ATLAS EXPERIMENT
http://atlas.ch

CMS

Top Quark physics at the Large Hadron Collider

2014-2015 Intercollegiate PostGraduate Course in Elementary Particle Physics

London, UCL Bloomsbury Campus
8th December 2014

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Outline

- **Why top quark? A historical perspective**
- **The tools of the trade**
  - **LHC:** a top factory at work
  - **The ATLAS and CMS detectors**: top observers
- Measuring **top quark production: top pair cross section**
  - **The emergence of boosted tops**
- Measuring **top quark properties:mass**
- **Conclusions**

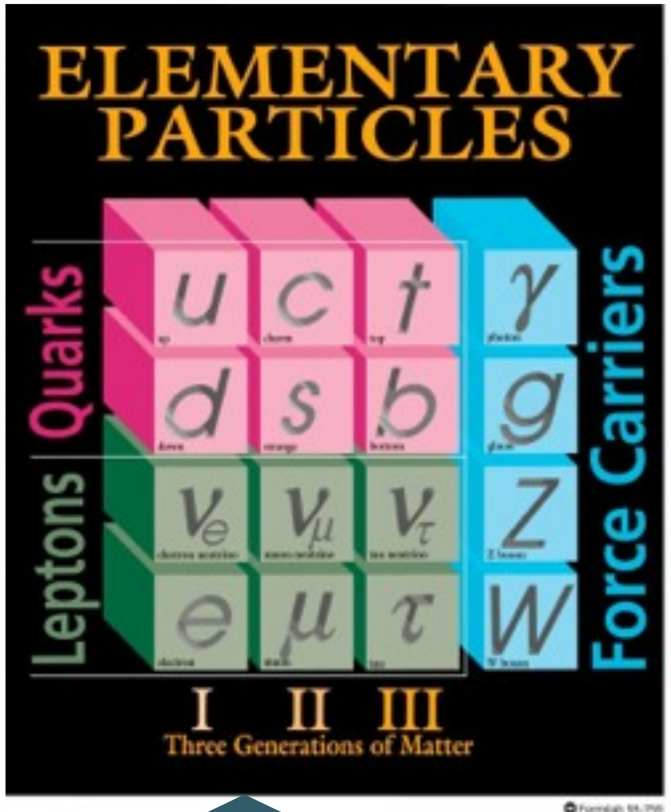
Attention, navigators!!

your rosetta stone
to the topic

essential clues =

A good moment to discuss, ask questions then and whenever items are not clear!

How we describe the micro world: the standard model



Quantum mechanics

smallest distances<10^{-15} → large momenta: p~h/d

\+

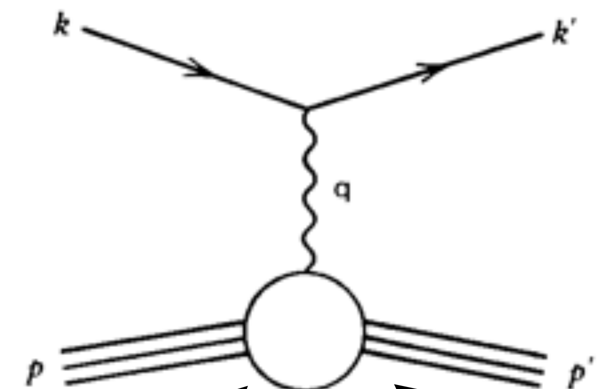
Relativity

large momenta → large energy E=cp~ch/d

quantum *field theory* (and more…)

- Lagrangian

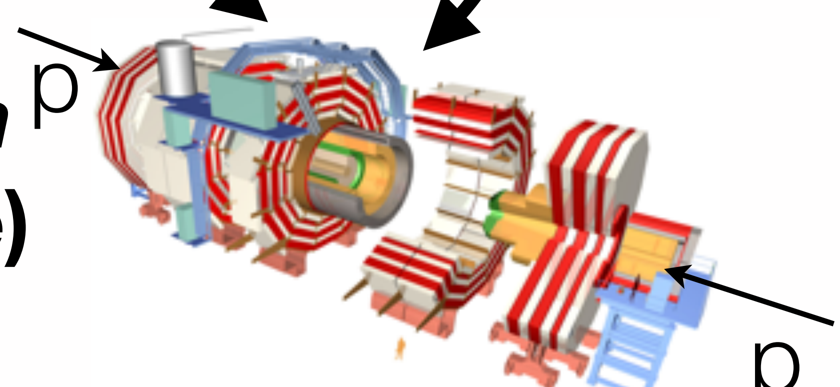
- Feynman diagrams



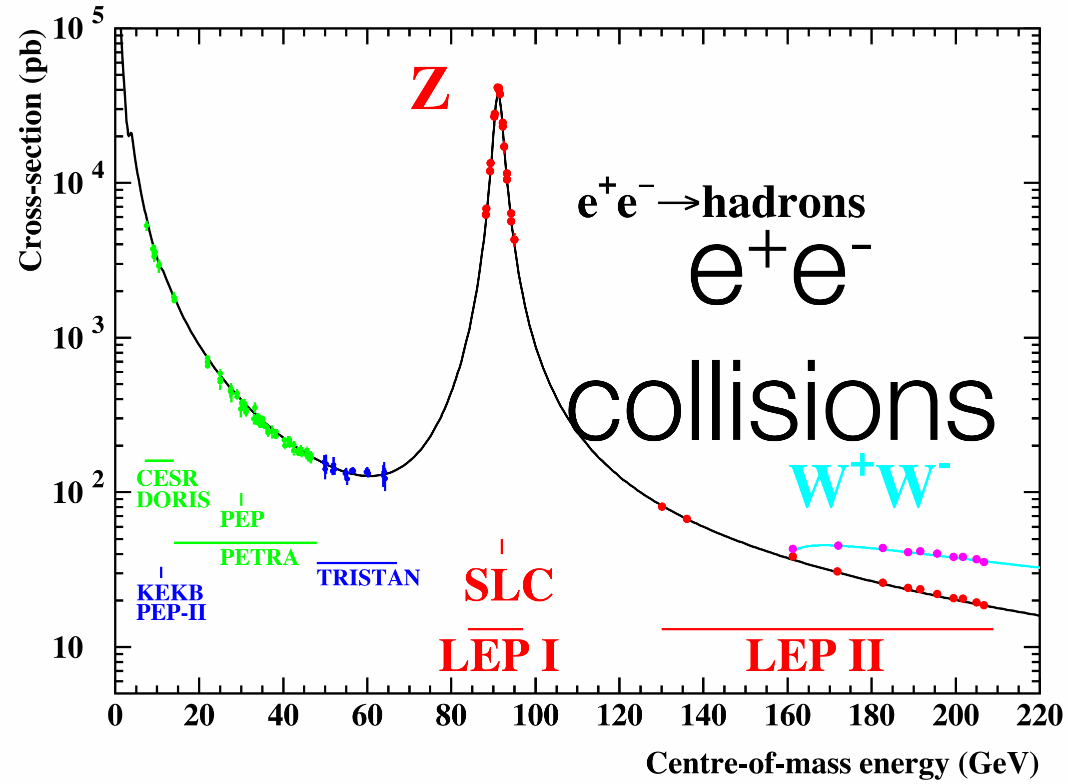
Theory

Experiment

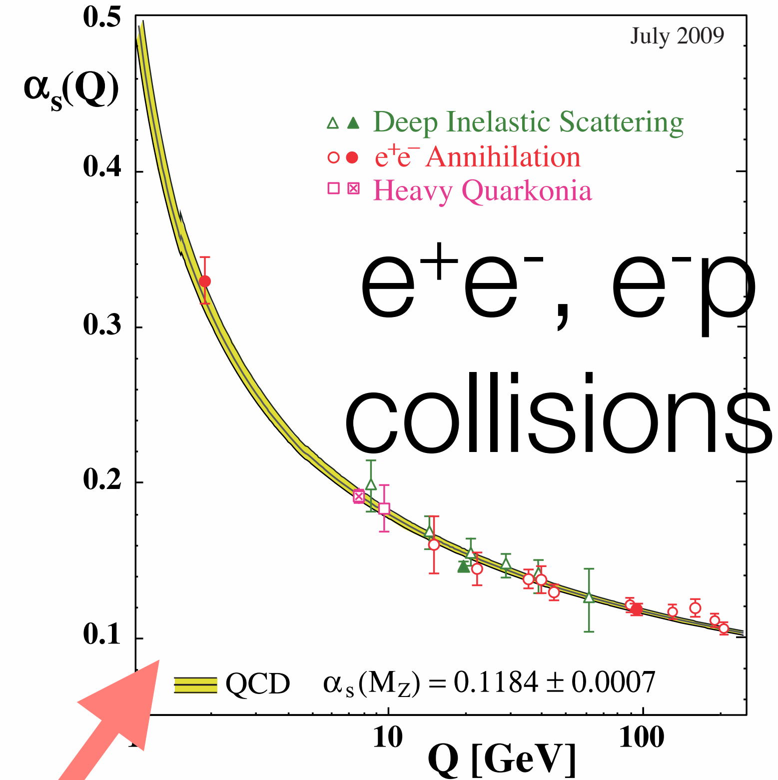
observe events at high energy density, small distance with **detectors *messengers from the sky*, artificial (man-made) collisions**



