChizz	$\tilde{\chi}^0_2\tilde{\chi}^0_3$	$\tilde{\chi}^0_2, \tilde{\chi}^0_3 \to Z\tilde{\chi}^0$	multi-leptons
T5gg	$\tilde{g}\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^0_2, \tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$	photons
T5Wg	$\tilde{g}\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}^0_2, \tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$ $\tilde{g} \to q\bar{q}\tilde{\chi}^\pm, \tilde{\chi}^\pm \to W^\pm\tilde{\chi}^0_1$	photons

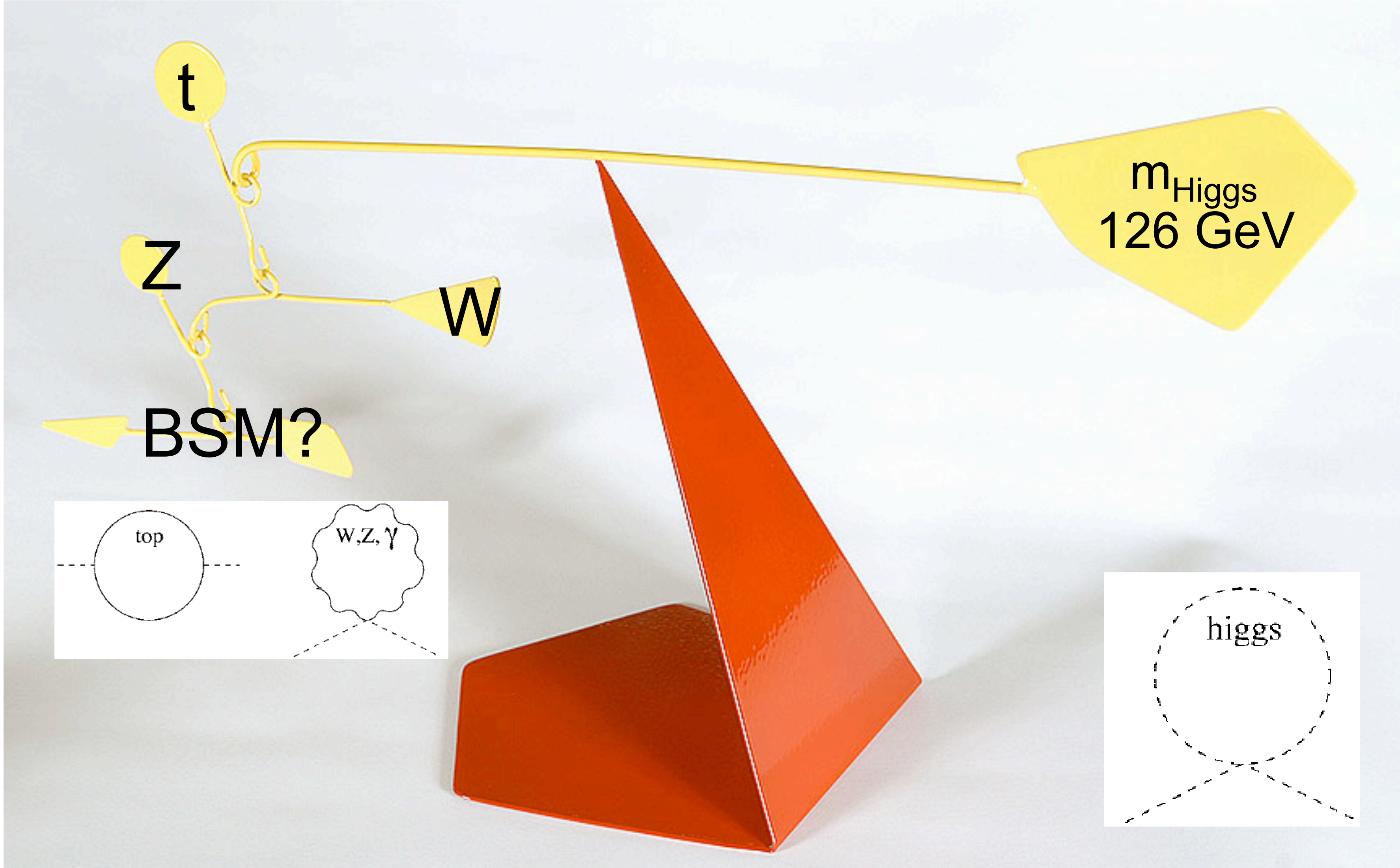




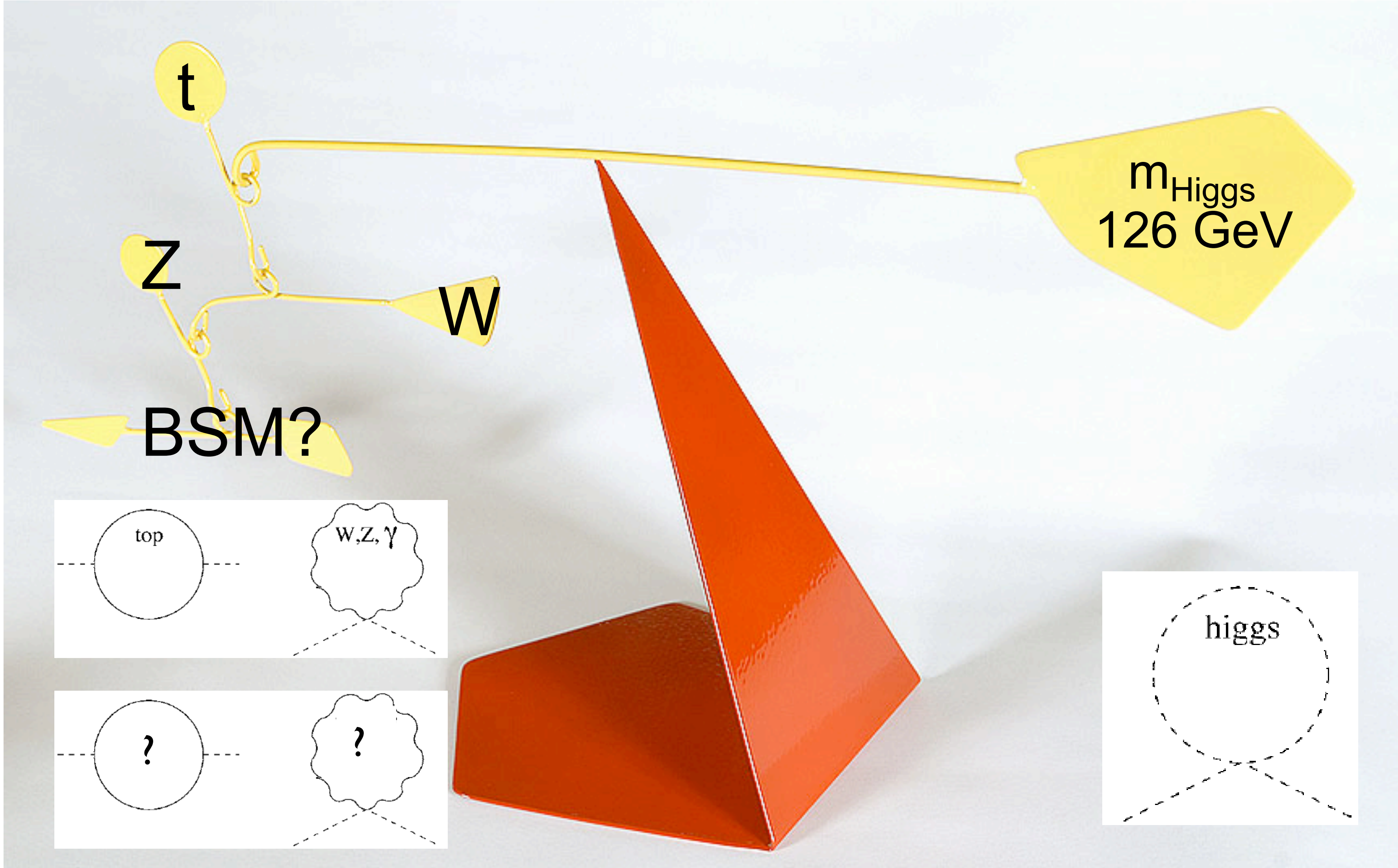
Little Hierarchy problem, Naturalness



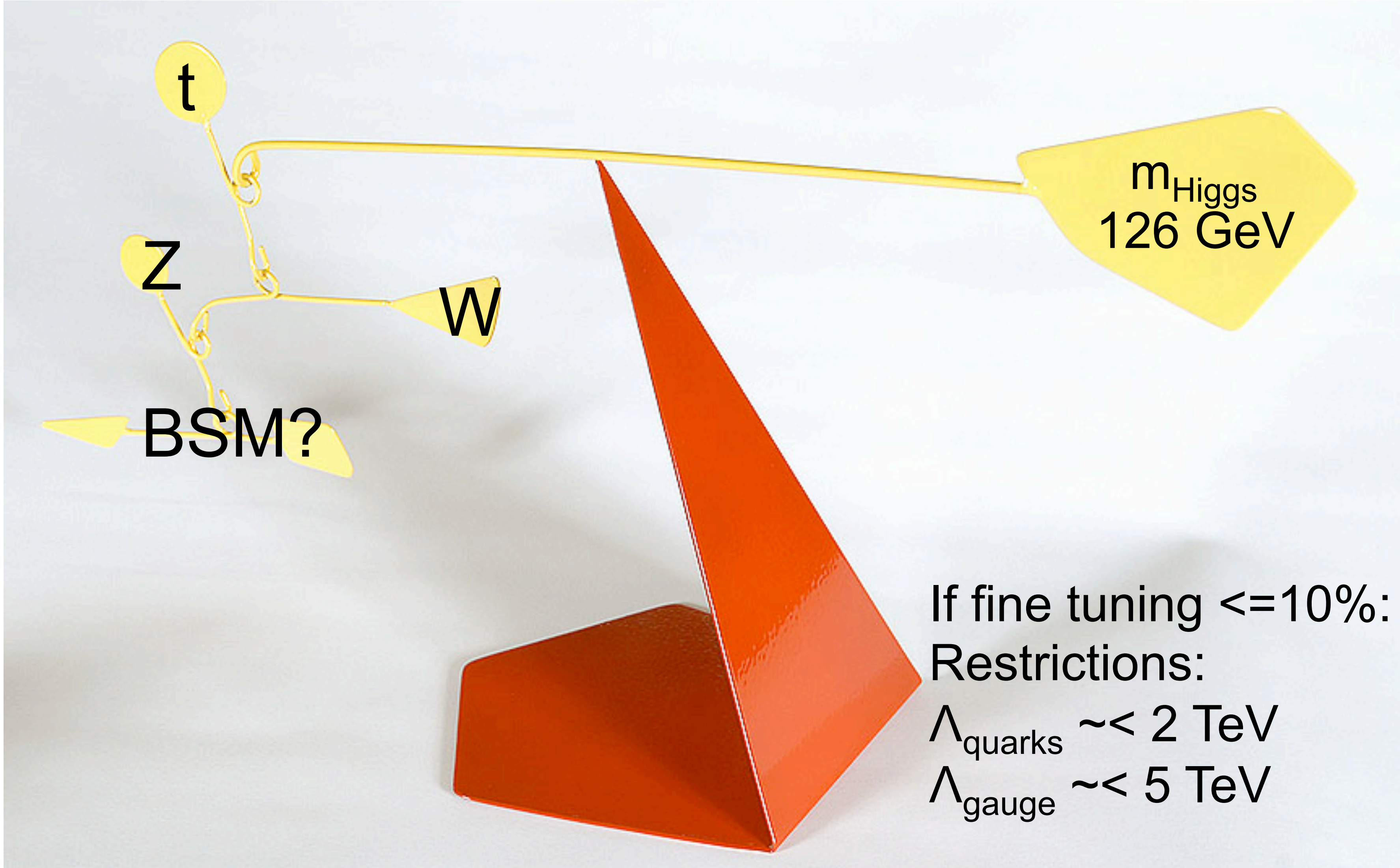
Little Hierarchy problem, Naturalness



Little Hierarchy problem, Naturalness

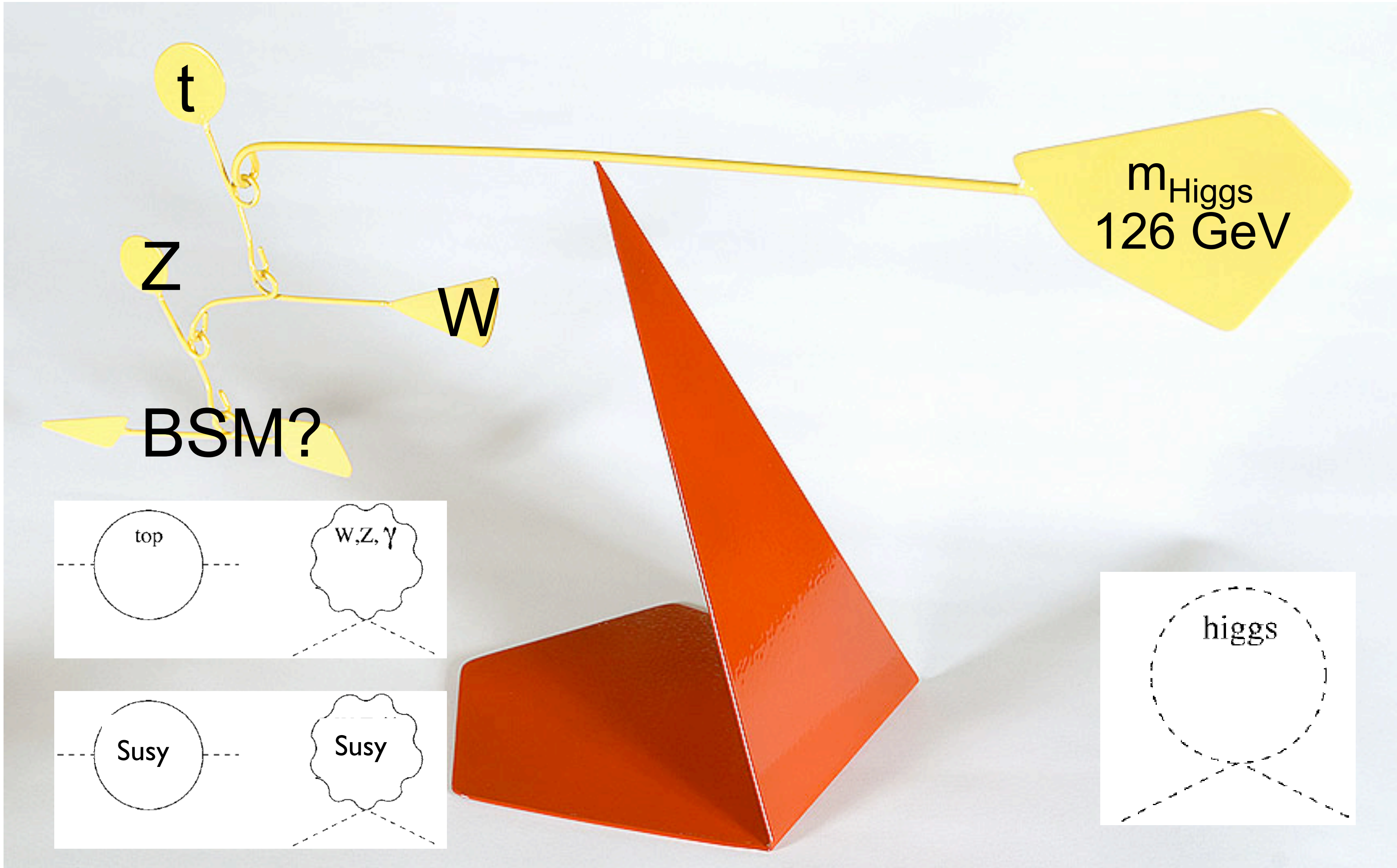


Little Hierarchy problem, Naturalness



If fine tuning <=10%:
Restrictions:
Λ_{quarks} ~< 2 TeV
Λ_{gauge} ~< 5 TeV

Little Hierarchy problem, Naturalness

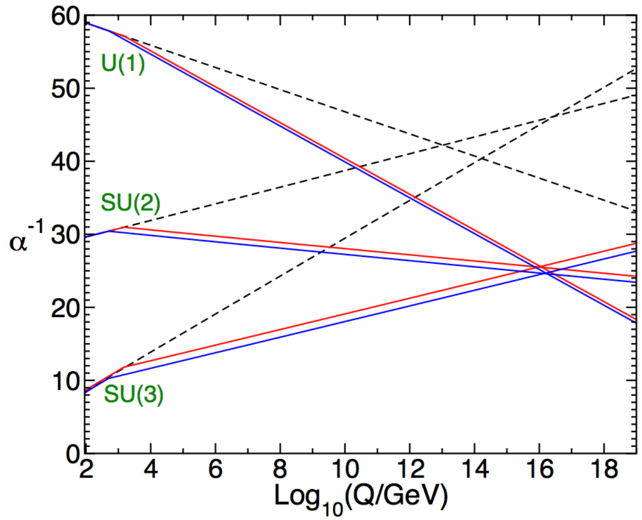


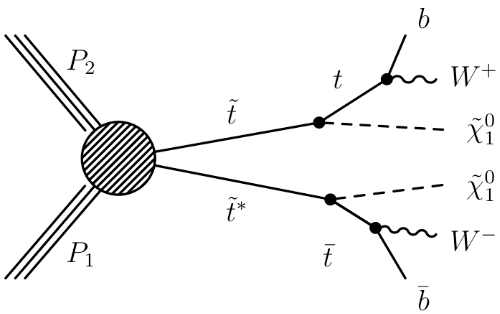
Supersymmetry - in top sector?

- Solves hierarchy problem, GUT convergence and can add CP violation

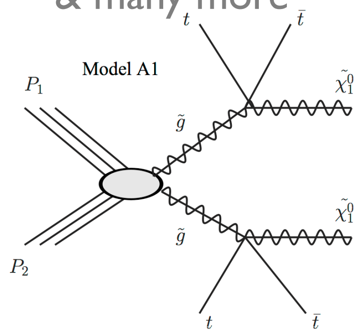
- Dark Matter candidates available

- Naturalness motivations can be interpreted to favor light stop
  - ttbar+MET, ttbar+X+MET signatures

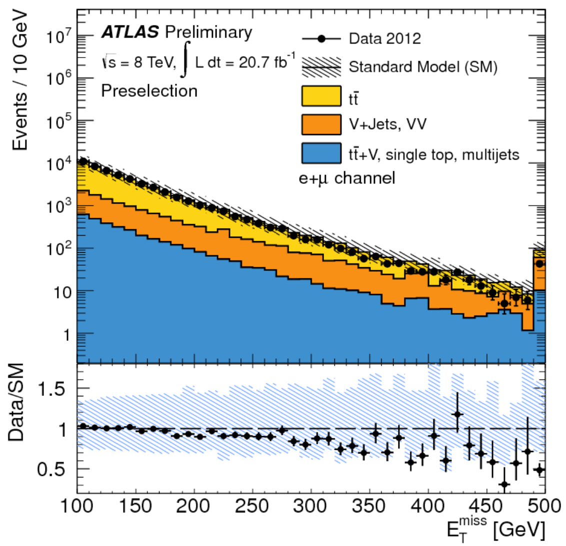


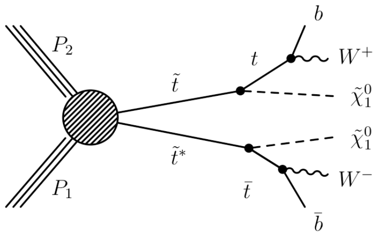


& many more

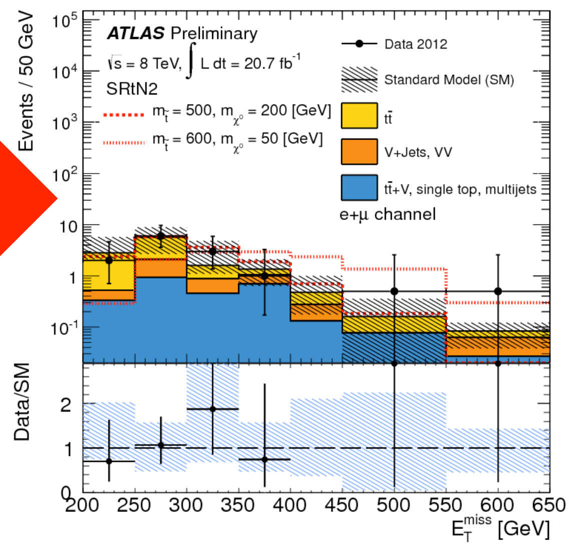


Example stop search in l+jets+MET





One signal region



By ATLAS

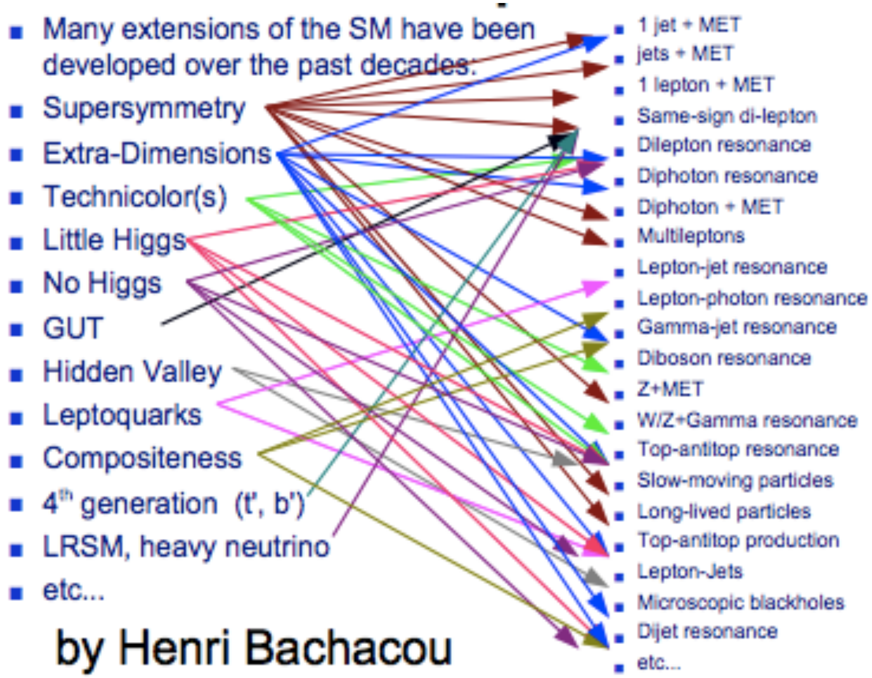
requires detailed understanding of top quark pair production at high missing ET

- Analysis works in many signal regions, looking in boxes constrained by number of b-tags, transverse mass, MET, etc
- Sensitivity for stop depends on scenario considered, each region has strengths/ weaknesses
- Strong limits on stop mass

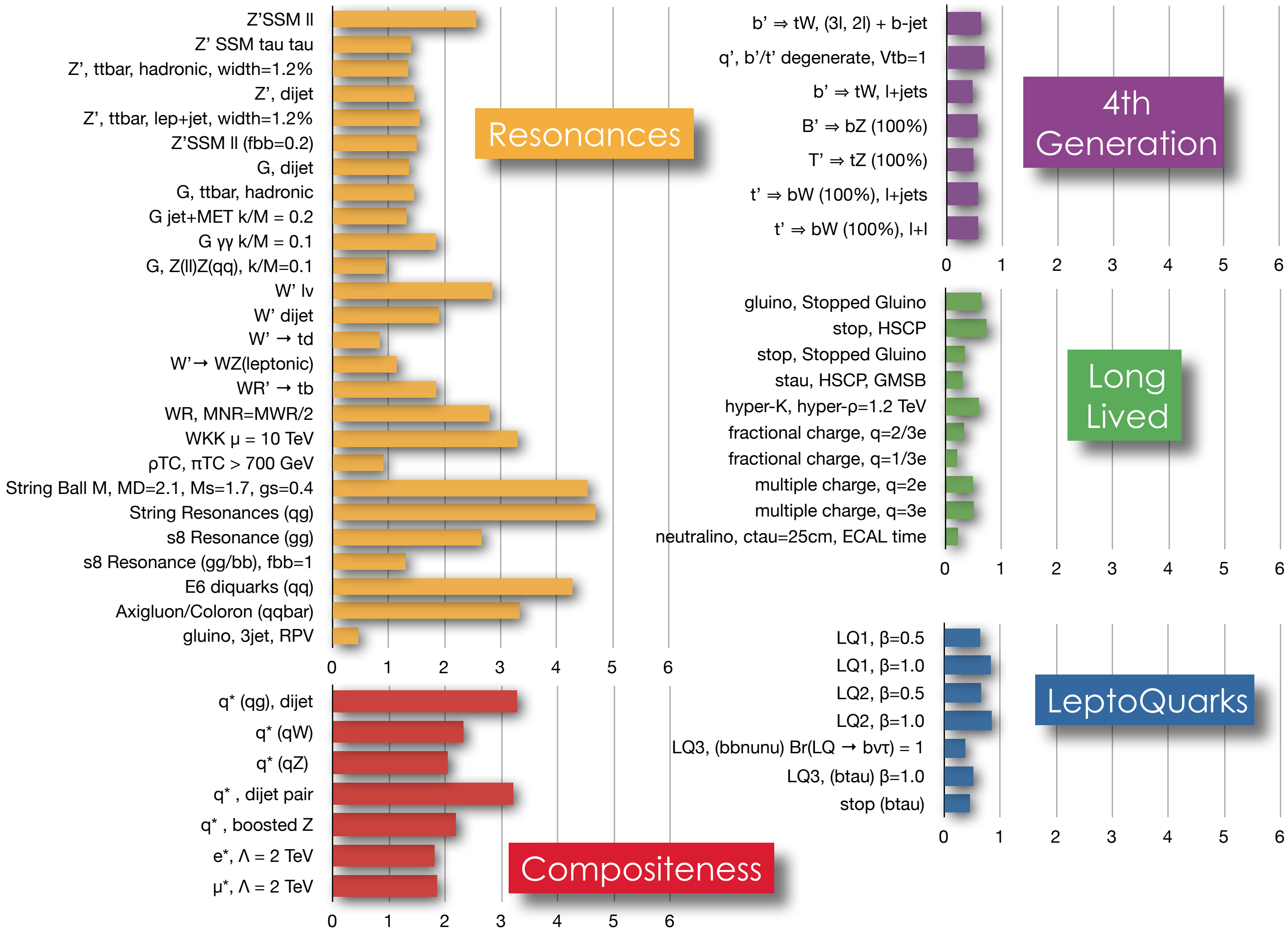
- Can exclude direct stop production with masses lower than 600 GeV (with some caveats on neutralino mass, etc)

BSM and Exotica: What is "Exotic"?

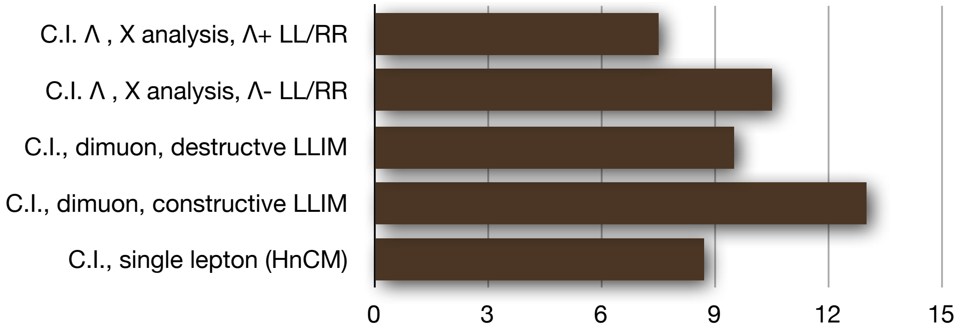
- Comprehensive search of the landscape of $\sqrt{s}$ = 8 TeV proton collisions
  - Unlike Higgs, no "EXO-Hunters Guide" to show you the way
  - no SUSY-like plot of parameter space to map out progress
- Wide variety of search strategies used
  - look for interesting features in the data – new resonant states e.g. Z', W'
  - look at all possible channels for disagreements with expectation – leptons, photons, jets
  - follow-up interesting new BSM models



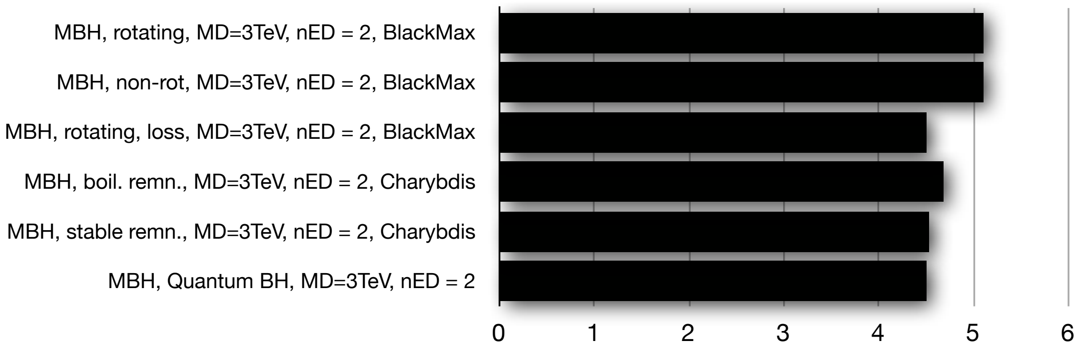
Exotica program even larger than SUSY



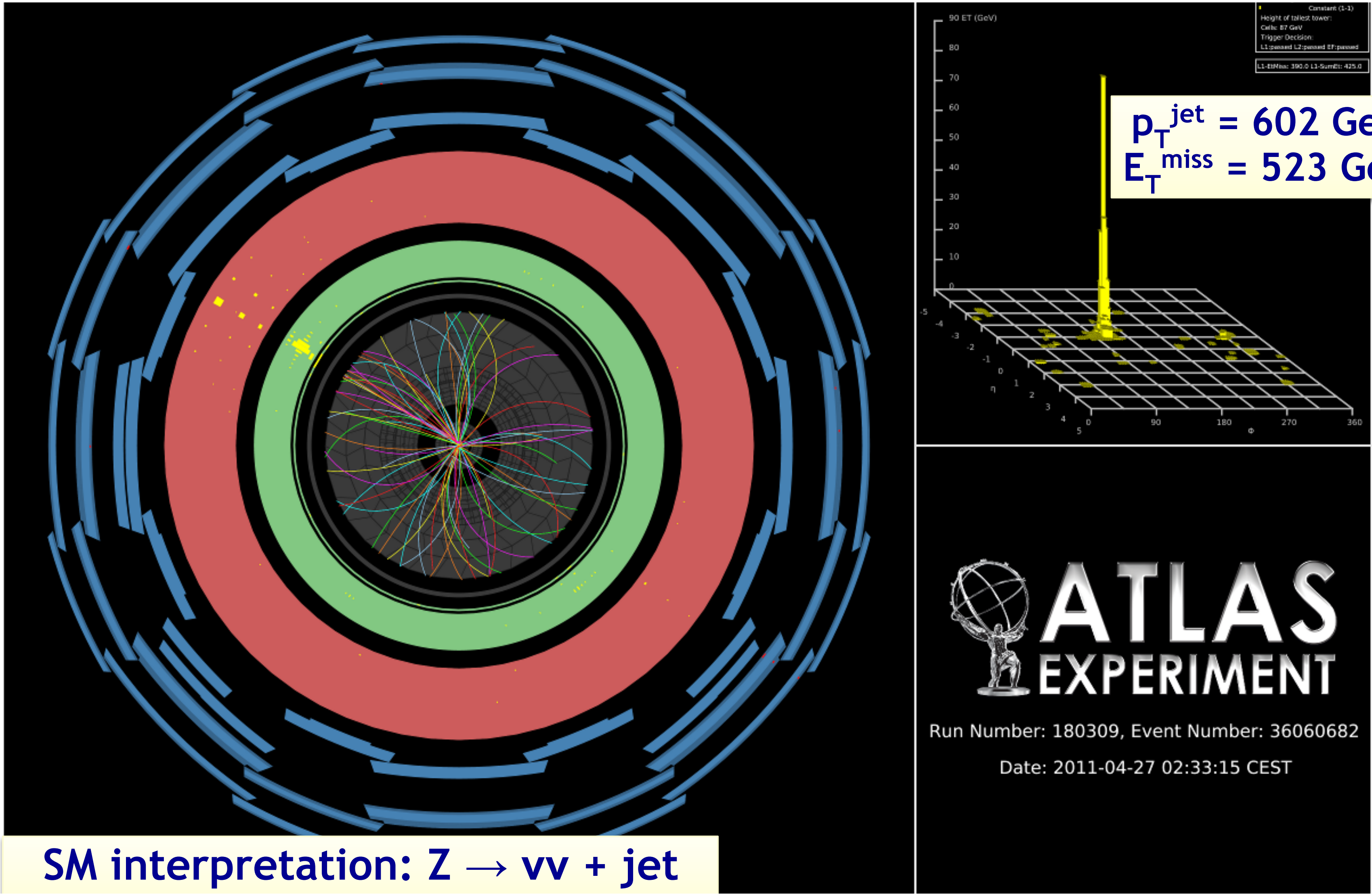
Does not even fit on one page



Contact Interaction



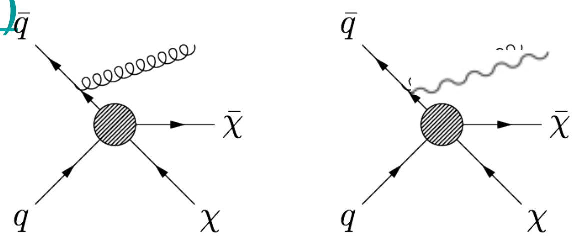
Black Holes



SM interpretation: $Z \rightarrow \nu\nu$ + jet

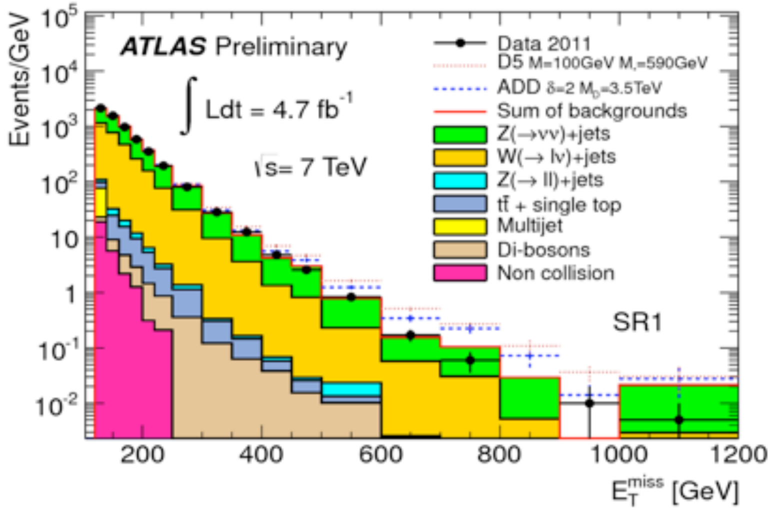
Monojet and Monophoton

- Look for missing energy and radiated jet (photon)

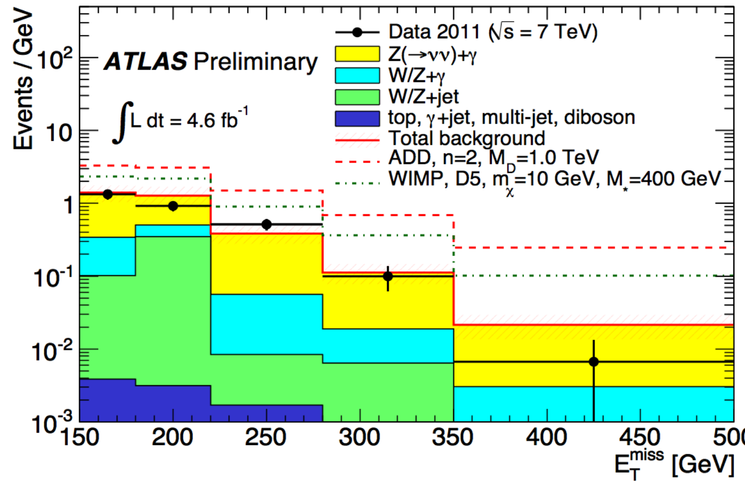


- Monojet Selection:
  - Leading jet p_T > 120 GeV, $|\eta|$ < 2
  - allow a second jet if not back-to-back
  - veto isolated leptons
- Backgrounds and Uncertainties
  - Z + (jets/γ) --> $\nu\nu$+(jets/γ)
  - W + (jets/γ) --> $l\nu$+(jets/γ)
  - smaller backgrounds from top, QCD, non-collision
- Missing Energy (E_T^{miss}) to distinguish signal