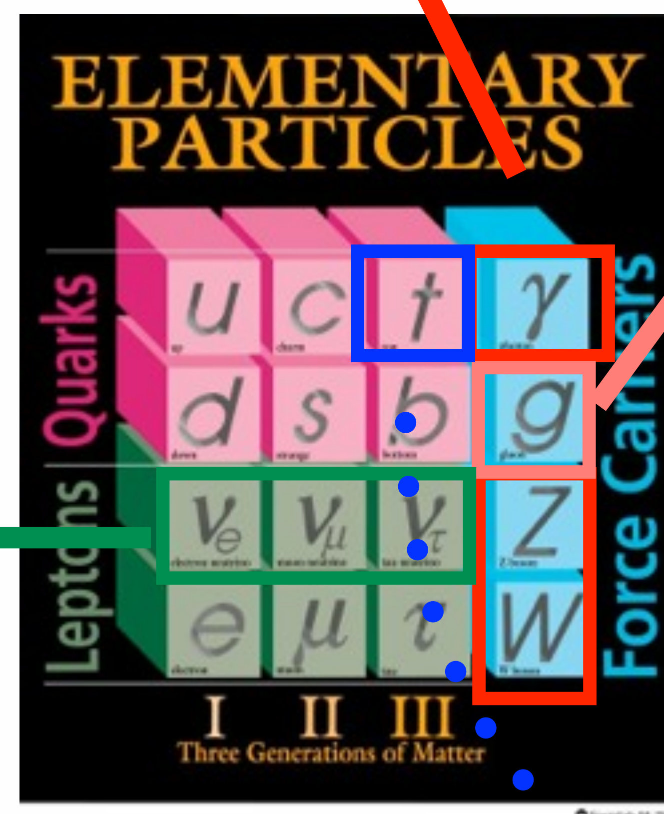
Standard (model) **successes** *at colliders*

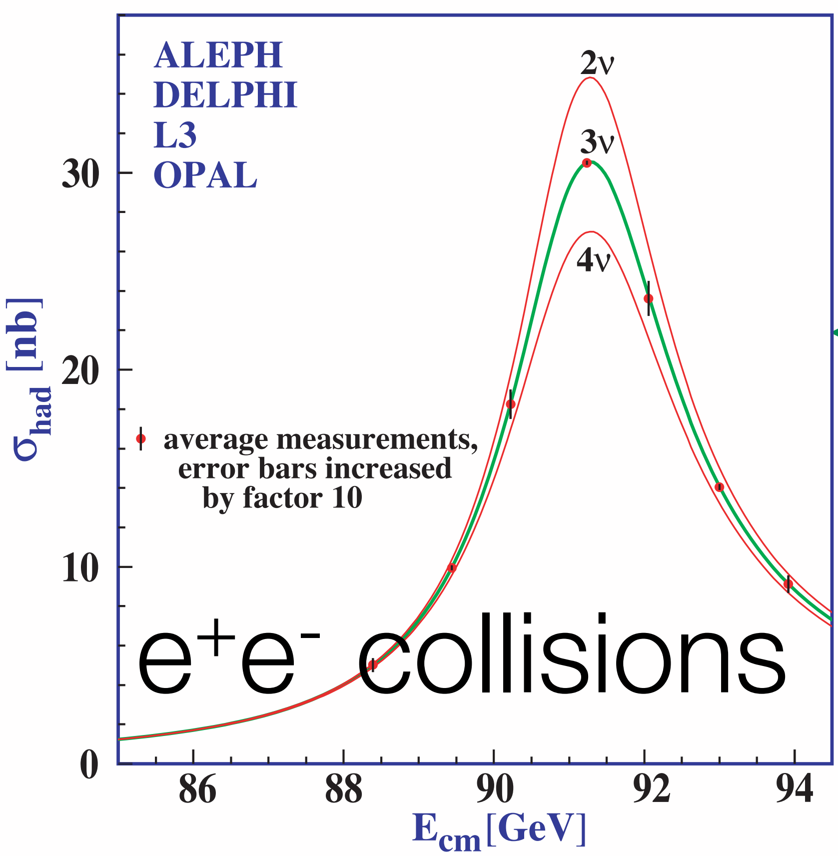


Electromagnetic force unified to Weak: electrons annihilate to W, Z, in addition to photons



Strong interaction strength changes with momentum exchange

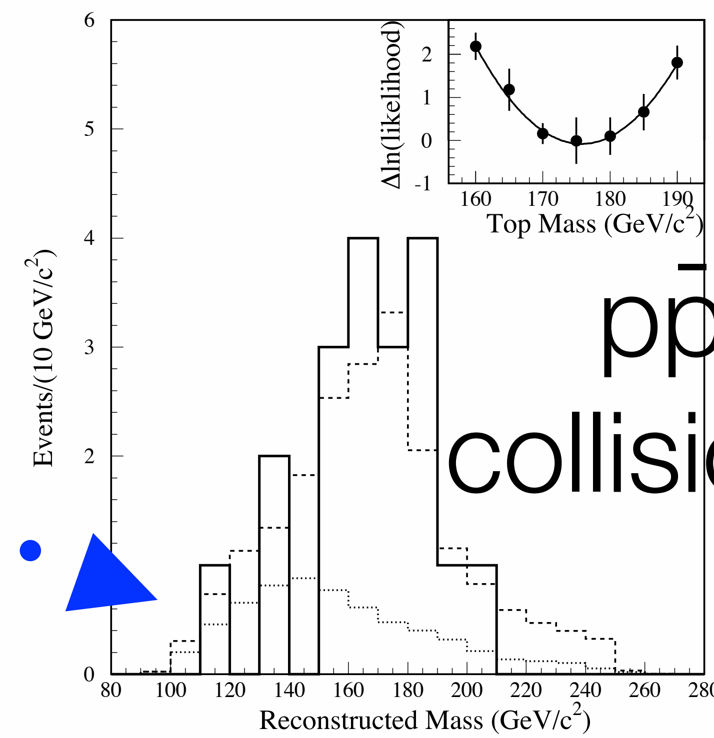




there are only 3 standard neutrinos

The known micro-world

a quick (biased) selection..



Top quark is found

Standard (model) **questions**

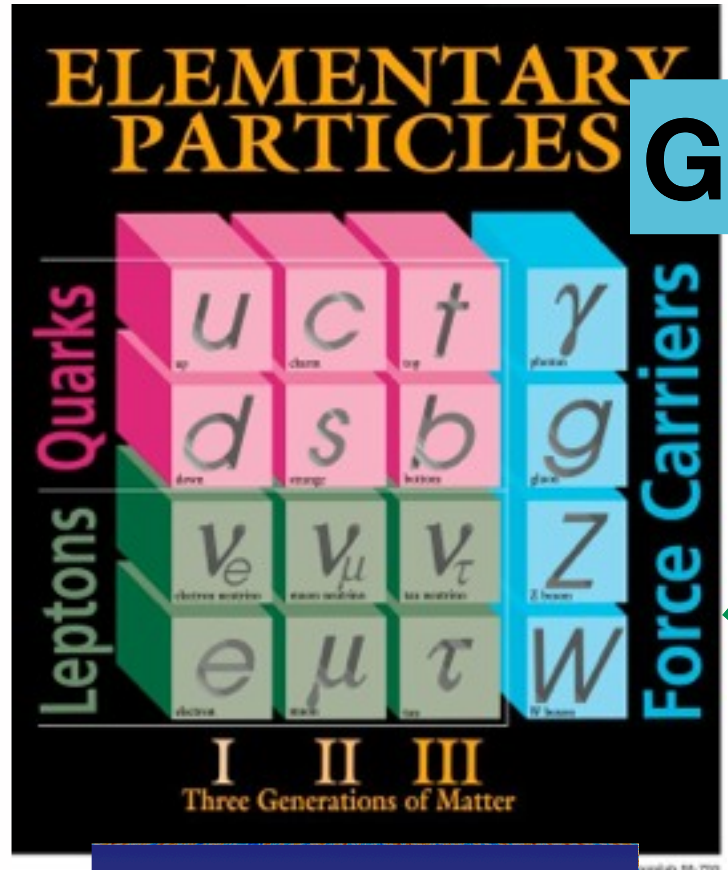
See for instance arXiv:0312096v1[hep-ph]

- *What is the **origin of mass**? Why are symmetries of forces different from those of particles?*