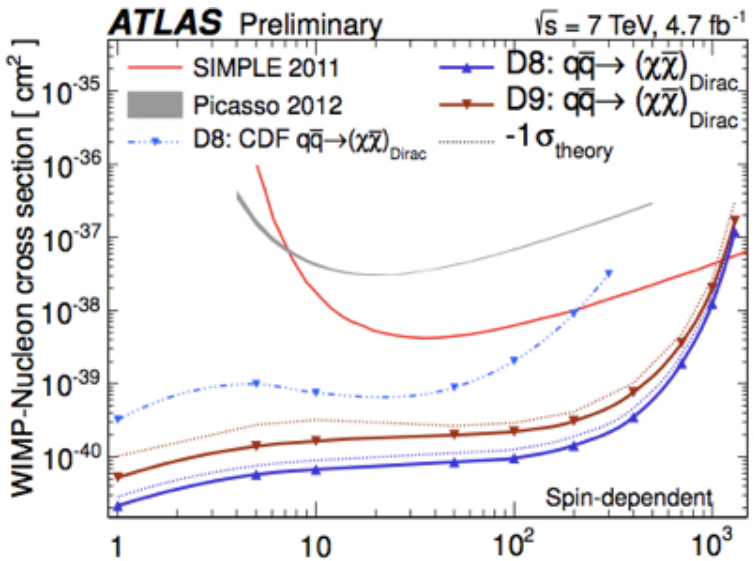
monojet



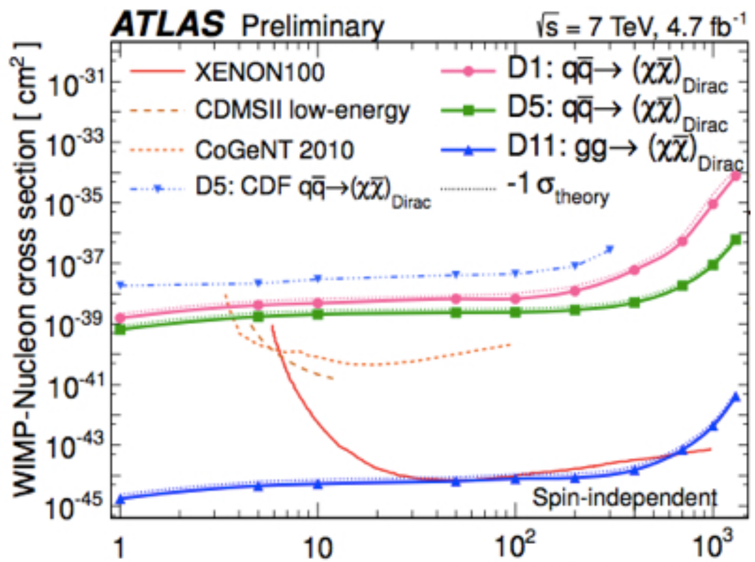
monophoton



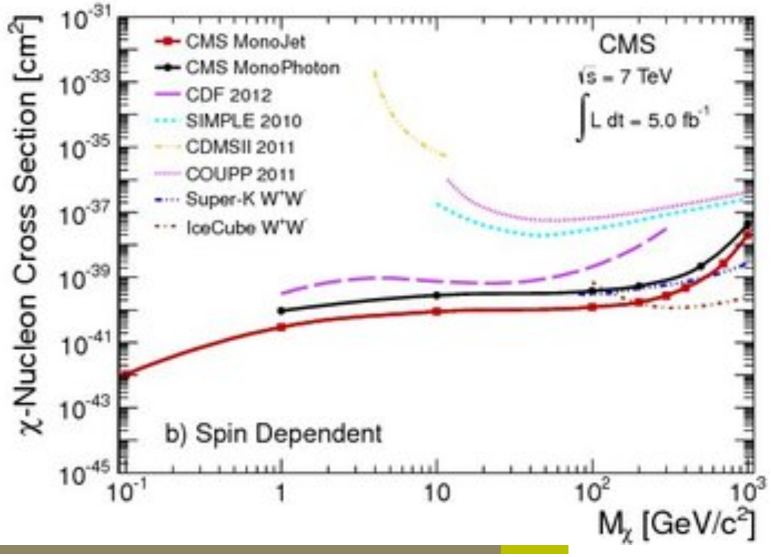
Dark Matter and Monojets

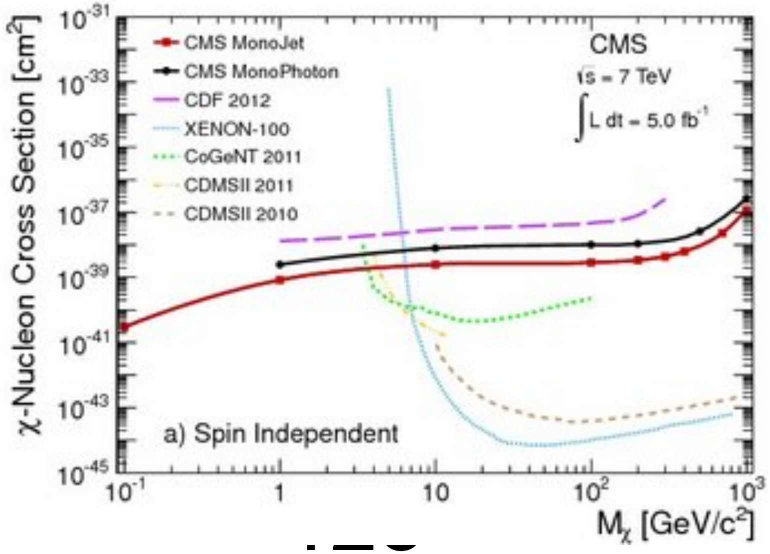


Spin-dependent



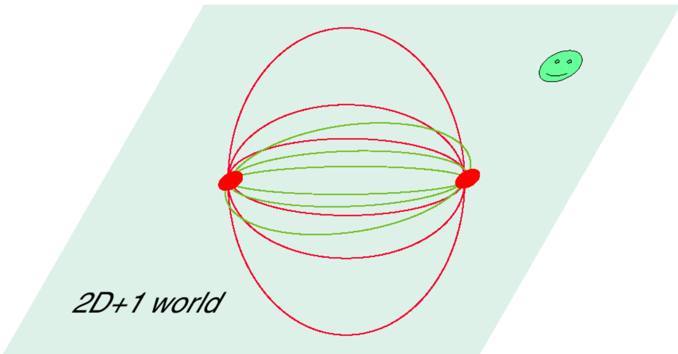
Spin-independent



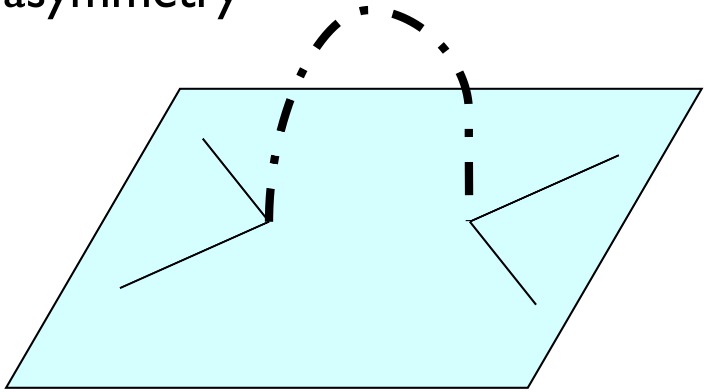


Forces and number of dimensions

- Number (D) of space-time dimensions affects power law behaviour of forces
  - Electromagnetism example
  - $F \sim 1/r^2$ in D=3+1
  - In D=2+1 EM is $F \sim 1/r$



- Same thing holds for resonances
  - Remember Z' predicted in ttbar spectrum as a consequence of Tevatron A_{fb} asymmetry



- Would create extra contributions at certain masses → Z' / W'
  - Peaks in di-particle spectrum

Bump Hunting

Table 2: Summary for resonant particle names, their quantum numbers, and possible underlying models.

Particle Names (leading coupling)	J	$SU(3)_C$	$\lvert Q_e \rvert$	B	Related models
$E^{\mu}_{3,6}$ (uu)	0, 1	$\mathbf{3}$, $\overline{\mathbf{6}}$	$\frac{4}{3}$	$-\frac{2}{3}$	scalar/vector diquarks
$D^{\mu}_{3,6}$ (ud)	0, 1	$\mathbf{3}$, $\overline{\mathbf{6}}$	$\frac{1}{3}$	$-\frac{2}{3}$	scalar/vector diquarks; $\tilde{d}$
$U^{\mu}_{3,6}$ (dd)	0, 1	$\mathbf{3}$, $\overline{\mathbf{6}}$	$\frac{2}{3}$	$-\frac{2}{3}$	scalar/vector diquarks; $\tilde{u}$
$u^{*}_{3,6}$ (ug)	$\frac{1}{2}$, $\frac{3}{2}$	$\mathbf{3}$, $\overline{\mathbf{6}}$	$\frac{2}{3}$	$\frac{1}{3}$	excited u; quixes; stringy
$d^{*}_{3,6}$ (dg)	$\frac{1}{2}$, $\frac{3}{2}$	$\mathbf{3}$, $\overline{\mathbf{6}}$	$\frac{1}{3}$	$\frac{1}{3}$	excited d; quixes; stringy
S_8 (gg)	0	$\mathbf{8}_S$	0	0	π_{TC}, η_{TC}
T_8 (gg)	2	$\mathbf{8}_S$	0	0	stringy
V^{0}_{8} $(u\bar{u},\ d\bar{d})$	1	$\mathbf{8}$	0	0	axigluon; g_{KK}, ρ_{TC}; coloron
$V^{\pm}_{8}$ $(u\bar{d})$	1	$\mathbf{8}$	1	0	$\rho^{\pm}_{TC}$; coloron

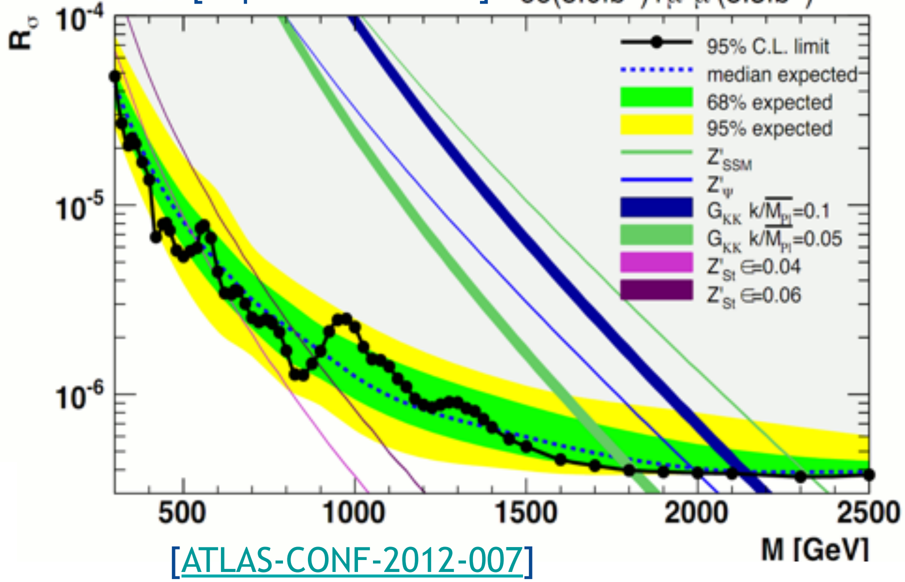
Han, Lewis & Liu

Z’ in 2011 CMS Data? – a lesson in caution

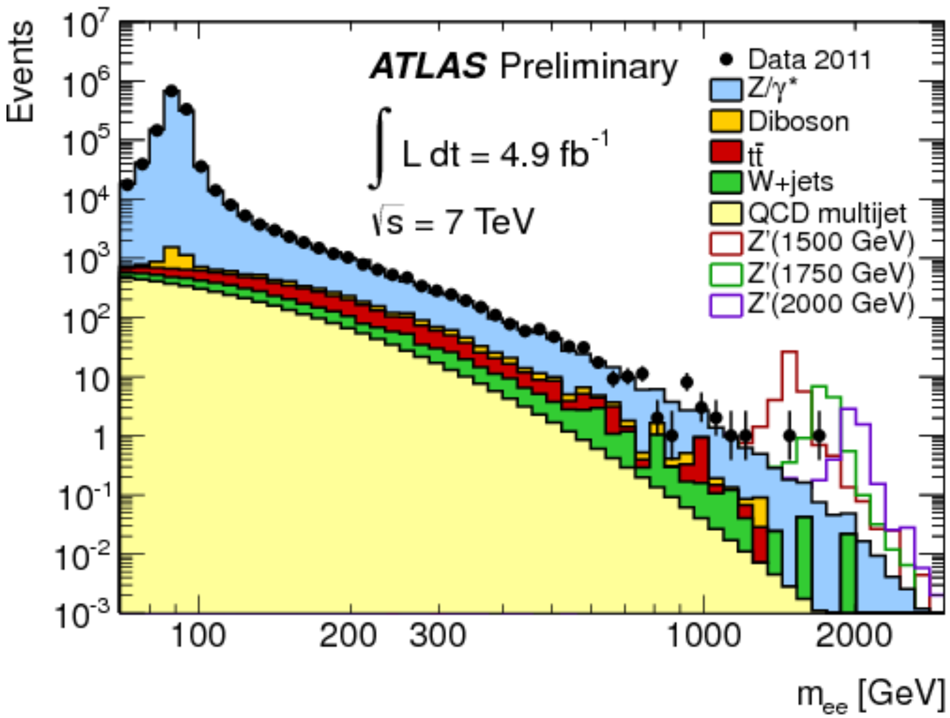
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

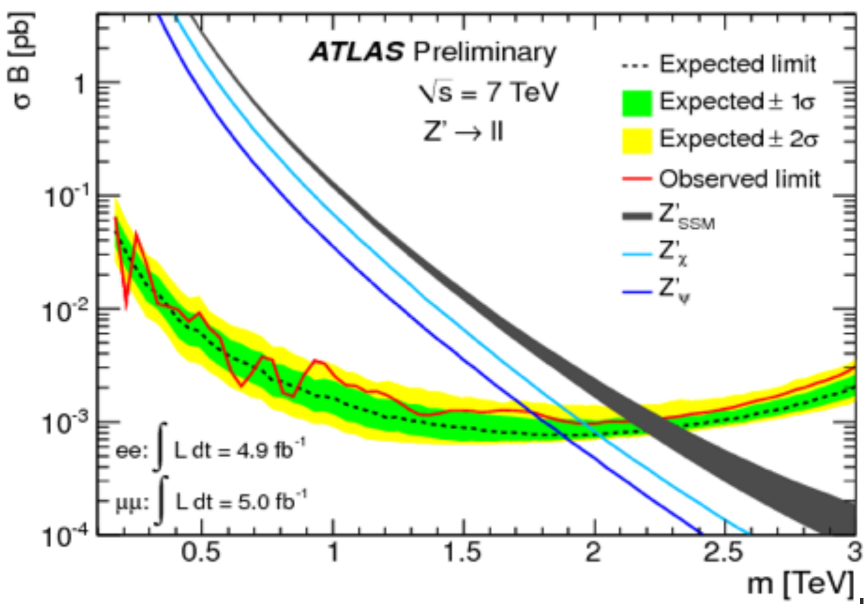
Worth watching in 2012’s 8 TeV data...

[hep-ex 1206.1849]

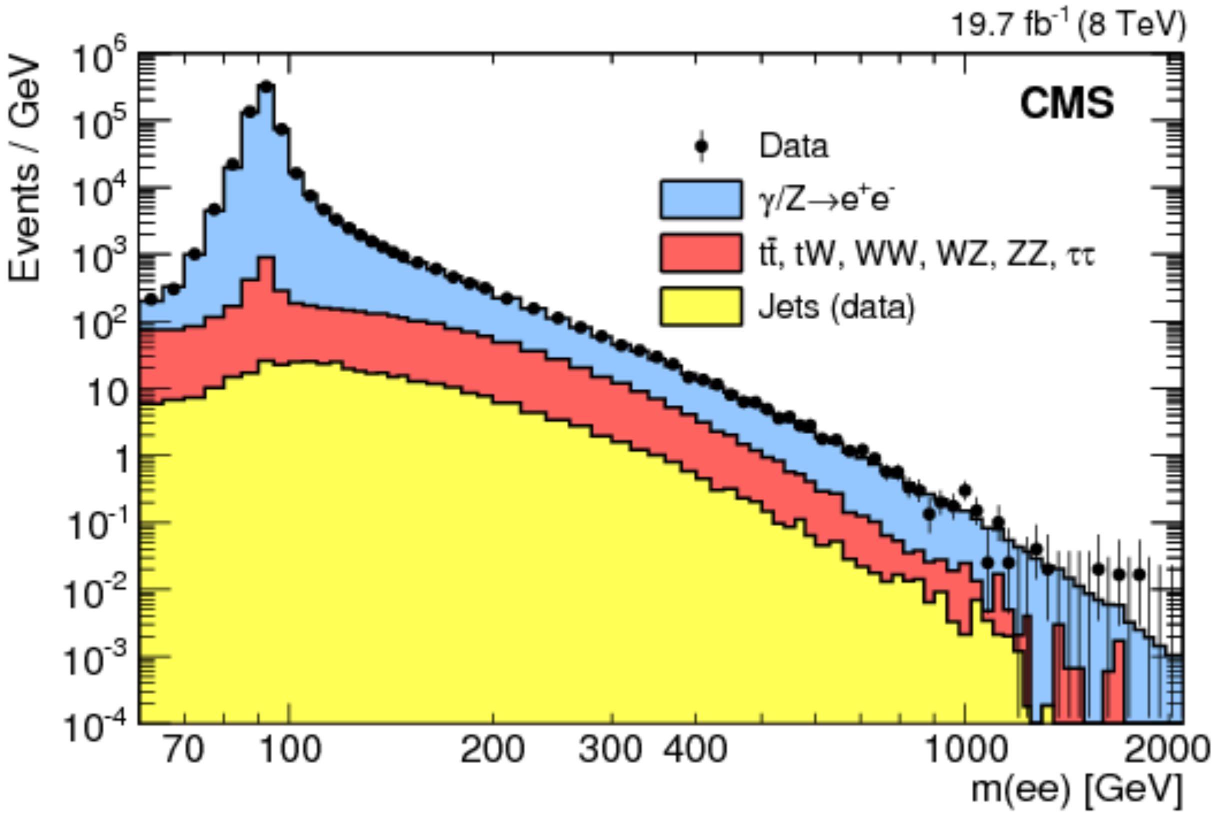


[ATLAS-CONF-2012-007]

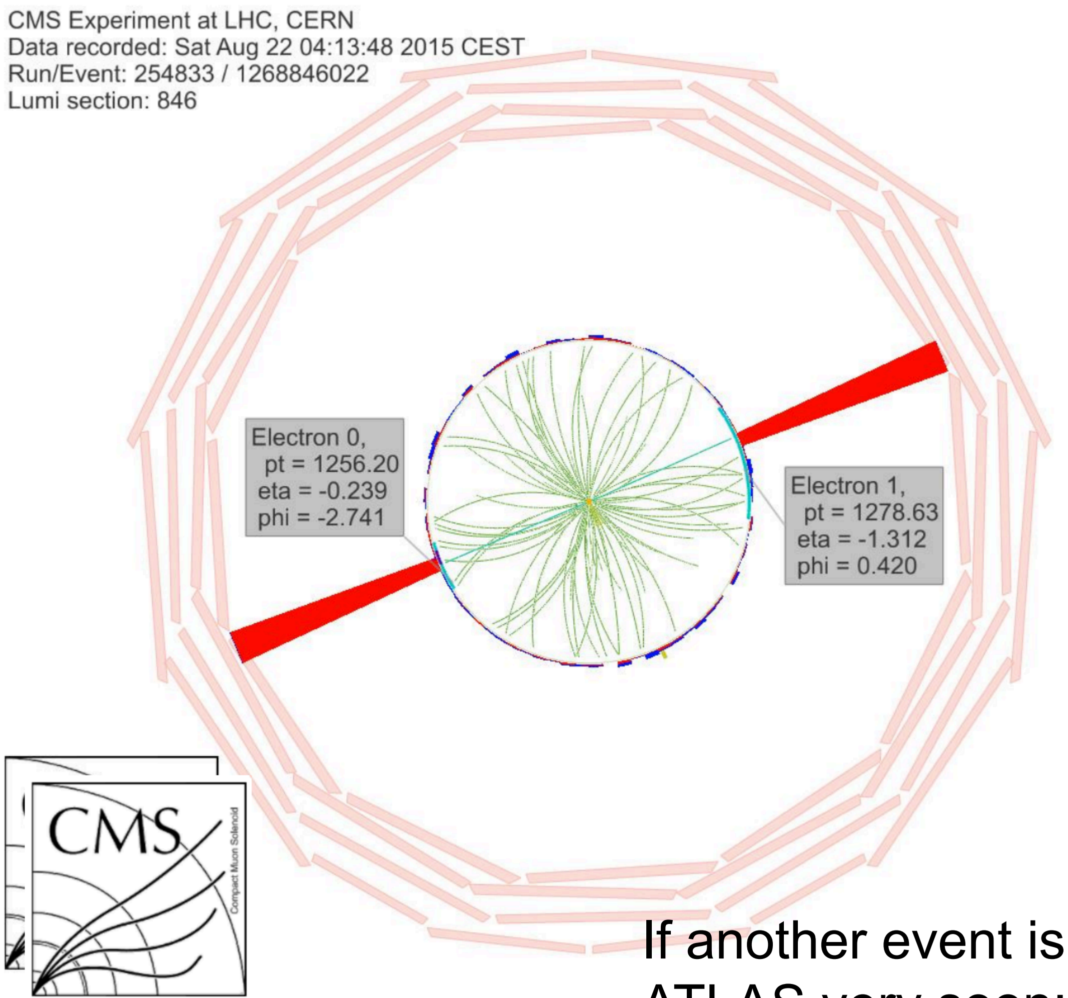




Nothing there…

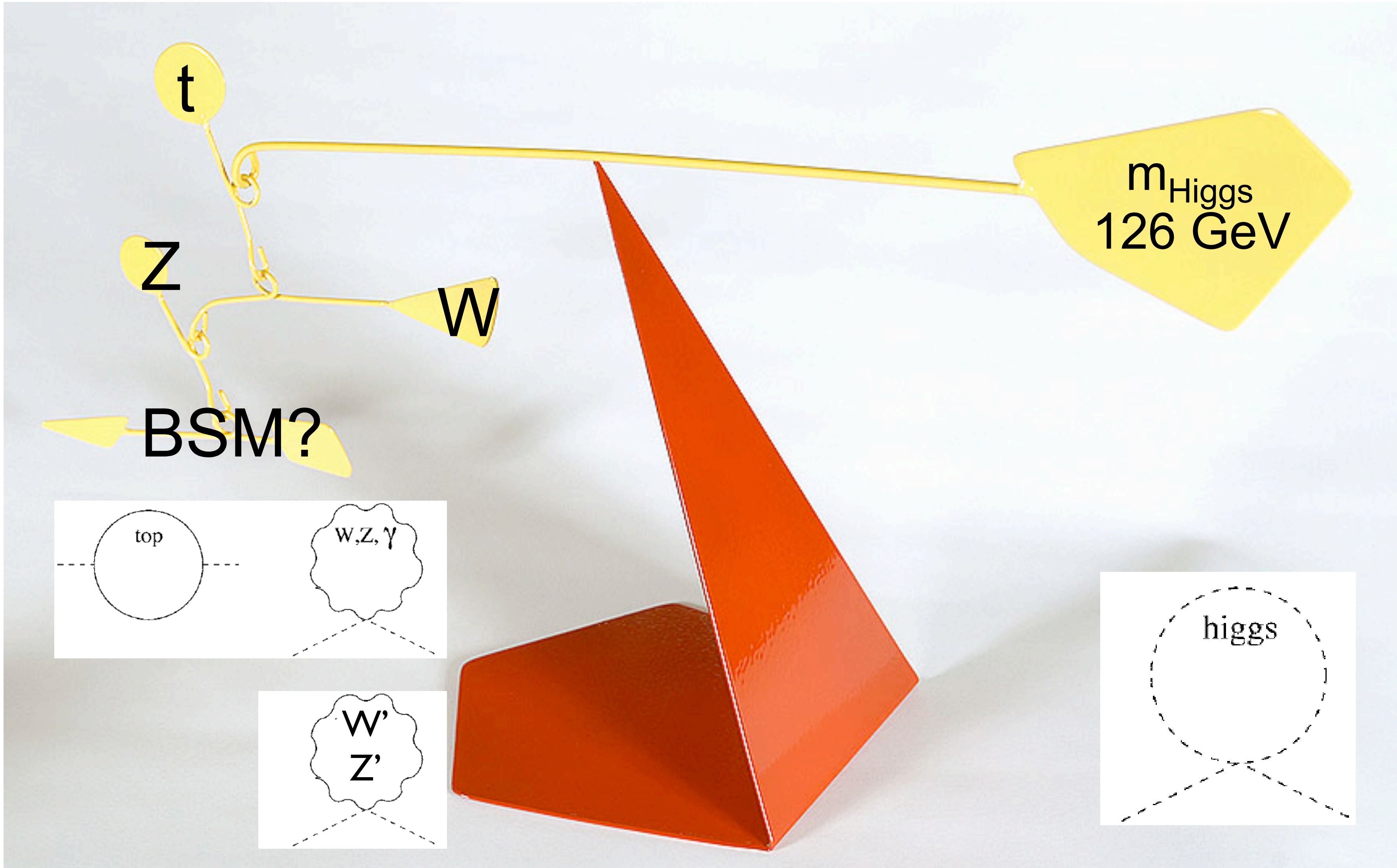


And in 2015?

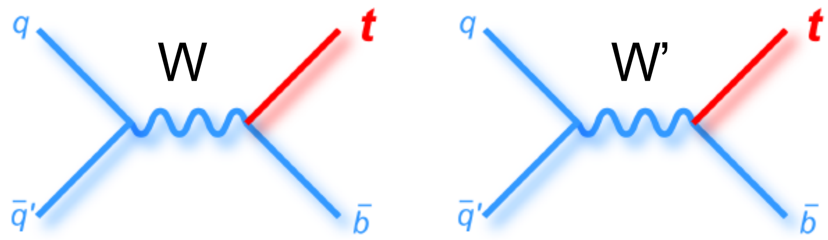


If another event is spotted in CMS or ATLAS very soon: expect some (possibly too early) excitement!

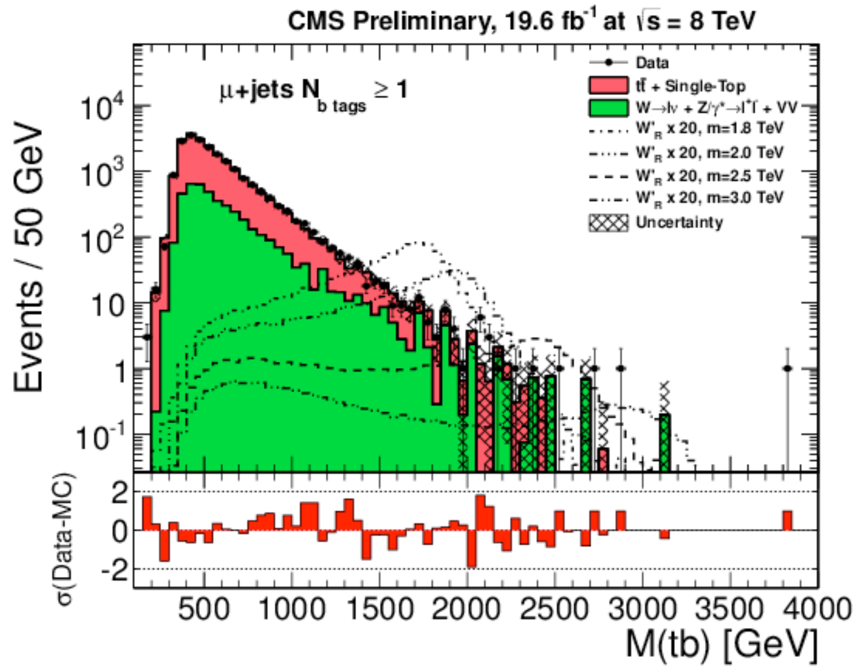
Little Hierarchy problem, Naturalness



W' to tb



- analogue to single top s-channel production
- Leptonic top decay:
  - Final state of lepton+MET+2 b jets
- Mass reconstruction also used in SM top physics, using W boson mass to constrain MET
  - With additional top mass constraint

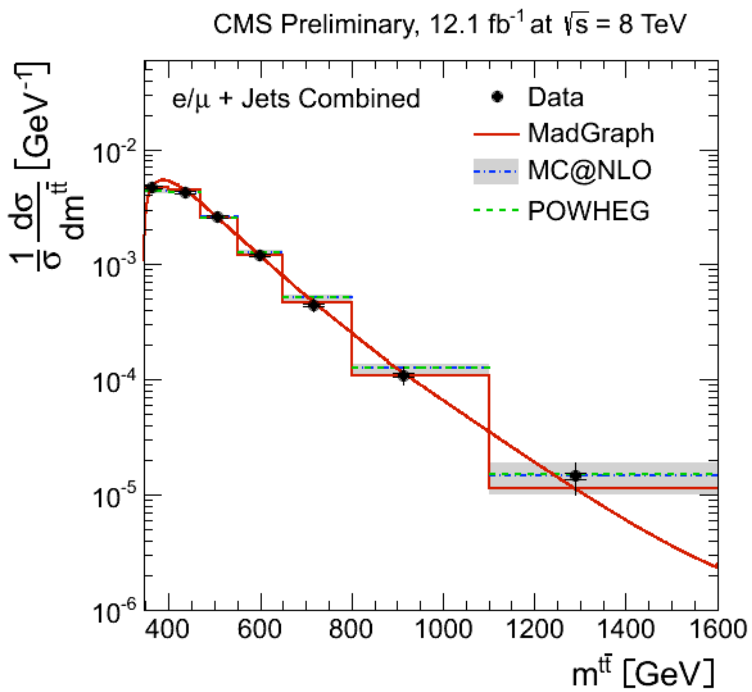


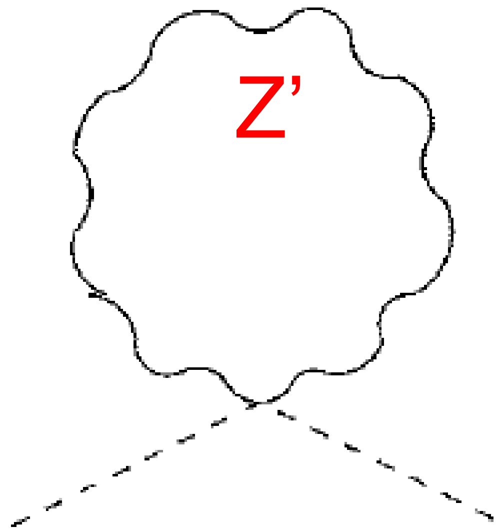
- Interpret in left and right handed W' scenarios

src: B2G-12-010 PAS

Investigating ttbar invariant mass distribution

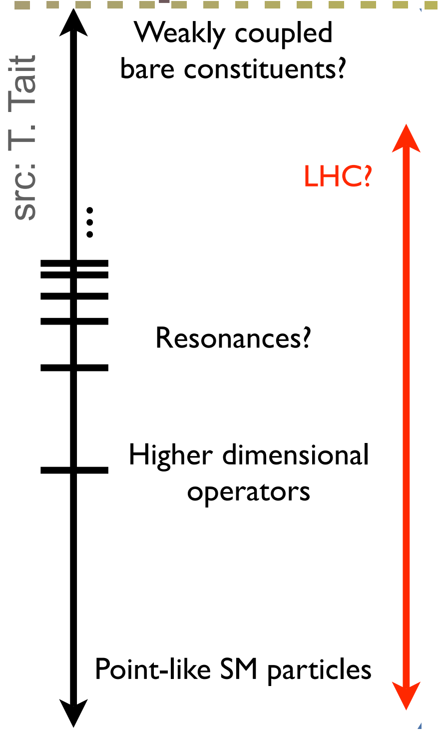
- Differential cross sections now available for 8 TeV sub-set
- Searches in tails of distributions ongoing for 8 TeV full sample

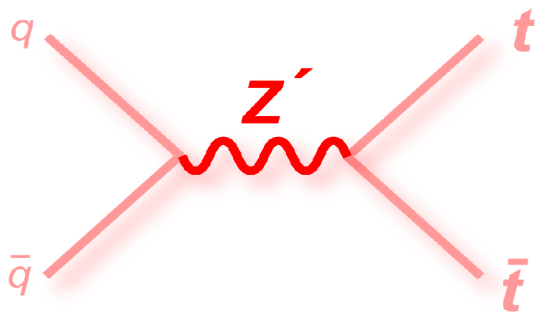




- Z' scenarios interwoven with natural EXO solutions and A_{FB}-explaining models
- M_{ttbar} distribution sensitive to many new physics scenarios

Top resonaces physics motivation

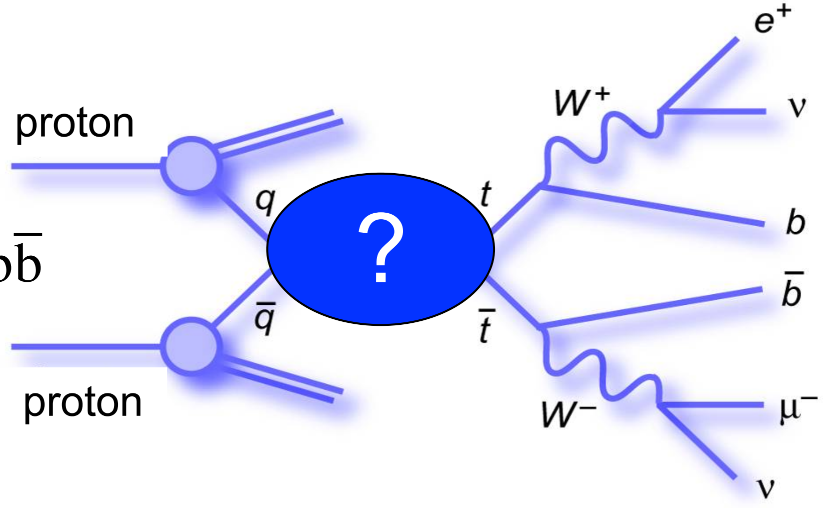




- Many new physics models predict extra exchange of massive particles in top quark production
  - Would be observed in a peaked or general excess/dip in the top-antitop invariant mass spectrum
  - Substantial number of theoretical models
  - Z', colorons, axigluons, Randall-Sundrum/ADD gravitons, Pseudo-scalar Higgs to ttbar
    - And many more
- Searches presented can be interpreted in any of these
  - For general comparison, "Topcolor-assisted technicolor" model: hep-ph/991.1288: Hill, Parke, Harris

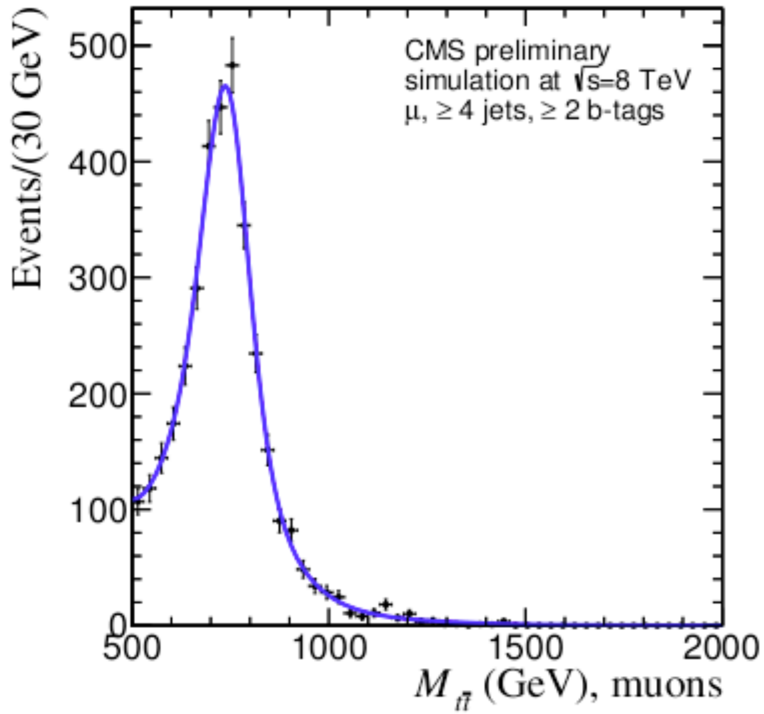
analysis strategy

- Searches in all available top decay channels
  - Dileptons $t\bar{t} \rightarrow \ell^- \ell^+ \nu \bar{\nu} b \bar{b}$
  - Semileptonic ≡ lepton+jets $t\bar{t} \rightarrow \ell \nu q \bar{q} b \bar{b}$
  - Hadronic ≡ alljets $t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$
- And in different regimes
  - Close to 2x(top mass) threshold
    - Sensitive to shape of SM M(ttbar) distribution
    - Conventional top physics techniques may be used
  - More boosted
    - Sensitive to more massive M(ttbar) BSM physics
    - Dedicated reconstruction techniques may be necessary



Semileptonic, threshold

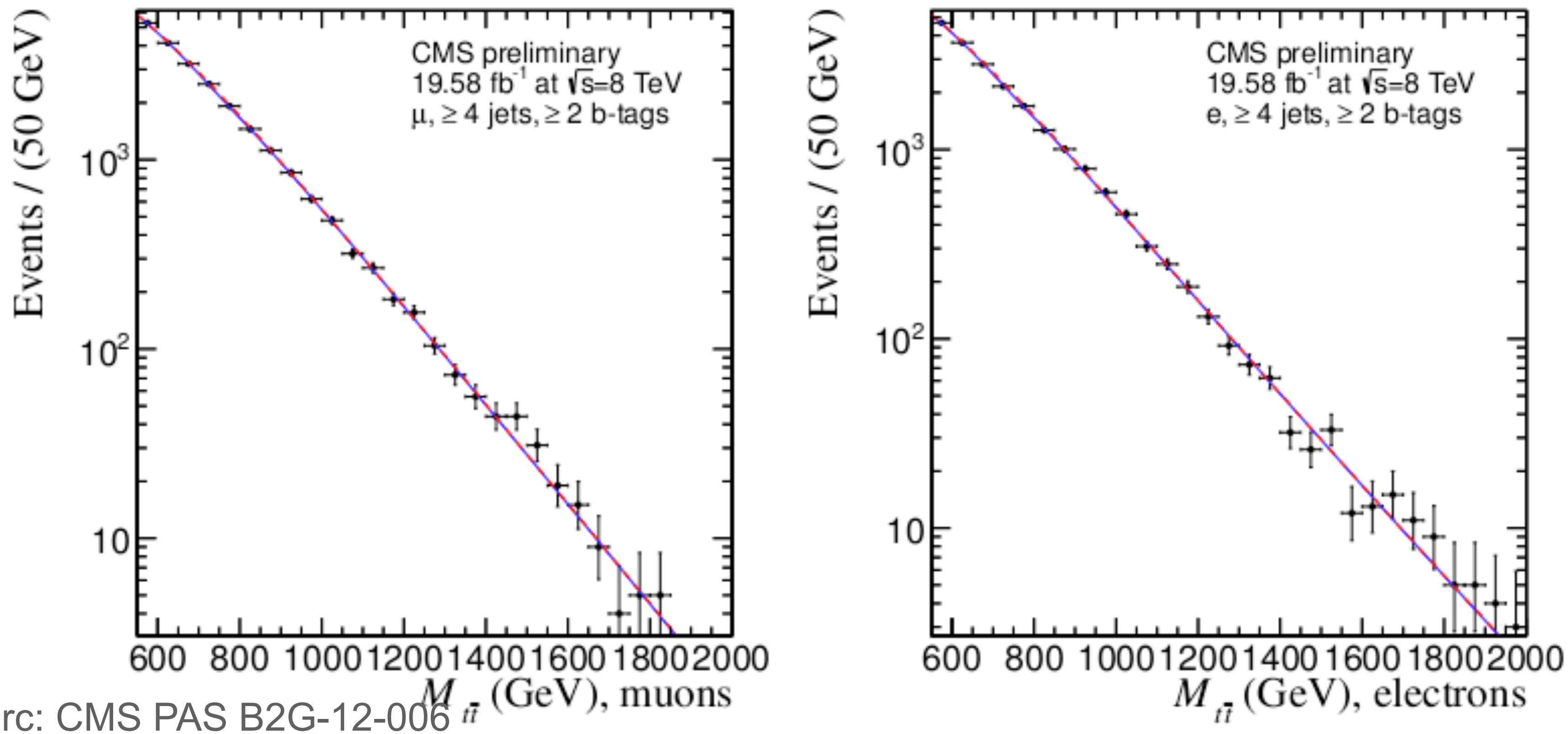
- Require only one lepton, >= 4 jets and split in b-tag multiplicity
- χ^2 sorting used to select best jet combination
- Using data-driven estimates for falling distribution of top pair mass spectrum above 500 GeV/c^2
- Systematic uncertainties take into account rate and shape changes for signal and background model



src: CMS PAS B2G-12-006

Semileptonic, threshold

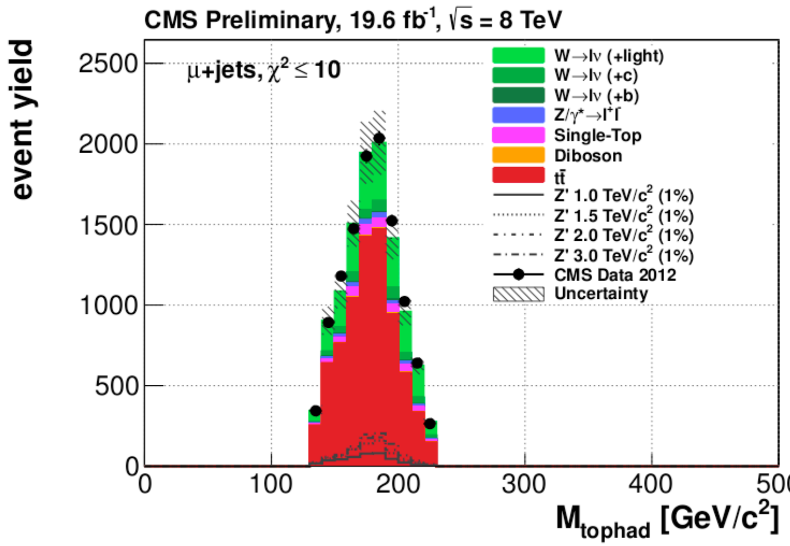
- Fit to falling distribution in electron/muon final states used to set limits (1 and ≥2 b-tag regions fit simultaneously)
  - **Fully data-driven method, only makes assumptions on resonant shape of signal**