- *How is **gravity** incorporated?*

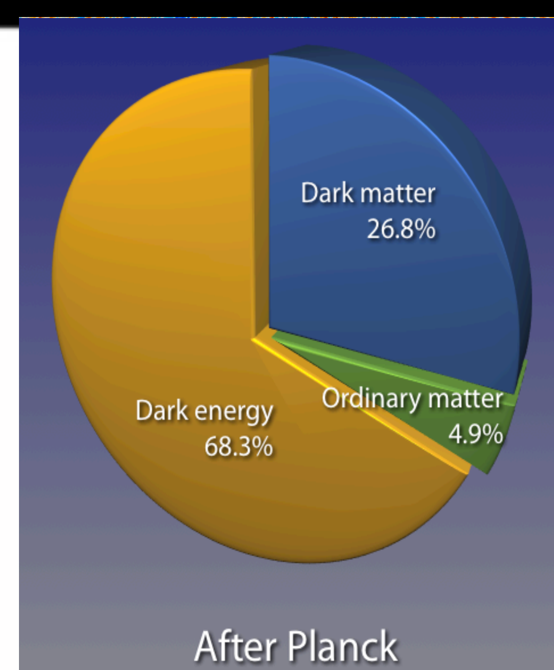
2/3

-1/3



- *Why **different forces** (ranges, strengths)?*

- *Why **3 generations of matter** with different quantum numbers ?*



(P. Natoli, Cosmology with Planck, LaThuile 2014)

- *What accounts for the energy balance of the universe?*

Standard (model) **questions**

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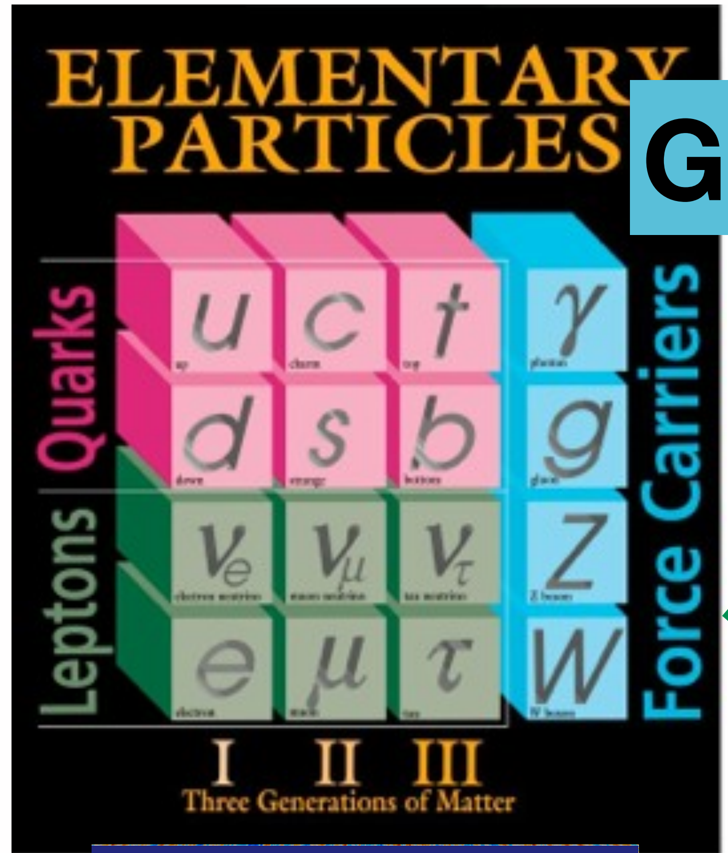
- ***What is the origin of mass? Why are symmetries of forces different from those of particles?***

Higgs, SuperSymmetry, New Strong forces..



- ***How is gravity incorporated?***

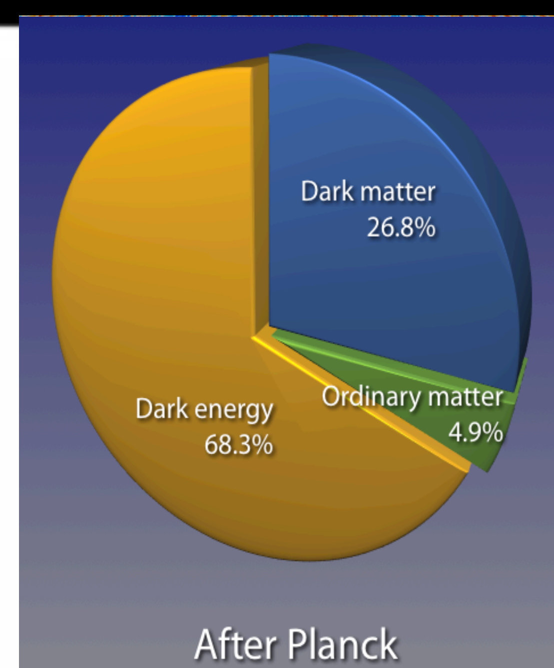
Quantum gravity
Extra dimensions...

- ***Why different forces (ranges, strengths)?***

String theory..

- ***Why 3 generations of matter with different quantum numbers ?***

4th generation...?



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Dark matter, Dark energy...

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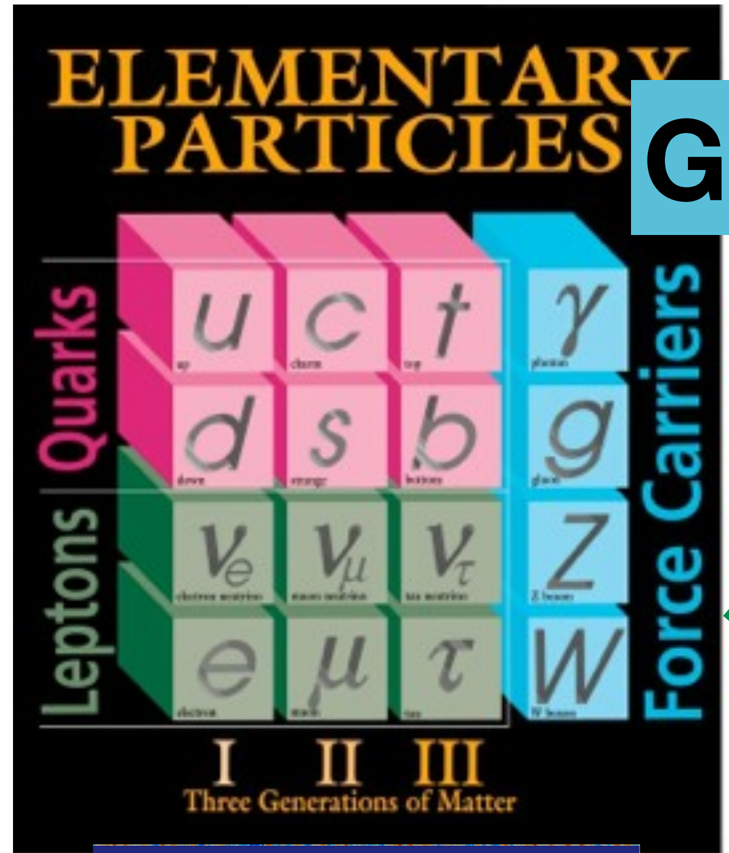

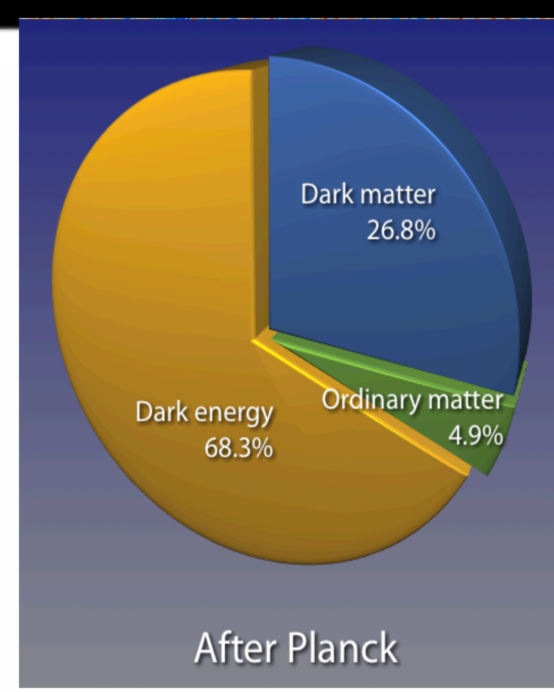

(P. Natoli, Cosmology with Planck, LaThuile 2014)

- ***Why different forces (ranges, strengths)?***

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- ***Why 3 generations of matter with different quantum numbers ?***

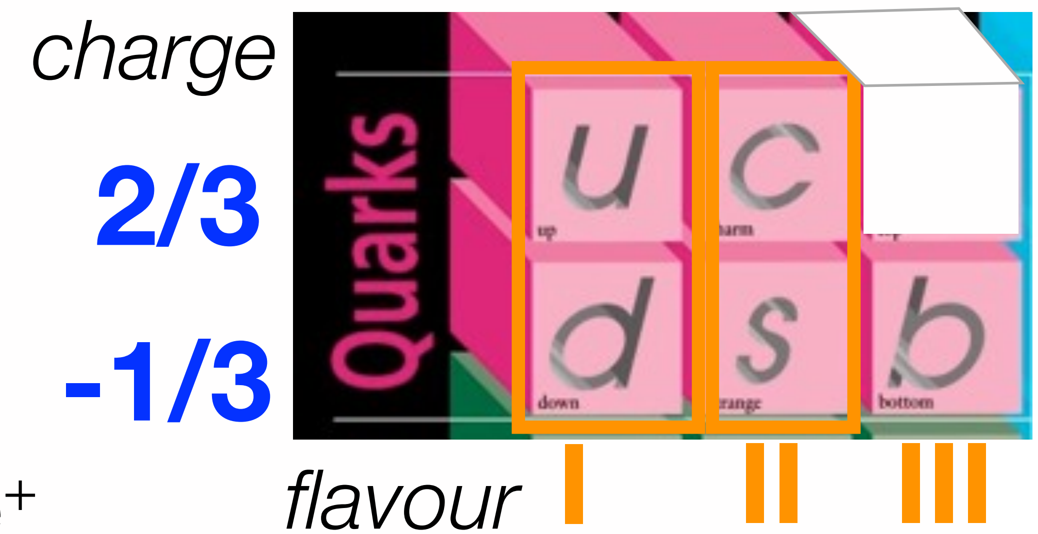
4th generation...?

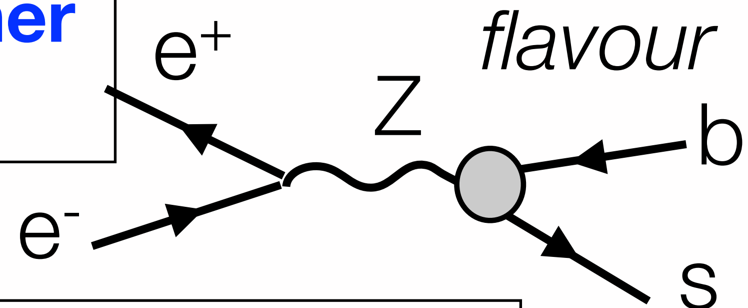
- ***What accounts for the energy balance of the universe?***

Dark matter, Dark energy...

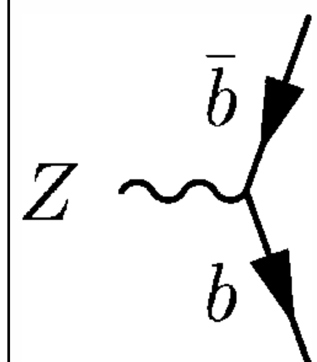
Particle phys as on 1994: "Waiting for the top"

No observed transition between **different flavours** with **same charge.** **GIM Mechanism requires another quark.**



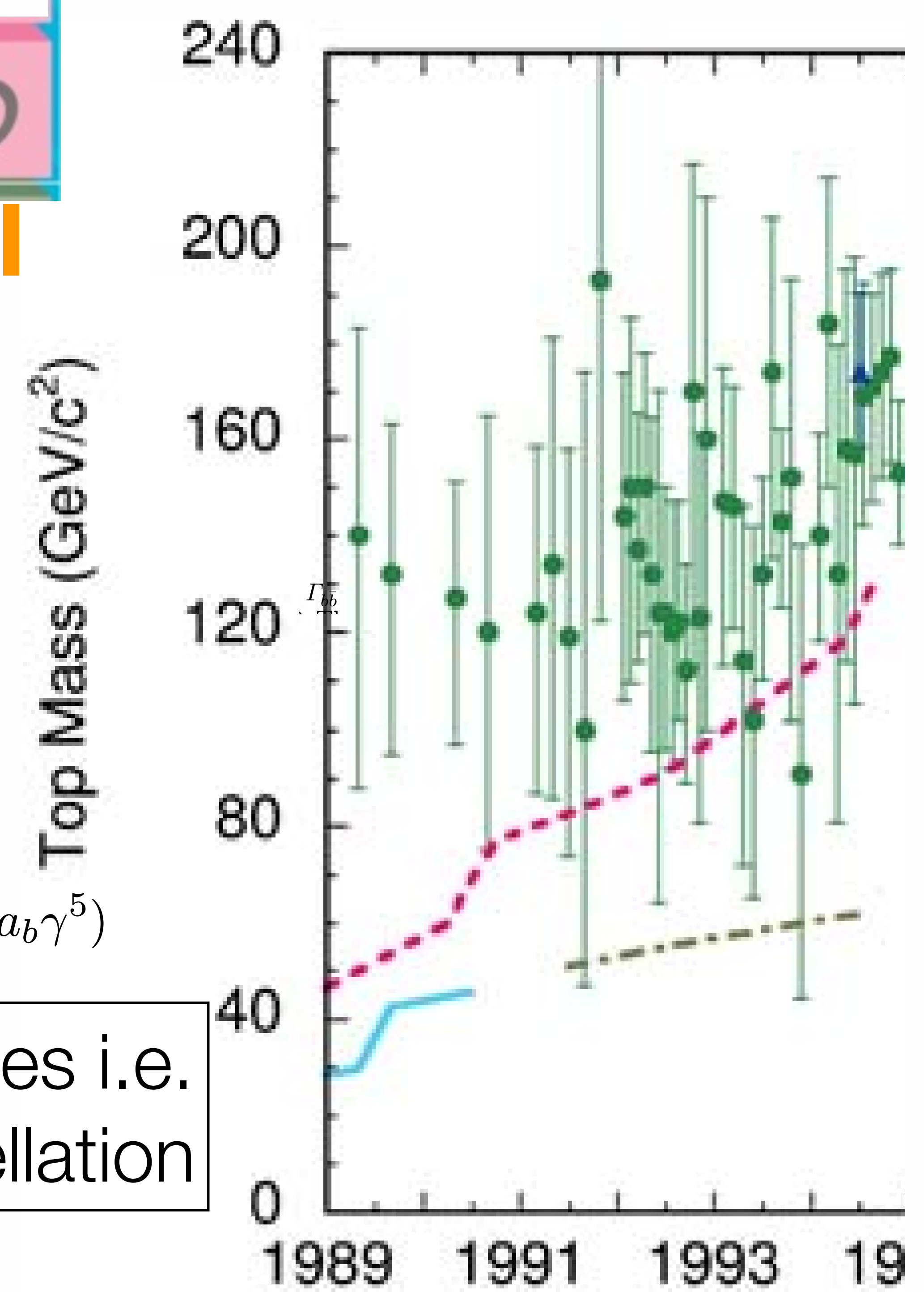


I_3 = -1.2 for b quark required by Z width in bb decay. Need additional quark, isospin partner of b, with I_3 = +1.2

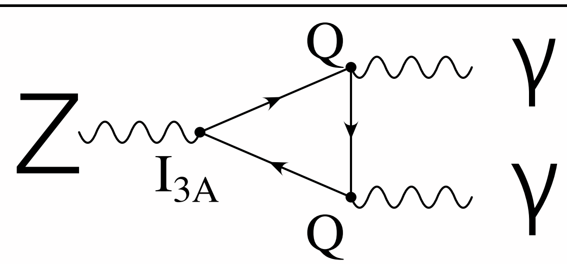


Width should be 13 times smaller

$$= -i\sqrt{\sqrt{2}G_F M_Z^2}\gamma^\mu(v_b - a_b\gamma^5)$$



No observed triangular fermion loops anomalies i.e. additional quark required for lept.-ferm. cancellation