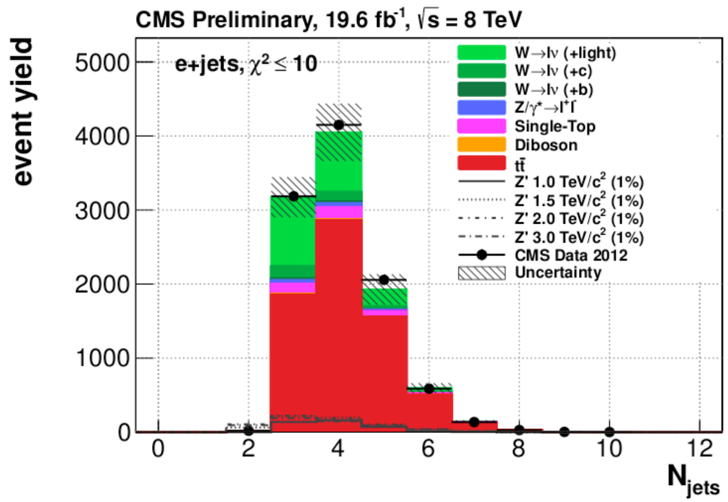


src: CMS PAS B2G-12-006

Semileptonic, non-isolated

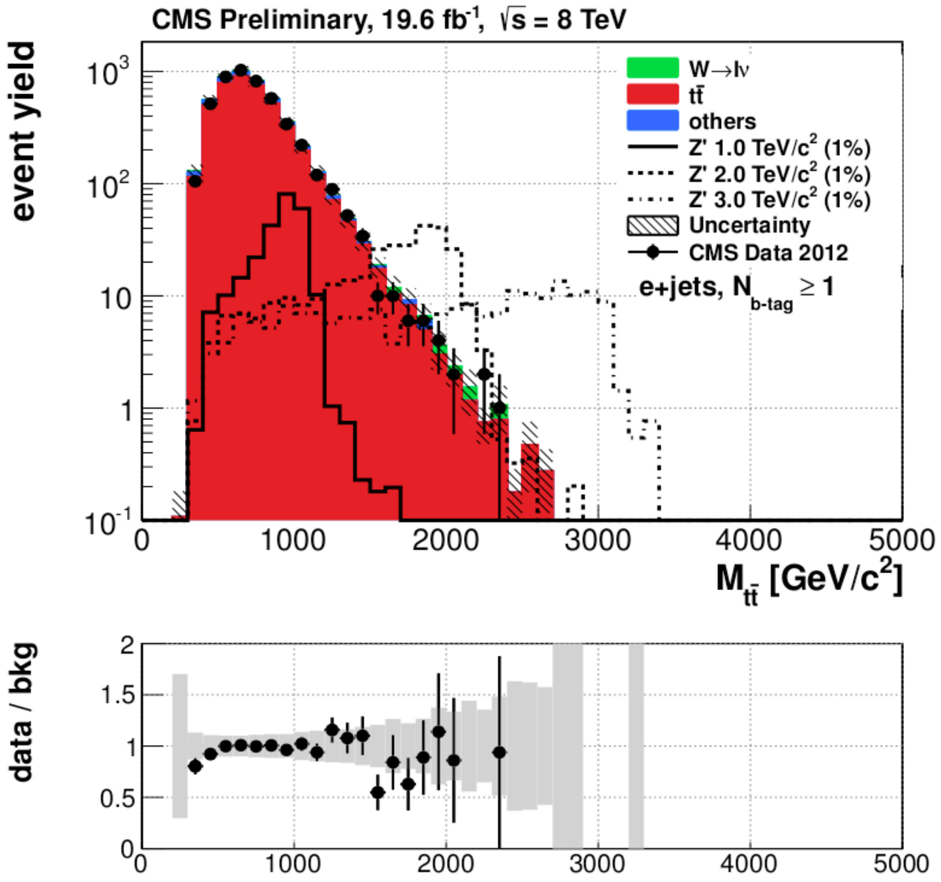
- Alternate analysis: Loosened lepton isolation criteria allow jet/lepton overlap
- Focus on mass tail: require harder cuts on leptons and jets
- Only at least 2 jets+lepton required
- χ^2 sorting used to select best jet combination
- Simultaneous template fit to M(ttbar) in different b-tag multiplicities and electron/muon final states used to set limits
- Backgrounds normalized to control region where SM ttbar is dominant





src: CMS PAS B2G-12-006

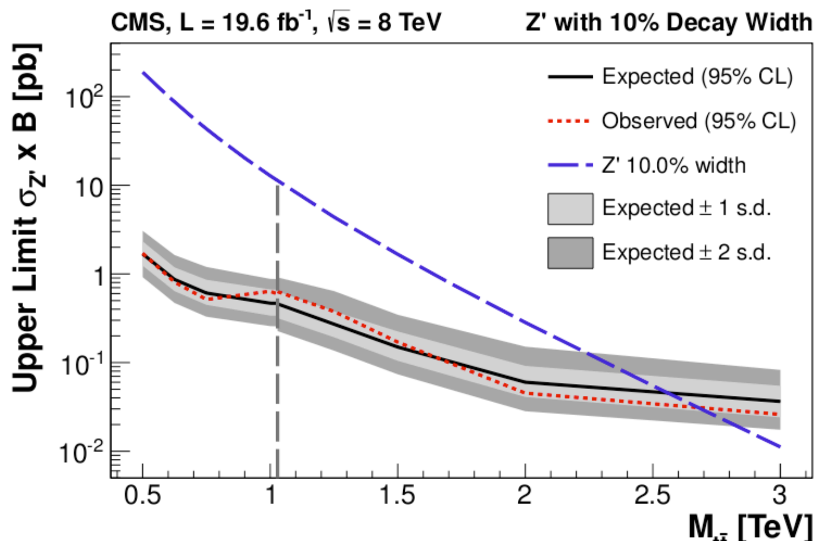
Semileptonic, non-isolated



B2G-13-001, Phys. Rev. Lett. 111, 211804

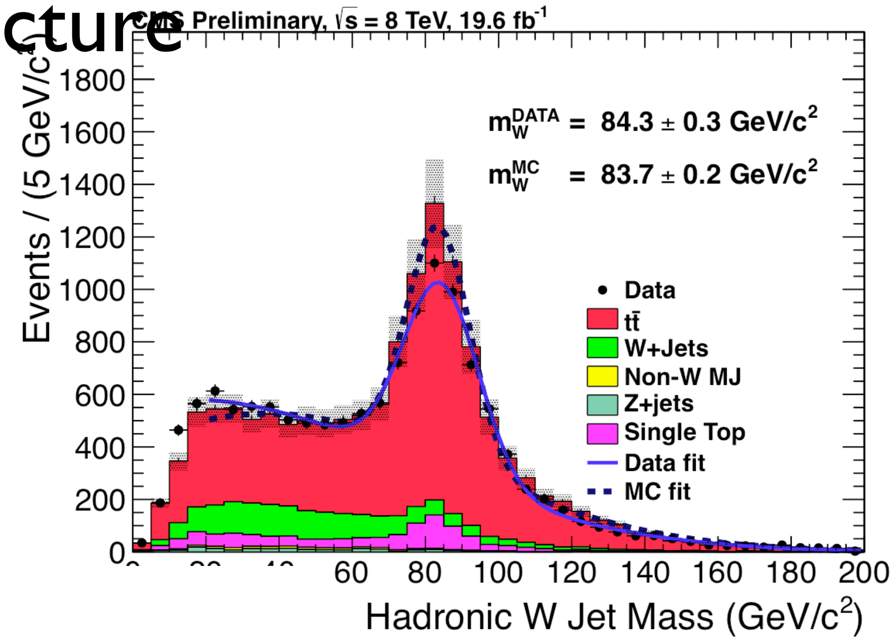
- Multiple scenarios considered
  - Worlds best limit on production of resonant ttbar:
    - Z' (width 1.2%): m > 2.10 TeV
    - Z' (width 10%): m > 2.68 TeV
    - KK gluons: m > 2.69 TeV
    - Resonances in low-mass region:

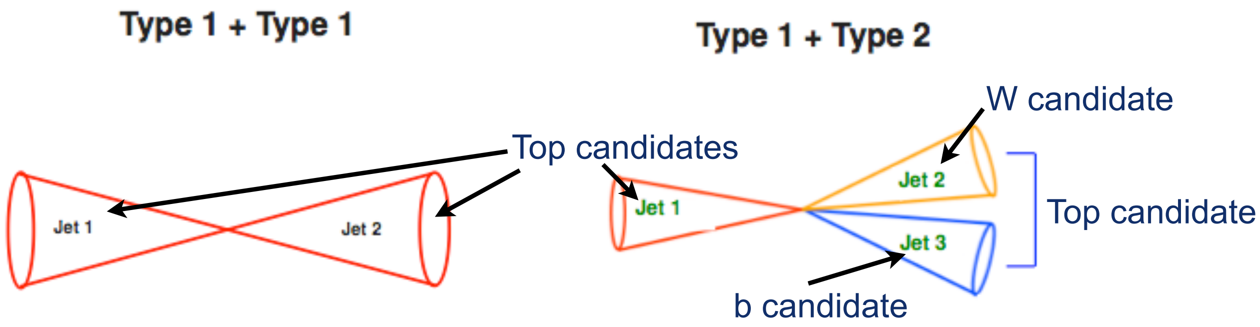
      excluded with xsec > 1-2 pb!!



All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - 'top jets'
  - 'W boson jets'





B2G-13-001, Phys. Rev. Lett. 111, 211804

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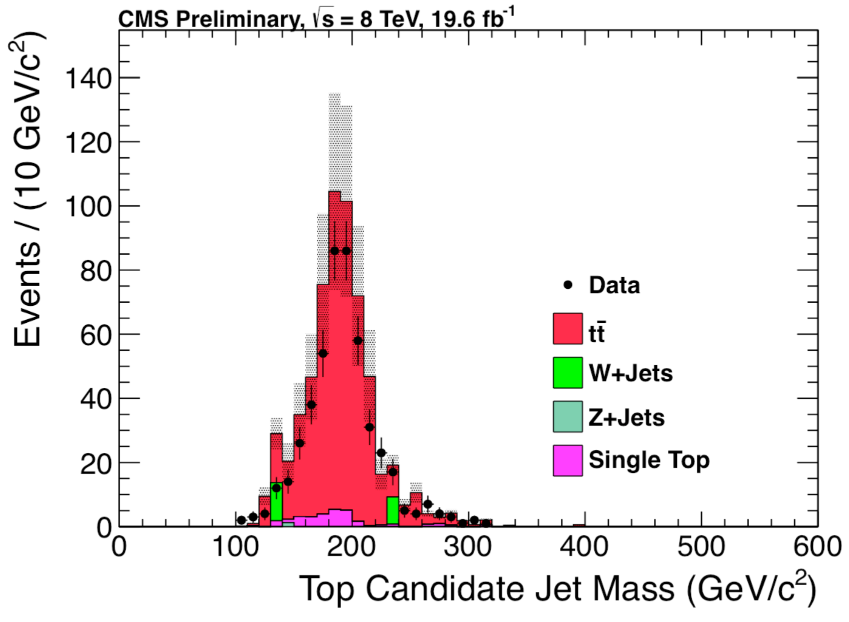
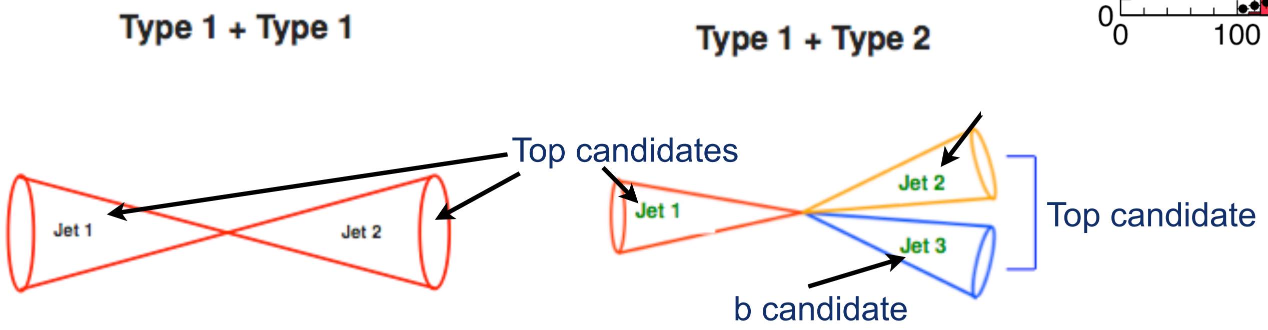
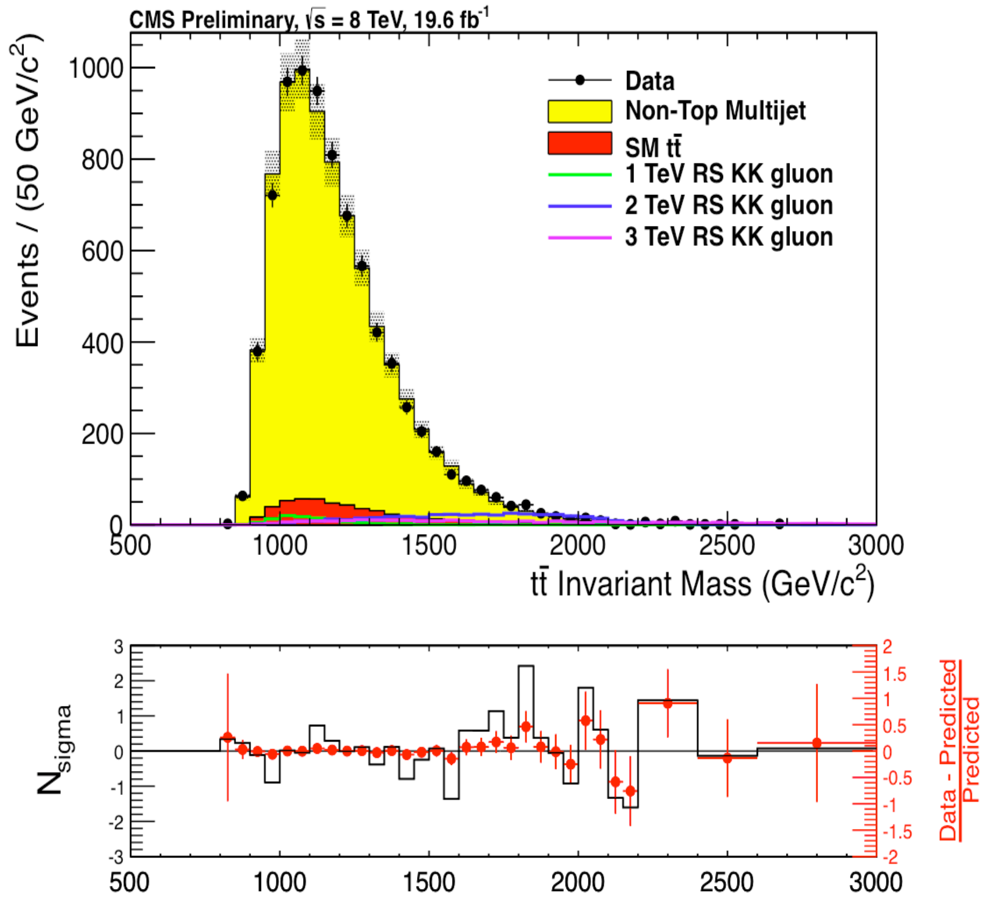