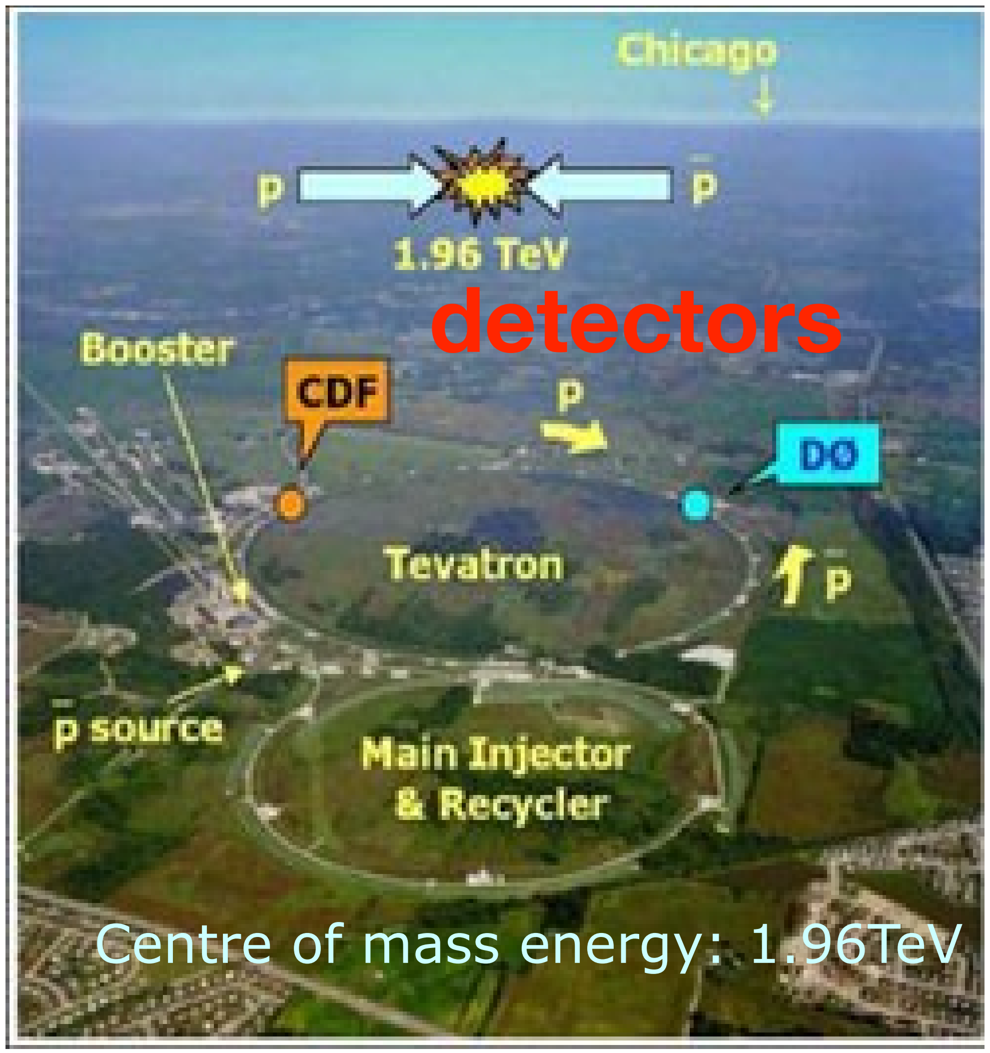
$$\sim \sum_L I_{3A} Q^2 = -\sum_L I_3 \left[I_3 + \frac{1}{2}Y\right]^2$$

$$\sim \sum_L Y \sim \sum_L Q$$

1995: top quark is discovered!

$m_{top} = 176 \pm 8(\text{stat.}) \pm 10(\text{sys.})\ \text{GeV}/c^2$

$\sqrt{s} = 1.8$ TeV $\quad \sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb.



19 sel. events
exp **background**:
6.9
4.8 s.d.significance

m_{top} from
likelihood
***fit** to shape*

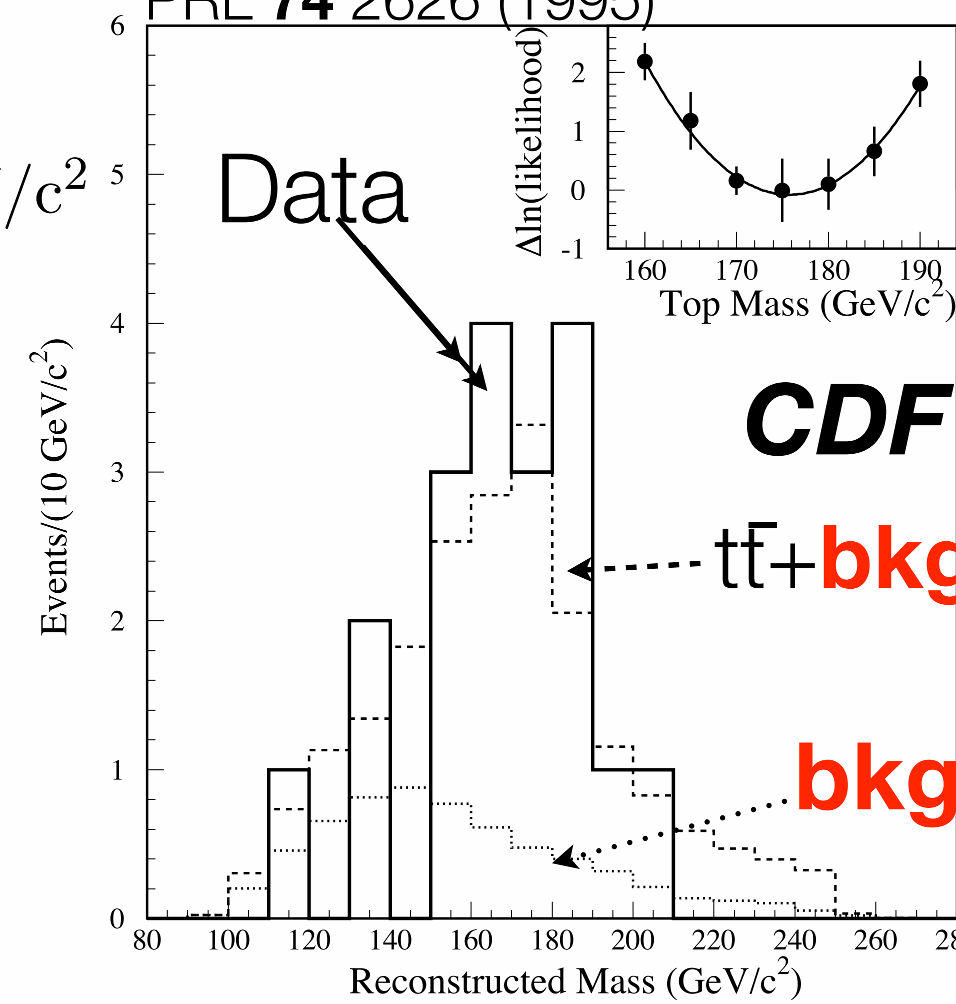
17 sel. events
exp **background:**
3.8
4.6 s.d. significance

on to learn about it all...

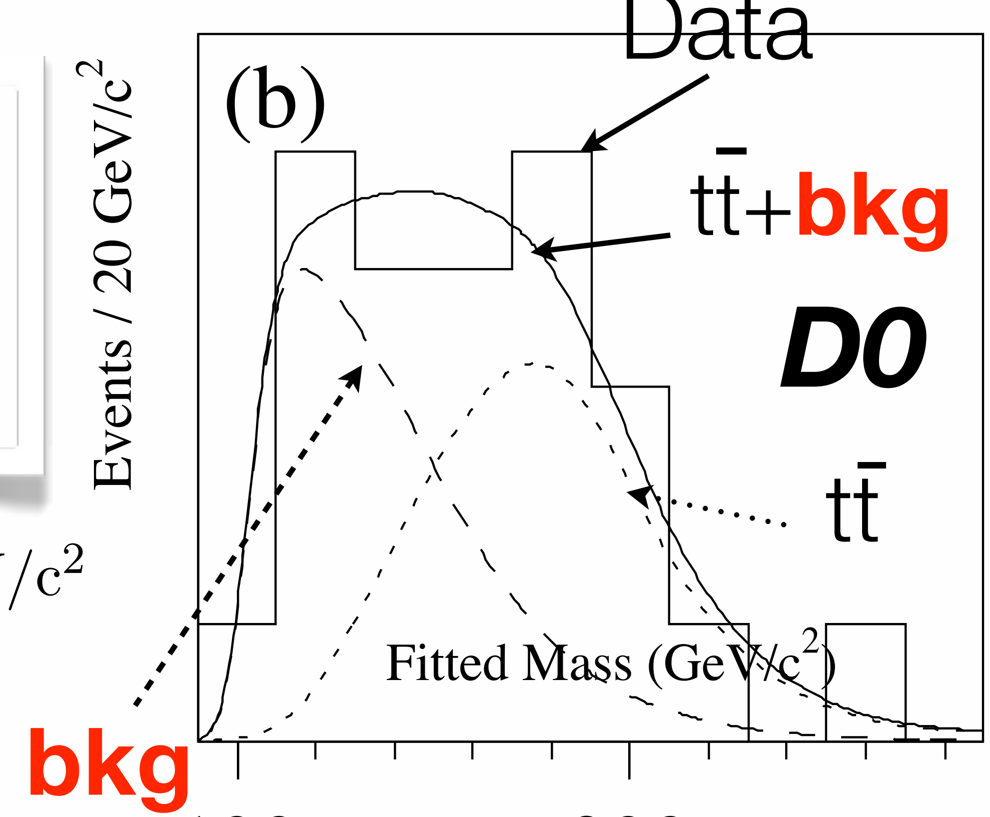
$m_{top} = 199^{+19}_{-21}\ (\text{stat.}) \pm 22\ (\text{syst.})\ \text{GeV}/c^2$

$\sigma_{t\bar{t}} = 6.4 \pm 2.2$ pb.