B2G-13-001, Phys. Rev. Lett. 111, 211804

All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits



B2G-13-001, Phys. Rev. Lett. 111, 211804

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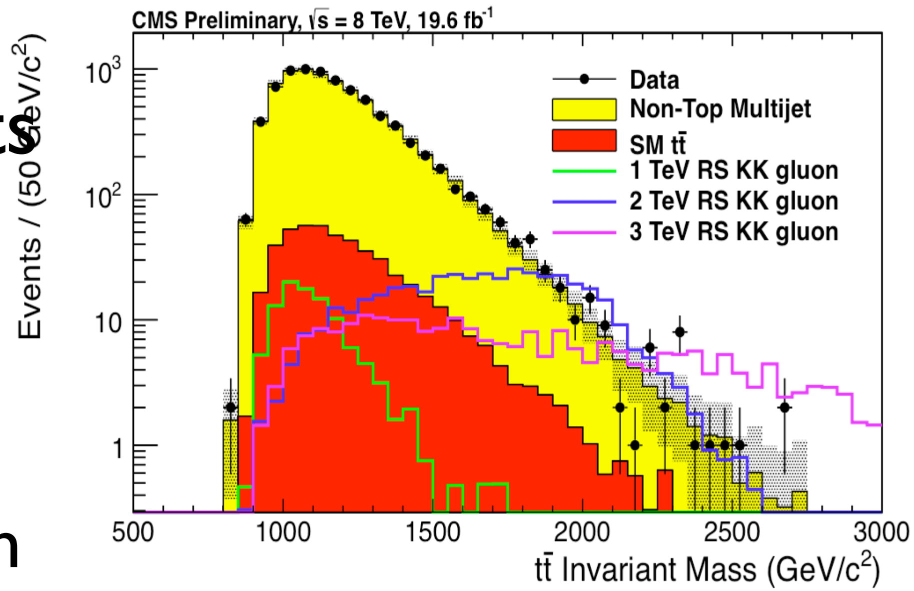
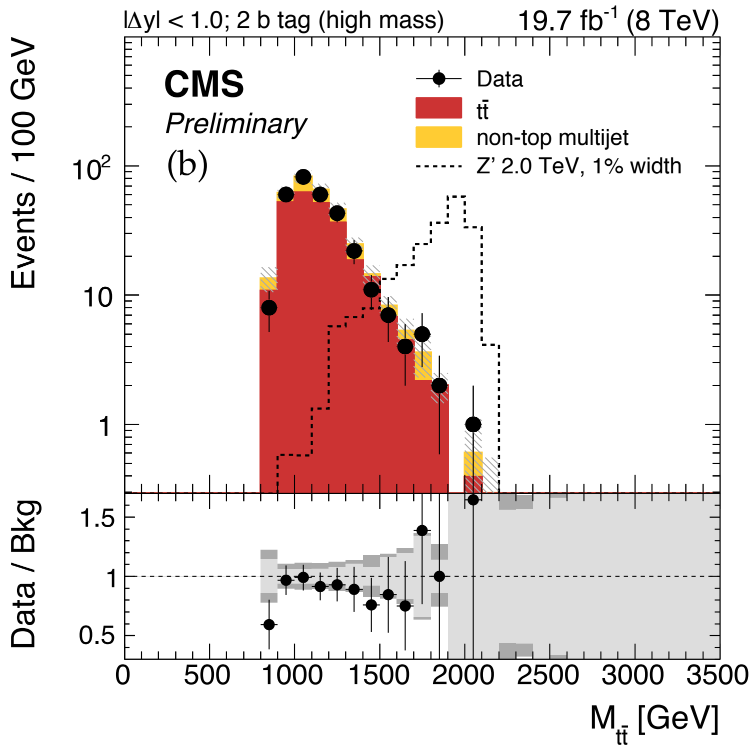


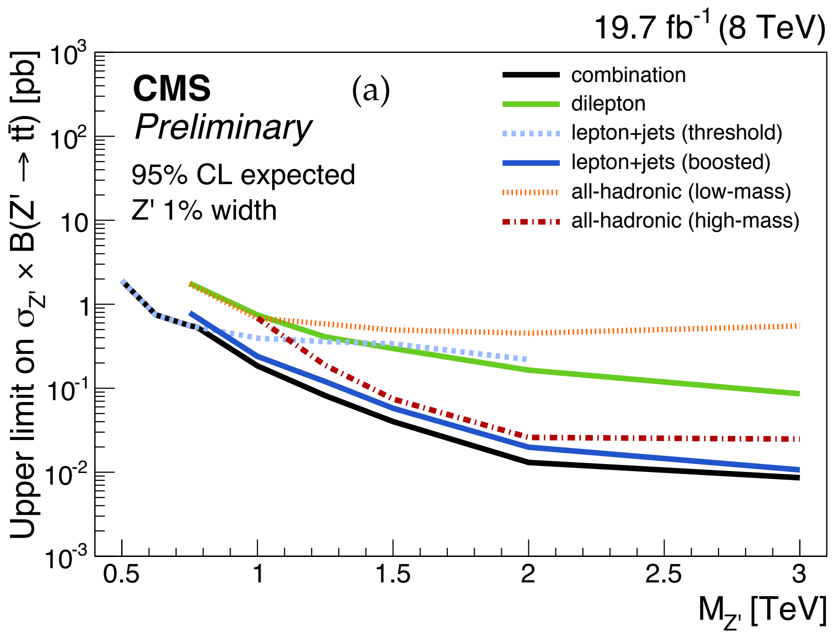
- 95% CL upper limits on increased cross section at high mass:

  $\sigma_{NP+SM} < 1.2\ \sigma_{SM}$ for masses above 1 TeV

B2G-13-001, Phys. Rev. Lett. 111, 211804

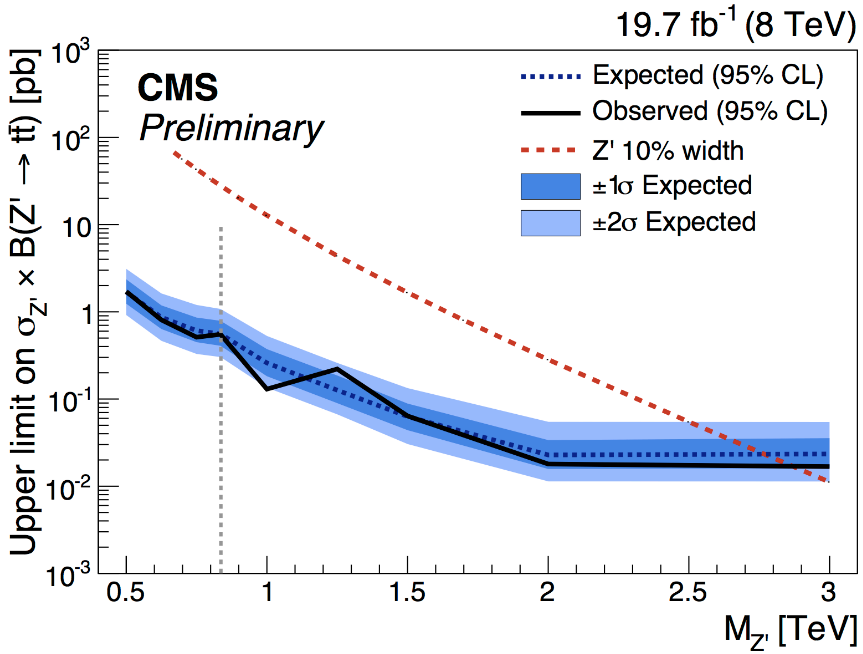
working on reconstruction profits physics

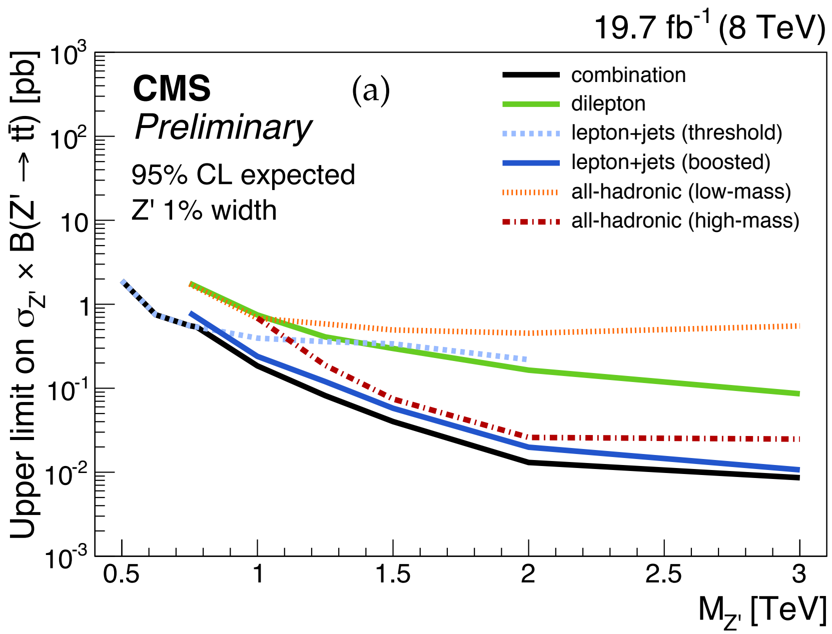




CMS PAS B2G-13-008: Submitted to Phys.Rev.D

working on reconstruction profits physics

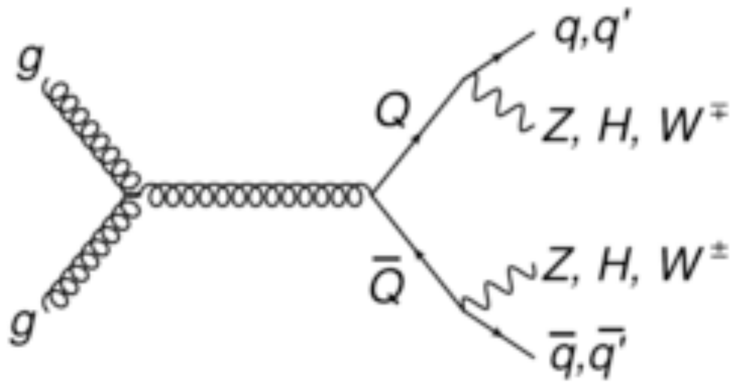




CMS PAS B2G-13-008: Submitted to Phys.Rev.D

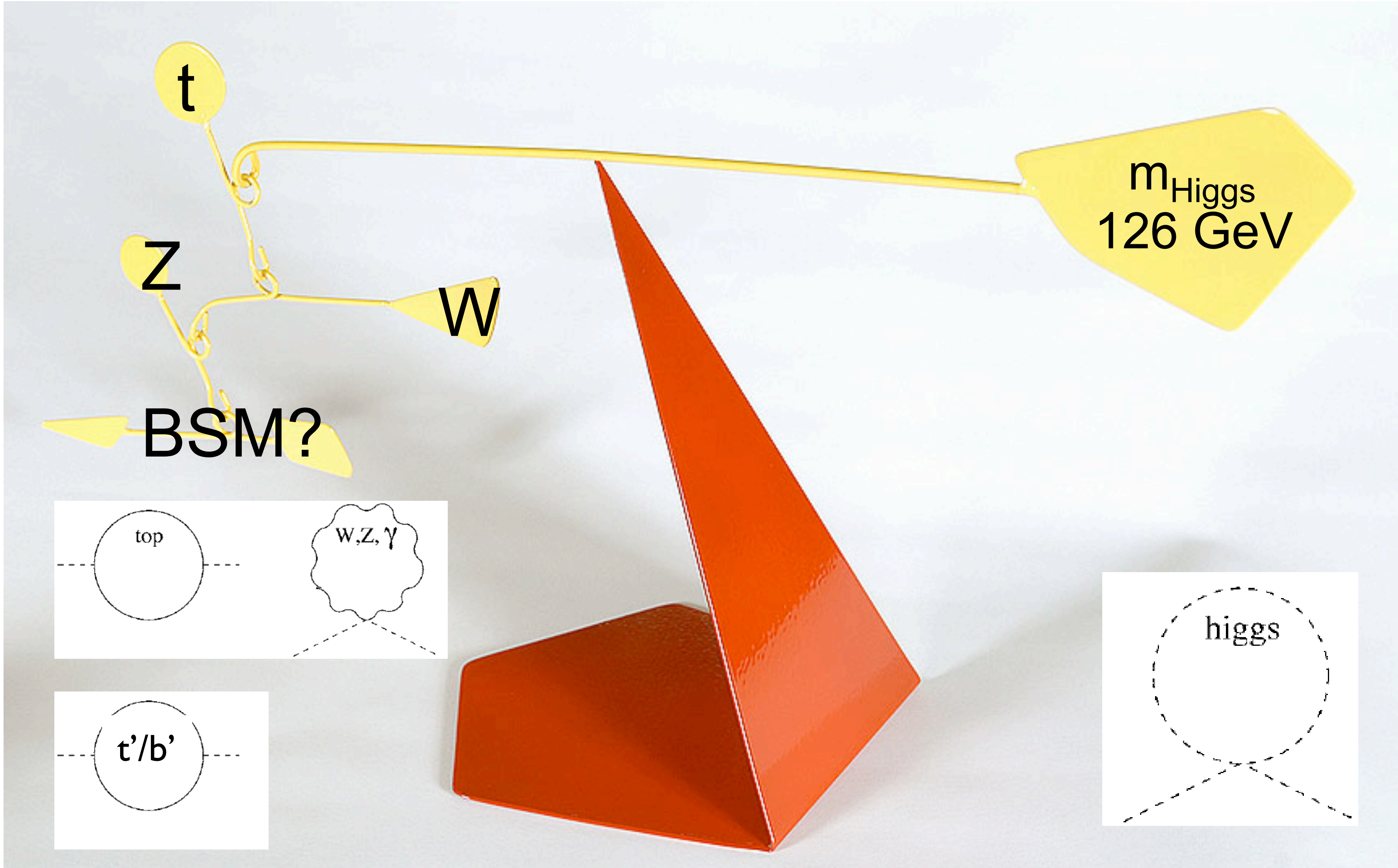
Vector like quarks intro

- Non- SM fourth generation
  - Can enhance CP violation
  - Heavy neutrino as DM candidate
- Vector-like fermions (non-chiral fermions):
  - Typical: exotic 4th generation top/bottom partner
    - 2HDM models
    - Little Higgs models
    - Warped extra dimensions
  - Not excluded by Higgs mass constraints/branching ratios as vector-like quark does not have yukawa coupling
- Models benchmark for new physics decaying top-like:
  - Extremely rich phenomenology with final states with multiple gauge bosons, b and t quarks:



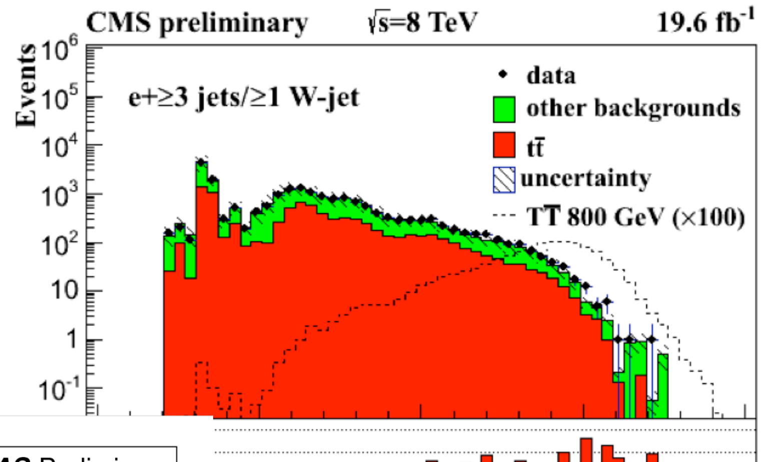
  - Current searches mostly pair production

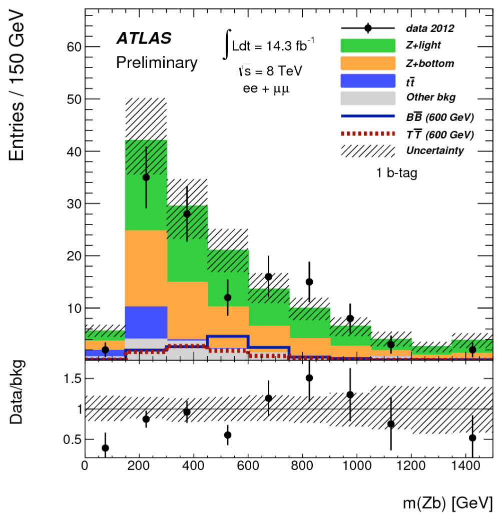
Little Hierarchy problem, Naturalness

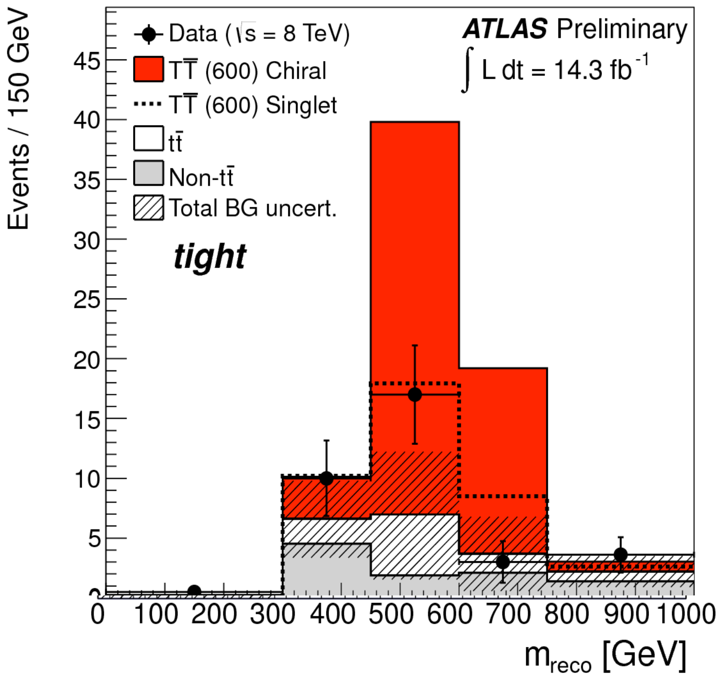


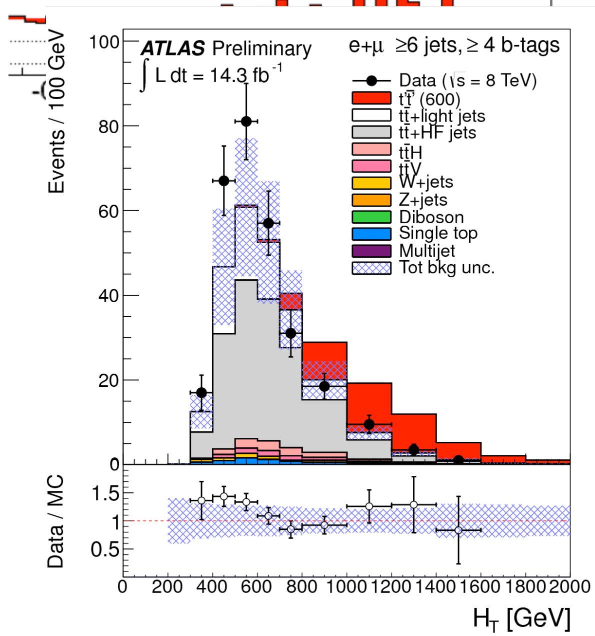
Vector-like quark partners

- CMS: 1,2,3 lepton channels combined
  - 1-lepton top quark partner analysis includes tagging of hadronic W bosons
- ATLAS: 4 separate channels including Z+b, multileptons and T to bW 1-lepton+jets with high b jet multiplicity (incl W tagging)



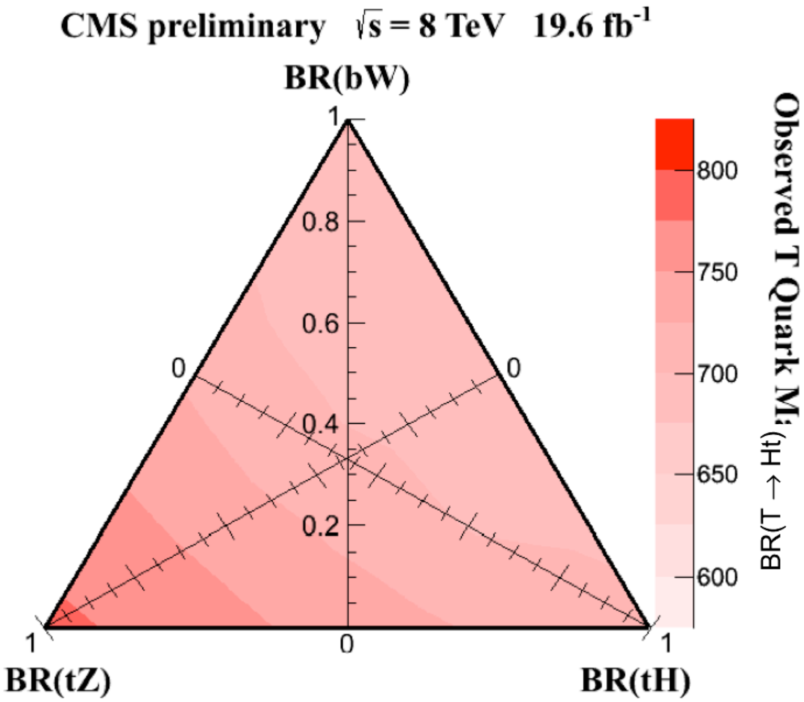




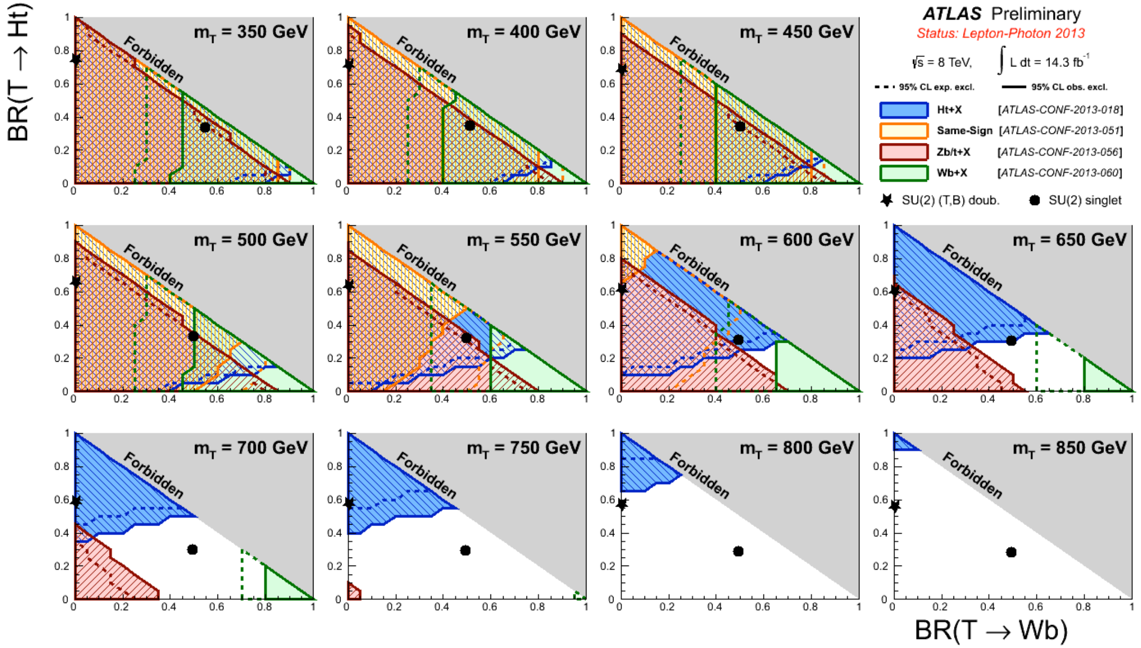


CMS PAS B2G-12-015
ATLAS-CONF-2013-060/018/051/056

Vector-like quark partners



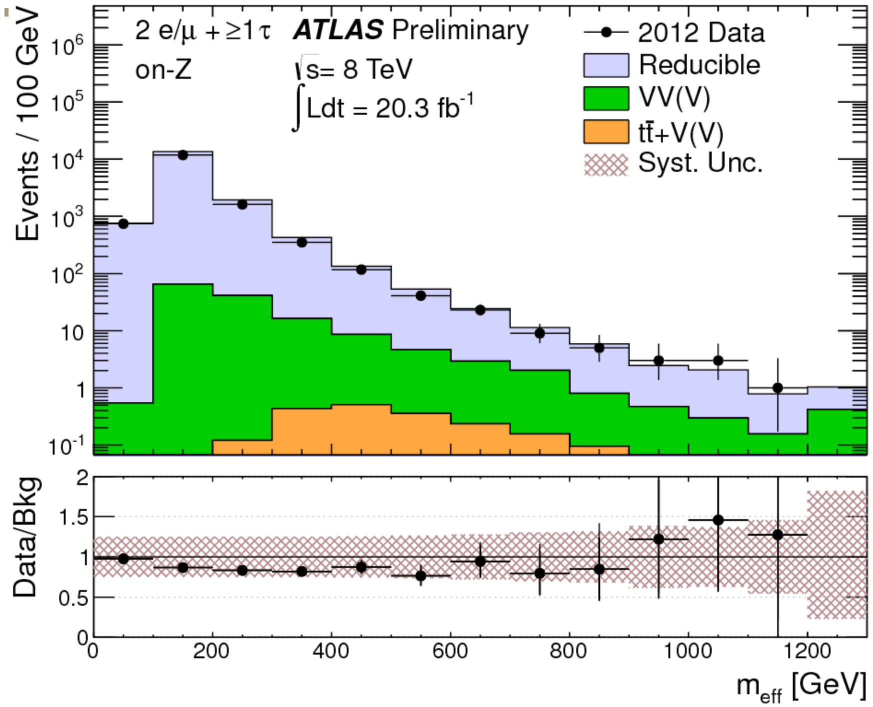
- CMS and ATLAS set limits in same space – presentation different but same message
- ATLAS also sets limit on bottom partners



For full LHC 8 TeV dataset typical 95% CL exclusion for masses are 800 GeV, depends on the decay channel

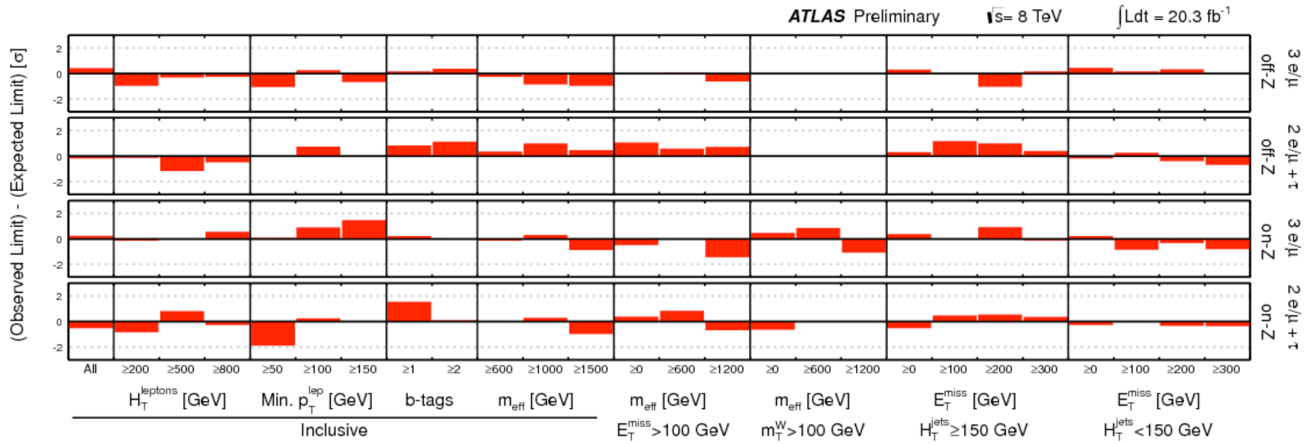
CMS PAS B2G-12-015
ATLAS-CONF-2013-060/018/051

General search multi-leptons



- Full ATLAS 8 TeV dataset examined in 3-lepton final states
  - On- and off-Z boson regions
  - Maximally one hadronic tau
  - Several kinematic variables examined
  - split by number of b tagged jets
- No excess above SM predictions

Limits on fourth generation, doubly charged Higgs (including Higgs triplets), various exotic neutrino models

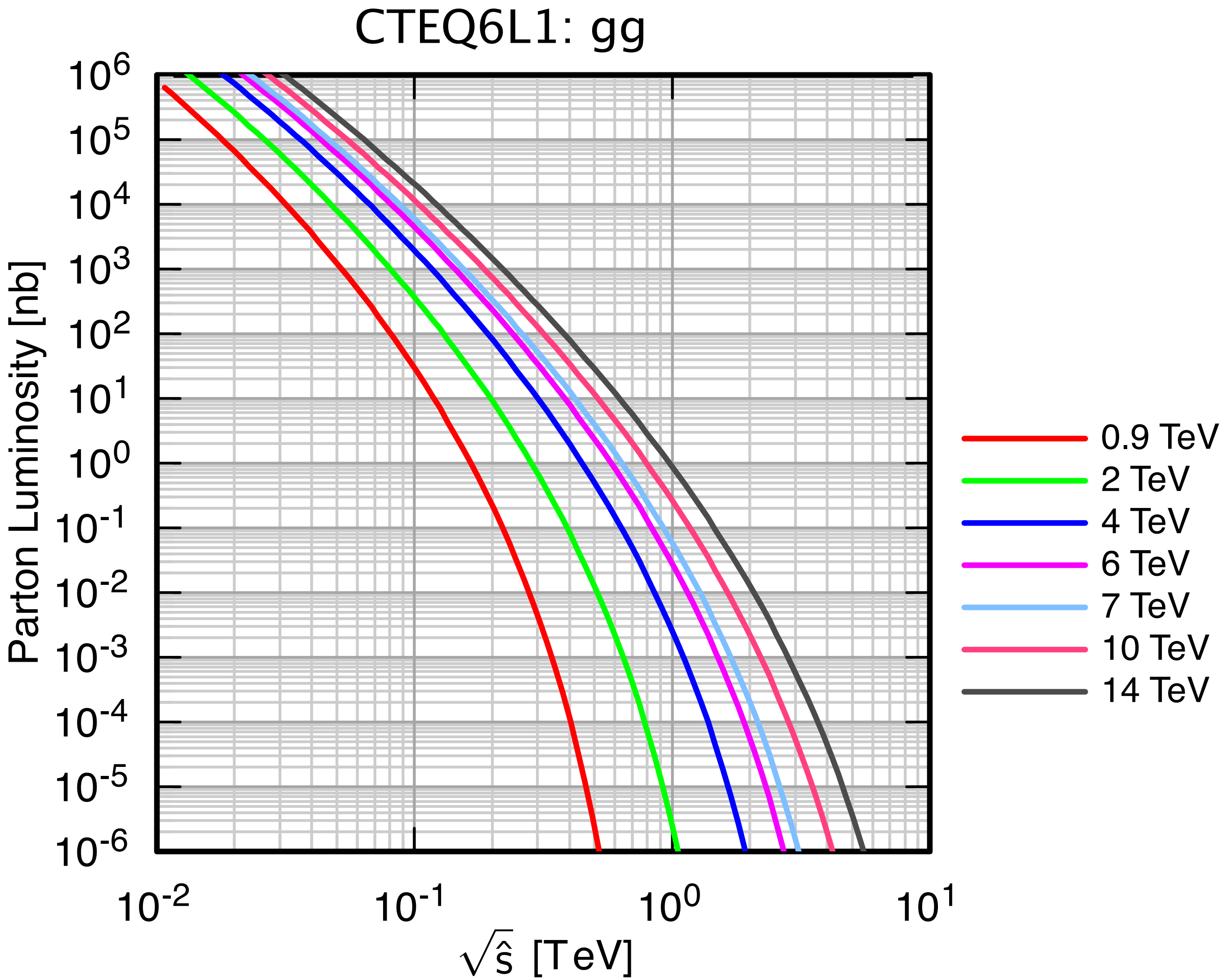


Summary and outlook

- LHC has just turned on at 13 TeV
- Very large data samples will be collected in the coming years
- How do I quickly compare existing analyses performance to future performance?

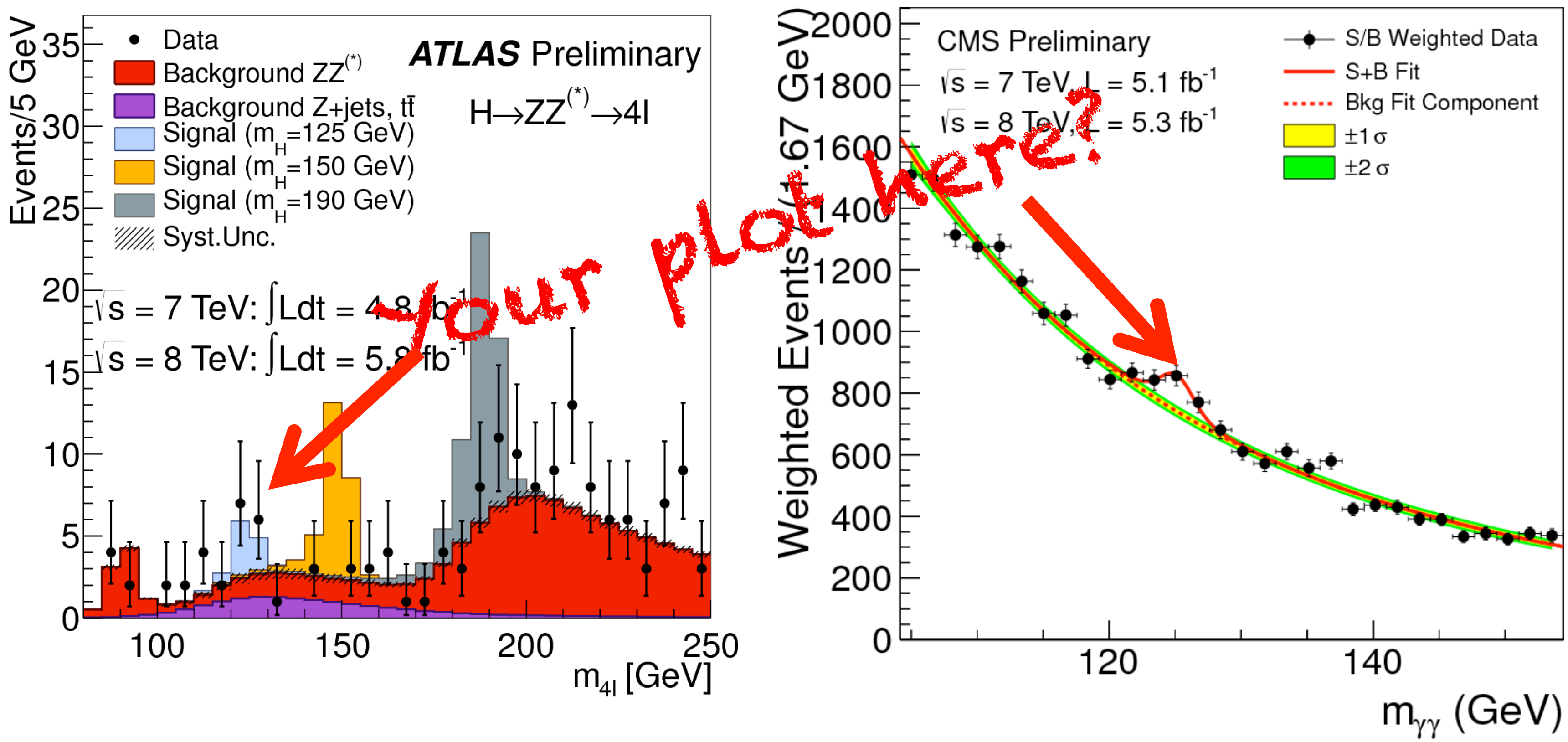
- The answer:
- Parton Luminosity scaling
- (also sometimes referred to as Stirling scaling)

Use to predict cross sections



http://lutece.fnal.gov/PartonLum/

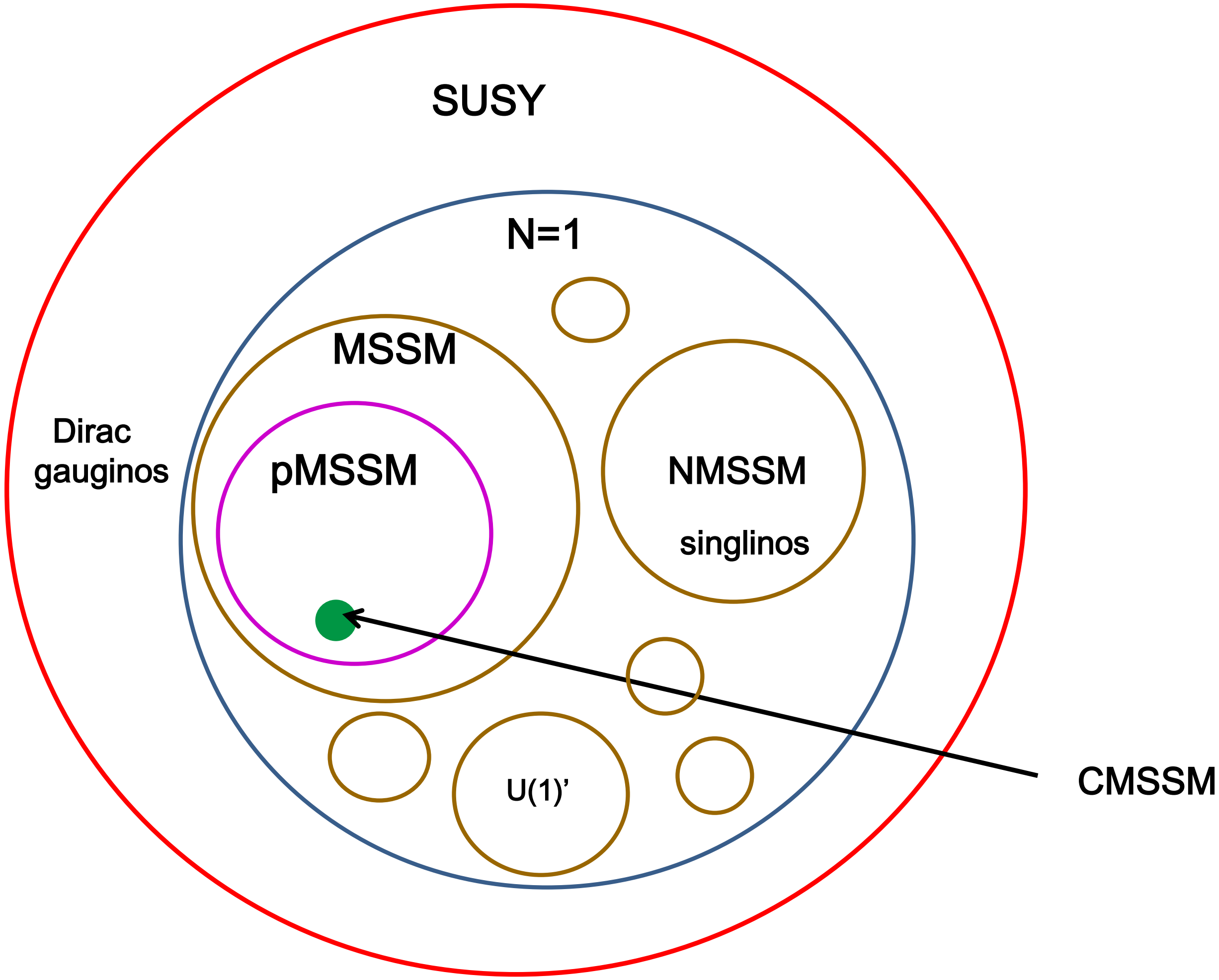
And finally…



- Let's hope for many new peaks in the coming few years.
  - <u>And don't forget to have fun !</u>

End of lecture two – questions?