PRL **74** 2626 (1995)

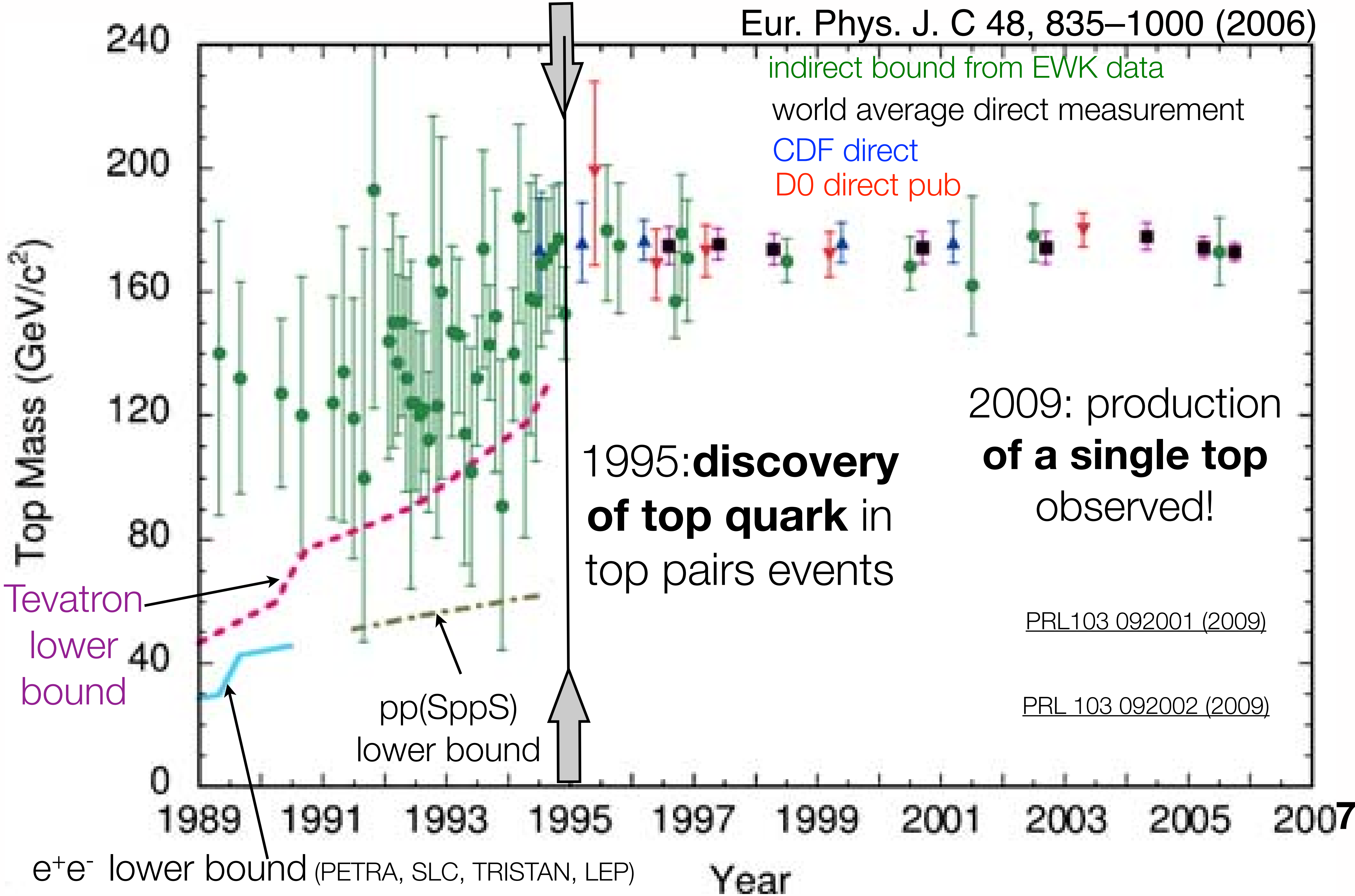


PRL **74** 2632 1995



From bottom to top: the global picture

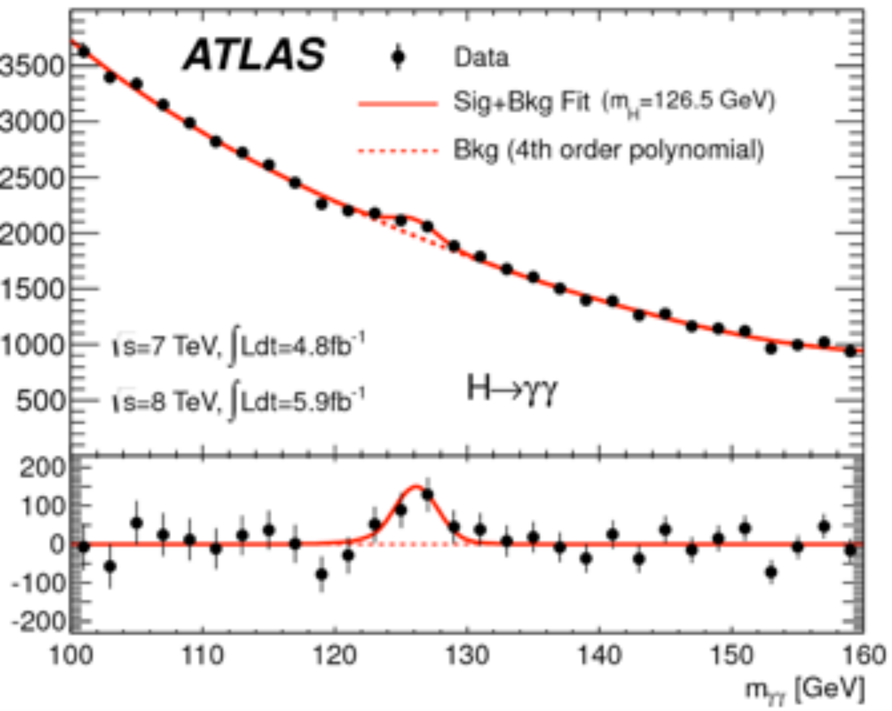
A.Quadt



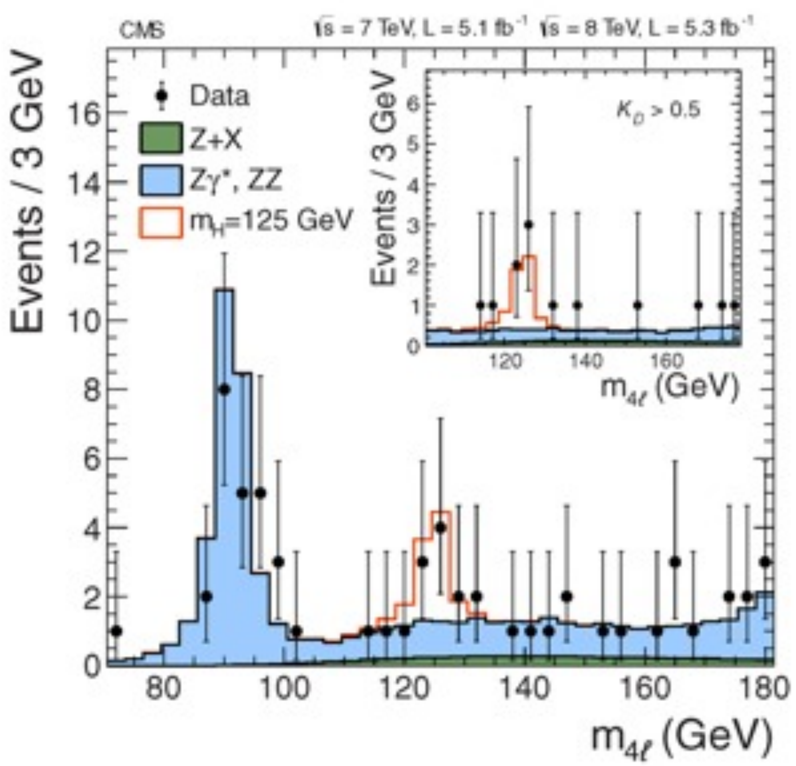
Standard (model) **news: scalar boson is observed!**

pp collisions

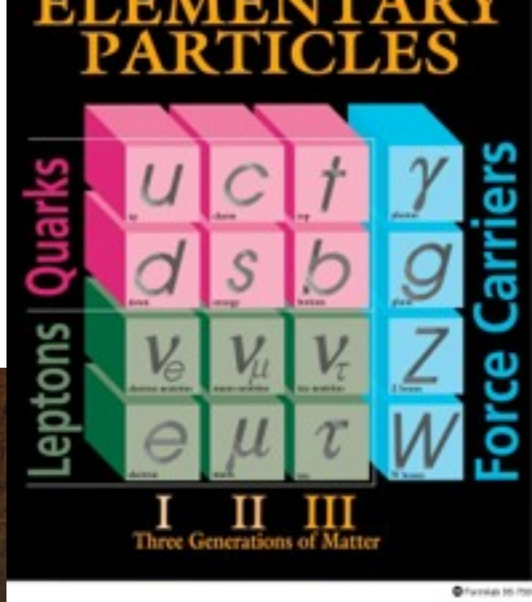
[*Phys. Lett. B 716 (2012) 1-29*]

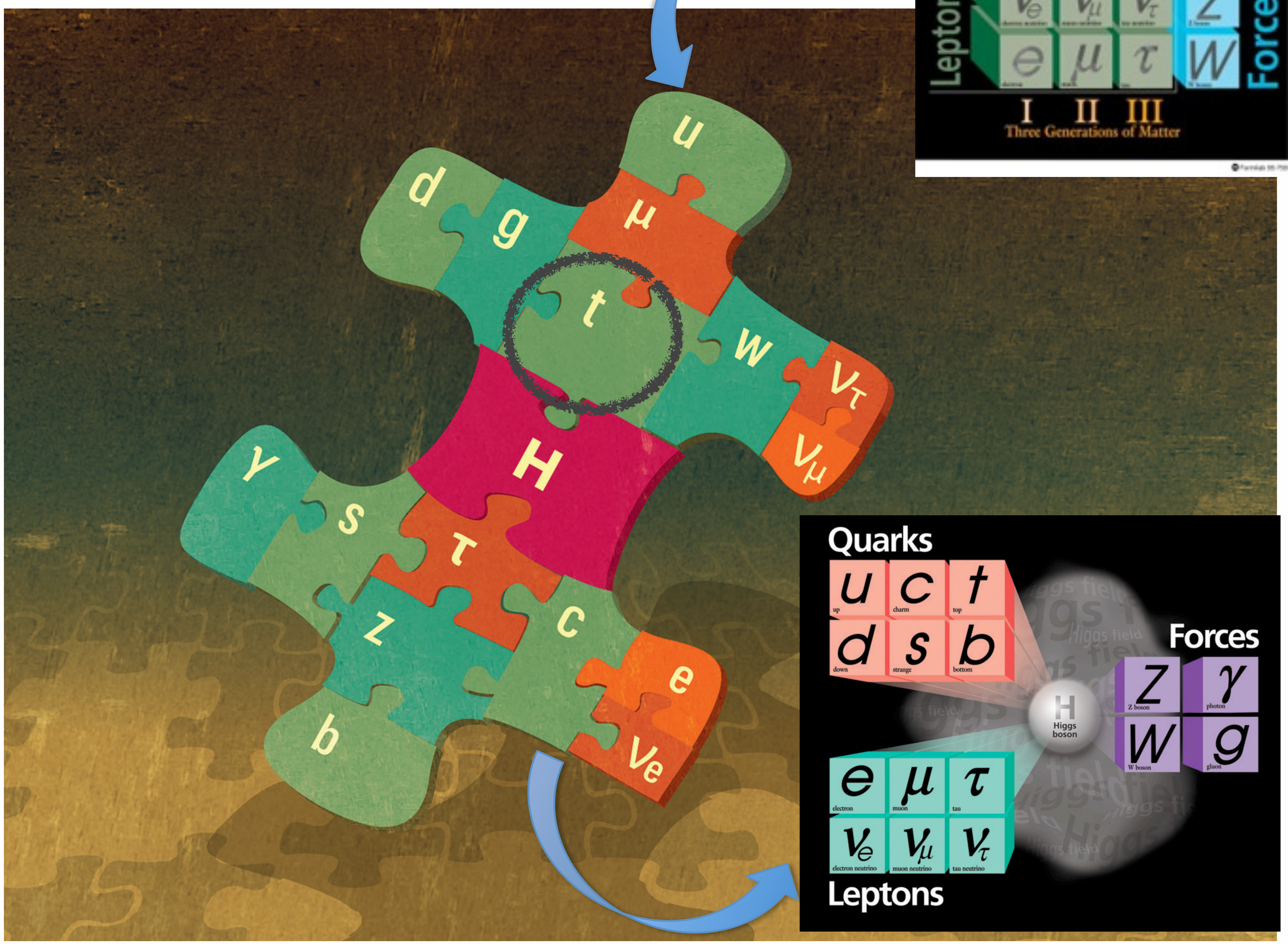


[*Phys. Lett. B 716 (2012) 30*]



[*Nobel for Phys 2013 - InfoForPublic*]





Even if the Higgs particle has completed the Standard Model puzzle, the Standard Model is not the final piece in the greater cosmic puzzle.

The puzzle is not complete..

Standard (model) **questions**

See for instance arXiv:0312096v1[hep-ph]

- *What is the **origin of mass**? Why are symmetries of **forces** different from those of **particles**?*

Higgs, SuperSymmetry

New Strong forces..

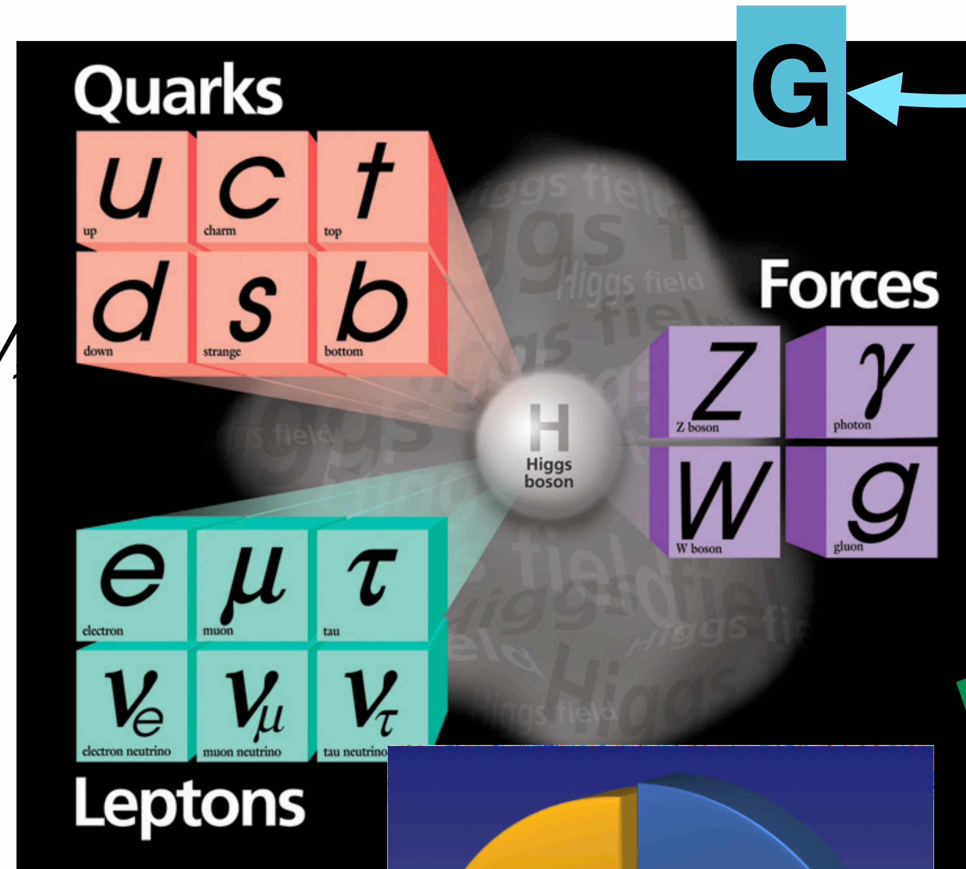
- *Why **3 generations of matter** with different quantum numbers ?*

4th generation...?

- *How is **gravity** incorporated?*

Quantum gravity

Extra dimensions...



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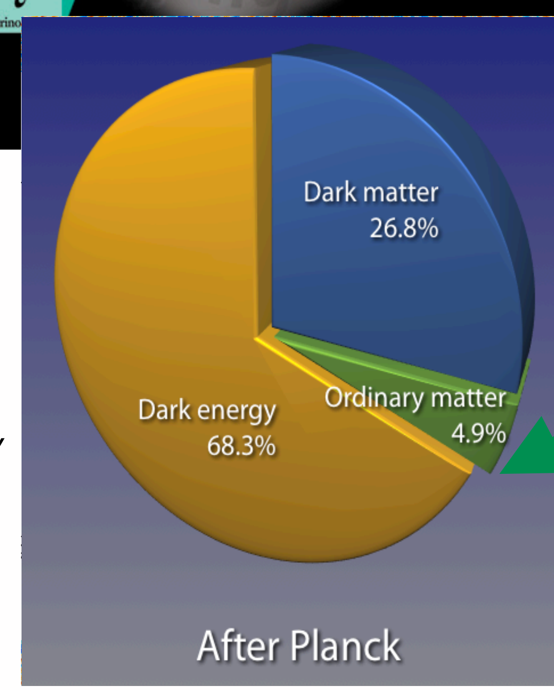