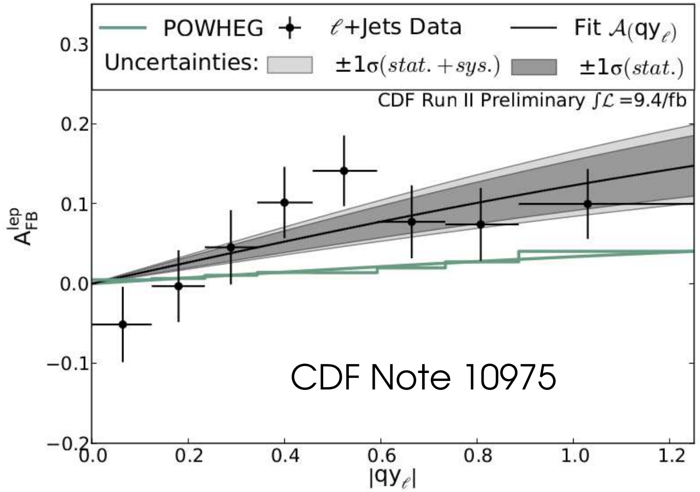
MSSM vs SUSY



- $A^{t\bar{t}}_{FB}$ measurement requires full reconstruction of $t\bar{t}$ system.
- Alternative method based on y of lepton from leptonic W decay.

$$A^{\ell}_{FB} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}$$

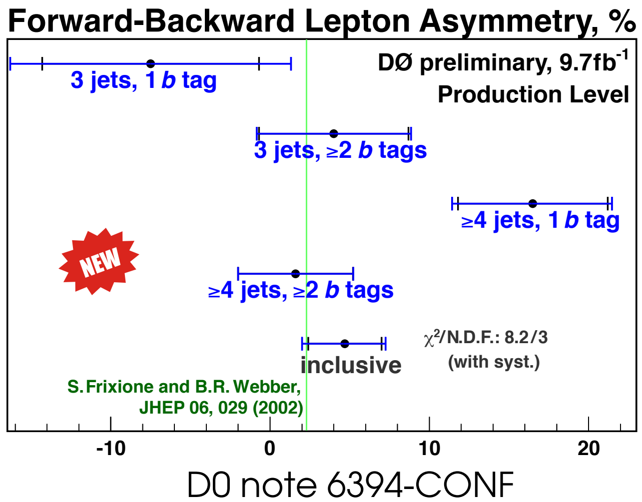
- $A^{\ell}_{FB} \approx 0.5 \cdot A^{t\bar{t}}_{FB}$ if no t polarization.
- Can also use events with jets out of acceptance (3-jet bin).



CDF: $A^{\ell}_{FB} = 0.094^{+0.032}_{-0.029}$

D0: $A^{\ell}_{FB} = 0.047 \pm 0.023(\text{stat})^{+0.011}_{-0.014}(\text{syst})$

- CDF result approximately 2σ above SM prediction.
- D0 measurement consistent with SM (and CDF) within errors.



Top Forward-Backward and Charge Asymmetries

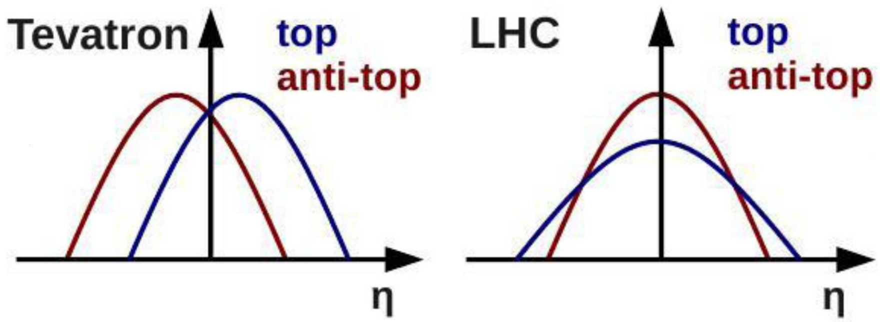
- New physics in top sector can alter angular distributions.
- Study forward-backward and charge asymmetries.

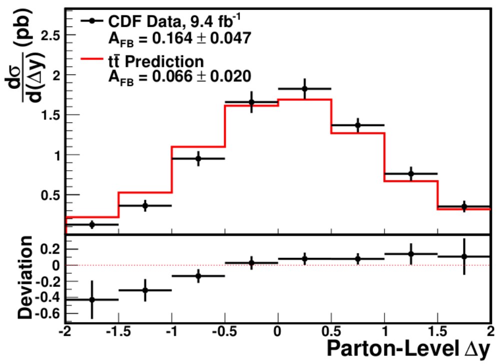
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_t - y_{\bar{t}}$

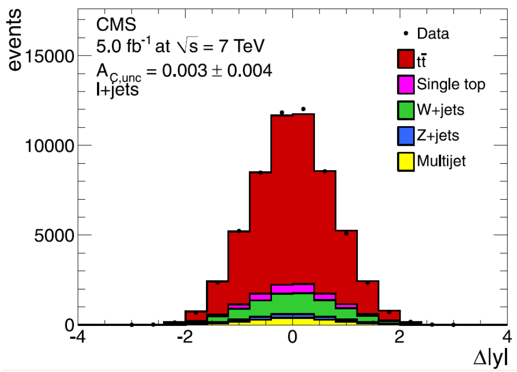
$$A_{C}^{t\bar{t}} = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

with $\Delta |y| = |y_t| - |y_{\bar{t}}|$

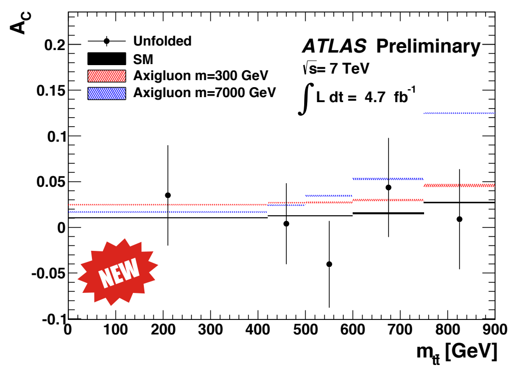




Phys. Rev. D 87 092002 (2013)



Phys. Lett. B 717, 129 (2012)



ATLAS-CONF-2013-078

- Tevatron $A_{FB}^{t\bar{t}}$ measurements in tension with SM at $\sim 2.5\sigma$.
- LHC $A_{C}^{t\bar{t}}$ measurements consistent with SM.

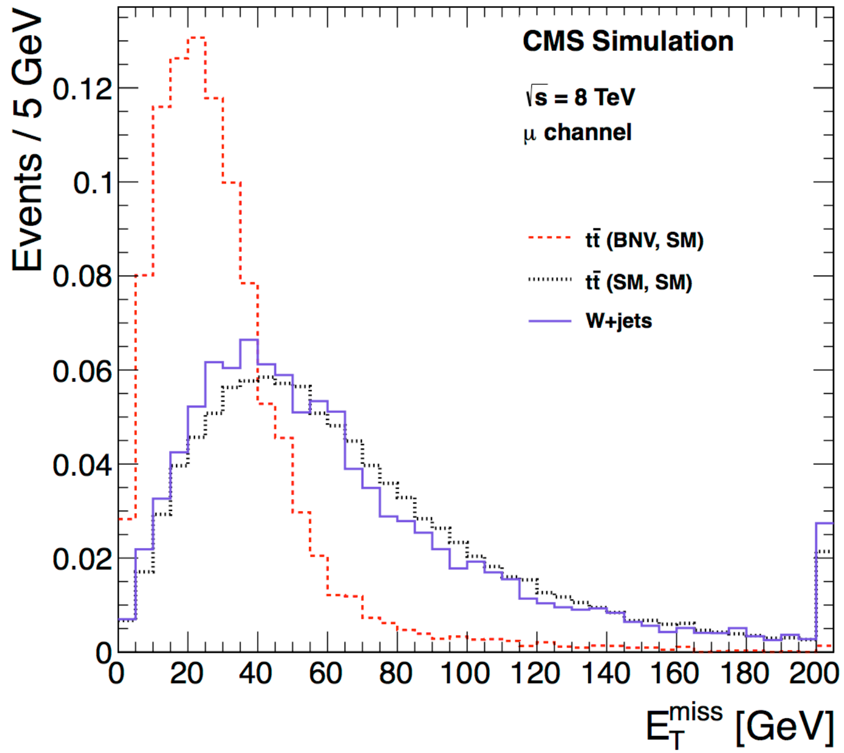
Baryon Number Conservation

- Baryon number conserved in Standard Model
  - Small violation possible from non-perturbative effects

- Supersymmetry, Grand Unified Theories and black-hole physics naturally allow Baryon Number violation (**BNV**).
  - stringent limits from precision measurements in nucleon, tau, HF mesons and Z bosons
  - Top decay (small BR) of type t to μbc not excluded

Search for BNV in tops

- Idea: should be visible as subtle increase of top events in lepton+jets with very low missing transverse energy
- Experimentally extremely challenging regime
  - Lepton
  - 5 jets
  - No MET



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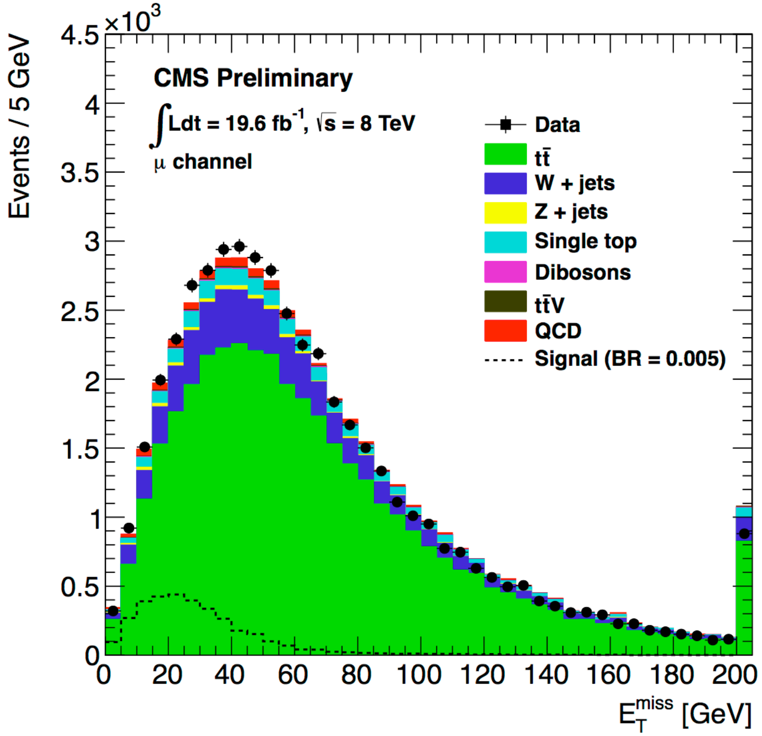
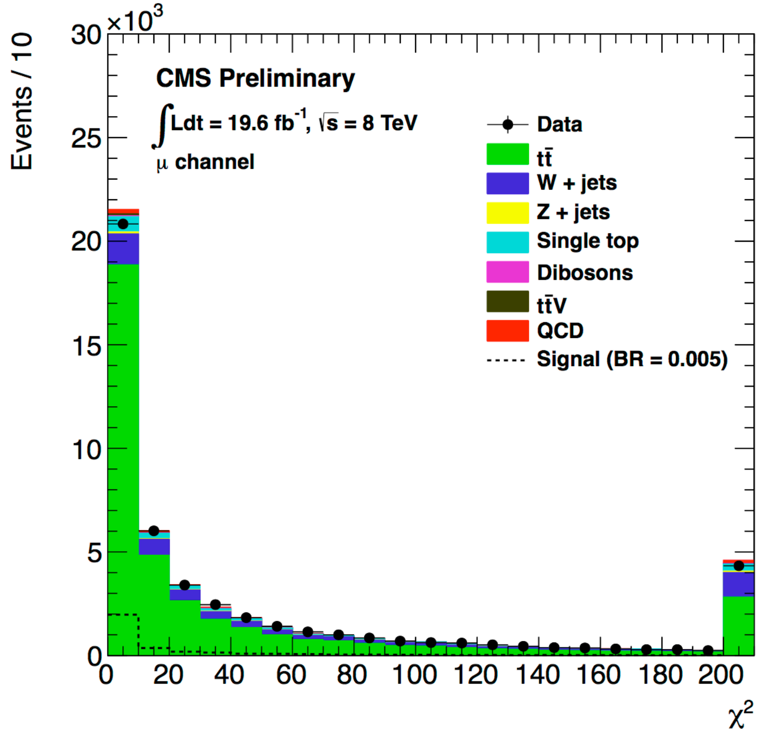
Search for BNV tops

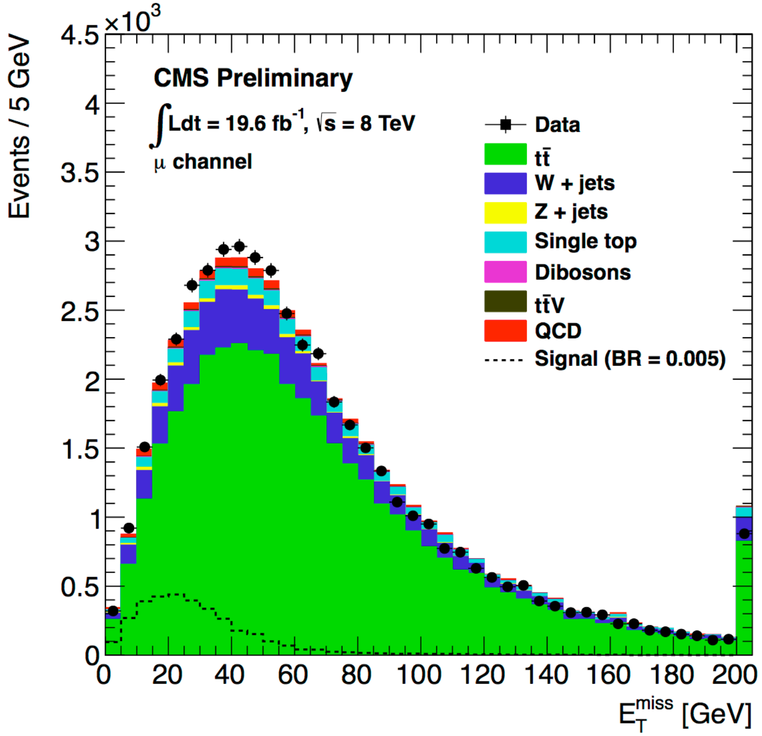


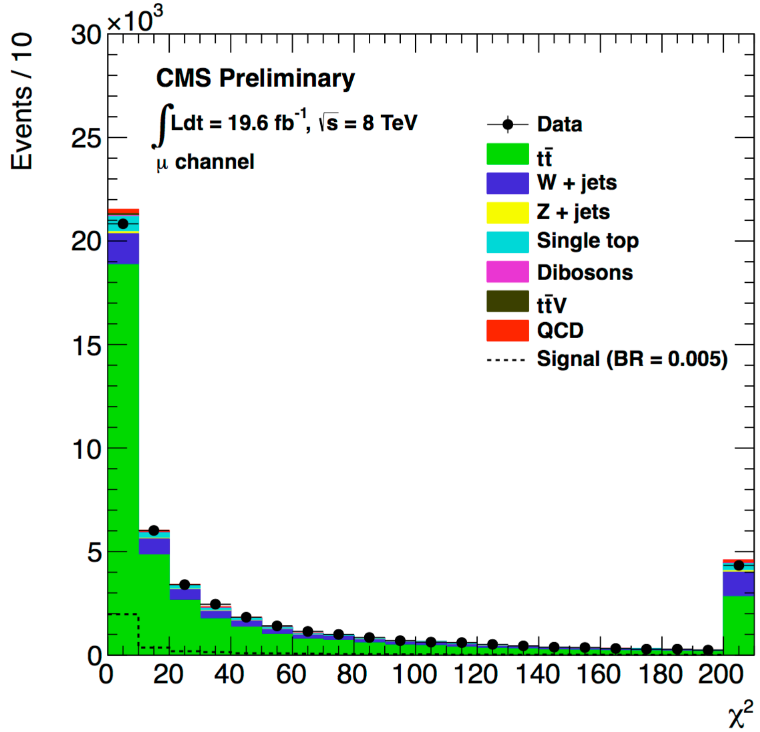


- Construct chi2 requirement on hadronic top system and make tight cut on chi2 (<20) and MET (<20) Constrain low MET, low chi2 region from bulk
- Fit to BR and selection efficiency instead of event counts

CMS PAS B2G-12-023

Search for BNV tops

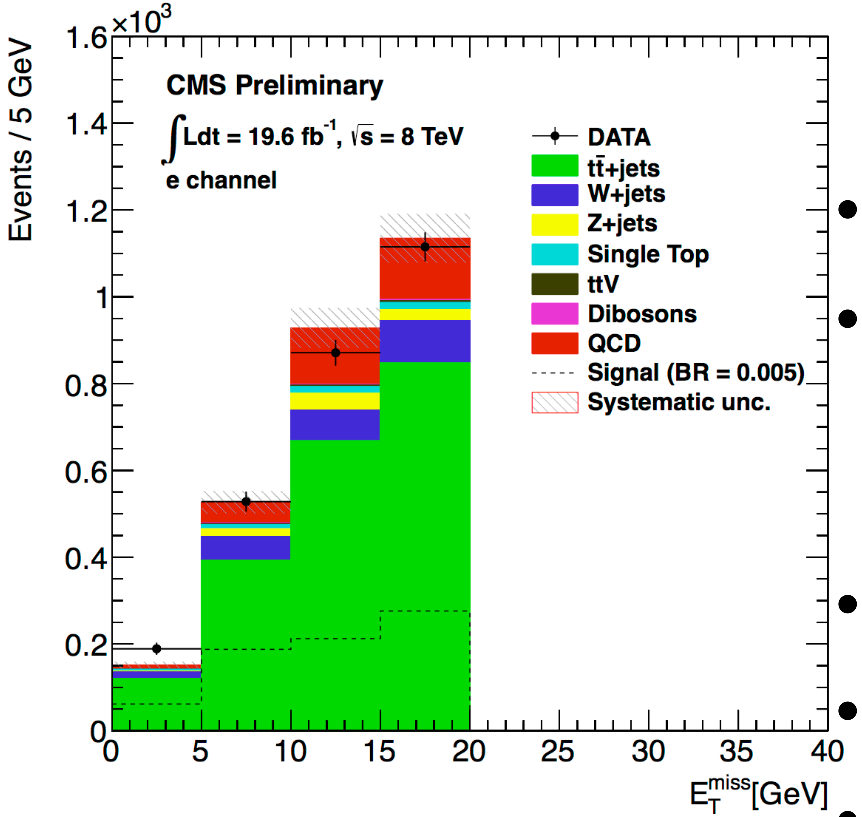




$$N^T_{exp} = \left(N^B_{obs} - N^B_{bck}\right)\left[\frac{1}{1+\frac{\sigma_{tW}\epsilon^B_{tW}(BR)}{\sigma_{t\bar{t}}\epsilon^B_{t\bar{t}}(BR)}} \times \frac{\epsilon^T_{t\bar{t}}(BR)}{\epsilon^B_{t\bar{t}}(BR)} + \frac{1}{1+\frac{\sigma_{t\bar{t}}\epsilon^B_{t\bar{t}}(BR)}{\sigma_{tW}\epsilon^B_{tW}(BR)}} \times \frac{\epsilon^T_{tW}(BR)}{\epsilon^B_{tW}(BR)}\right] + N^T_{bck}$$

CMS PAS B2G-12-023

Search for BNV tops



- Modeling of QCD multijet background derived in Z+jets events
- Fit to efficiencies and BR
- Even in challenging e+jets channel decent data-MC agreement
- Limits on in μ (e) channels:
- BF< 0.016 (0.017)
- First limit ever on BNV in top sector!