- *What accounts for the energy balance of the universe?*

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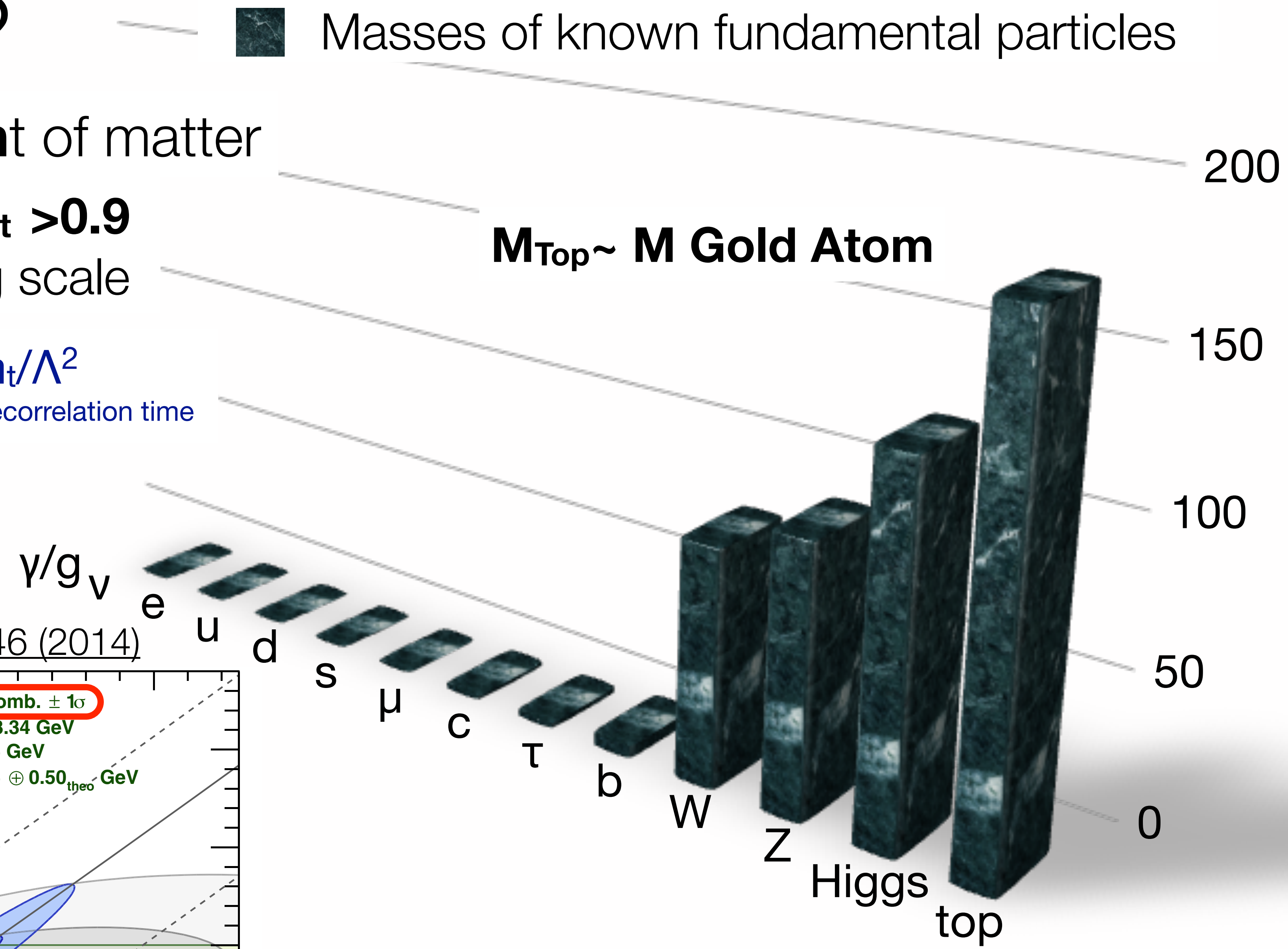
Why Top (quark)?



Most massive known **constituent** of matter

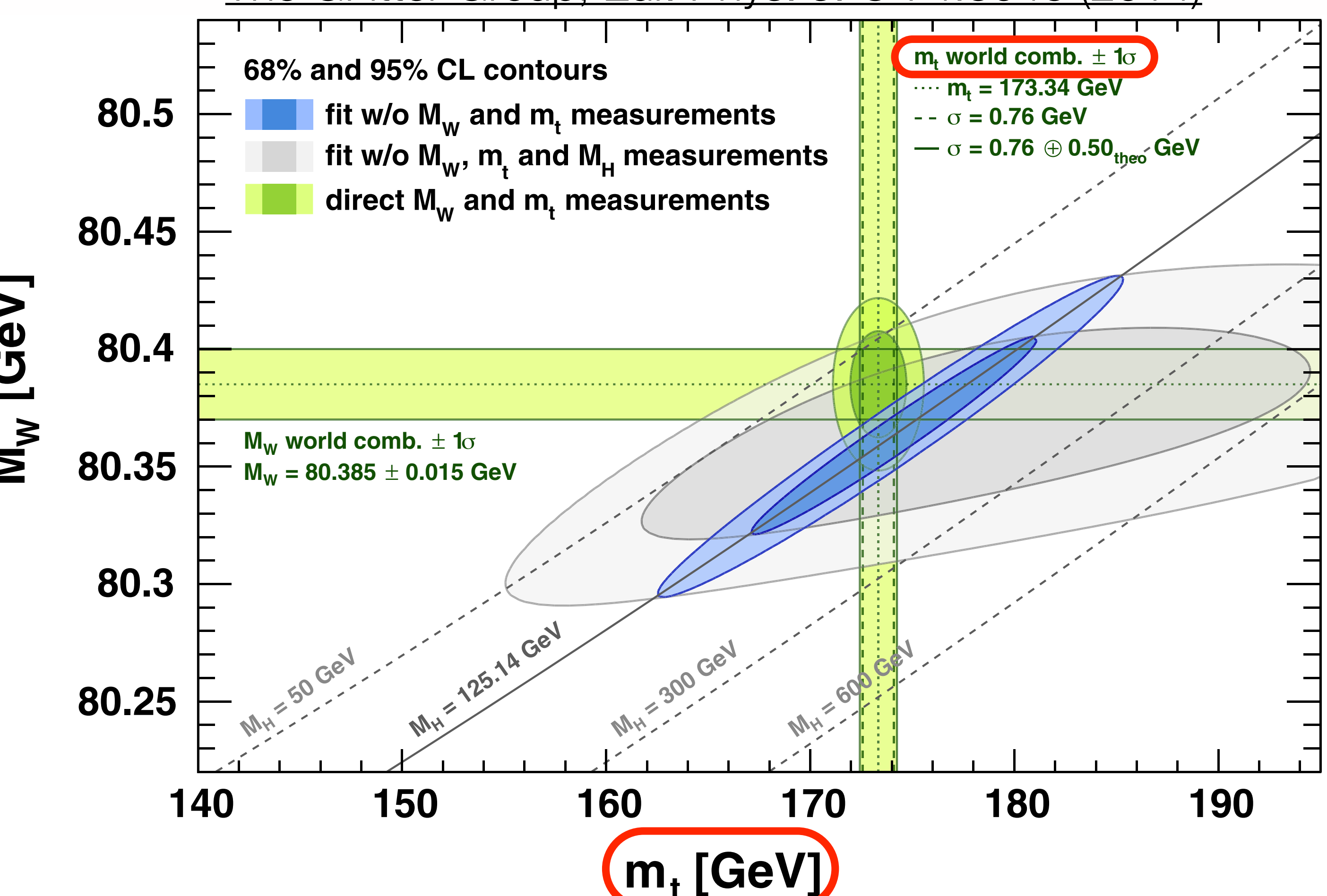
Largest coupling to Higgs in SM: Y_t >0.9

M_{top}~ electroweak symmetry breaking scale

$1/m_t$	<	$1/\Gamma_t$	<	$1/\Lambda$	<	m_t/Λ^2
Production time	<	Lifetime	<	Hadronization time	<	Spin decorrelation time

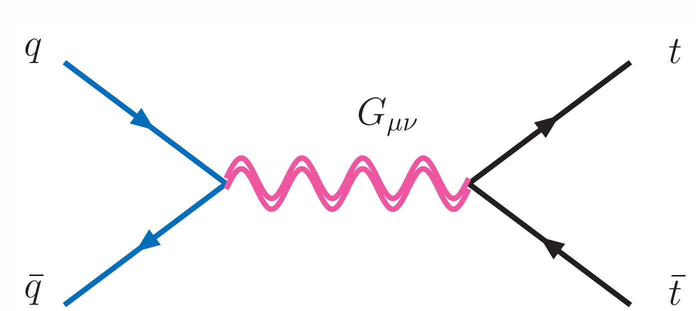
Strong, EWK production and decay rate test standard model

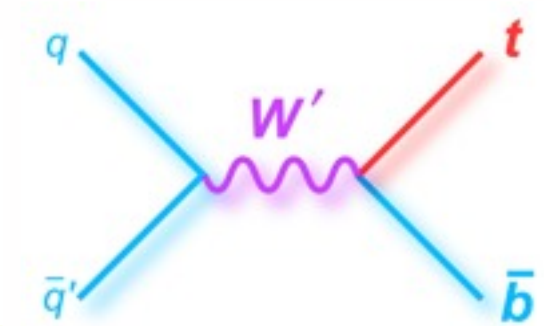
The GFitter Group, Eur. Phys. J. C 74:3046 (2014)



It can mimic Higgs and possible **new physics** (SUSY,..)

In many scenarios top quark has **direct/indirect coupling to new physics:** from extra dimensions to new strong forces

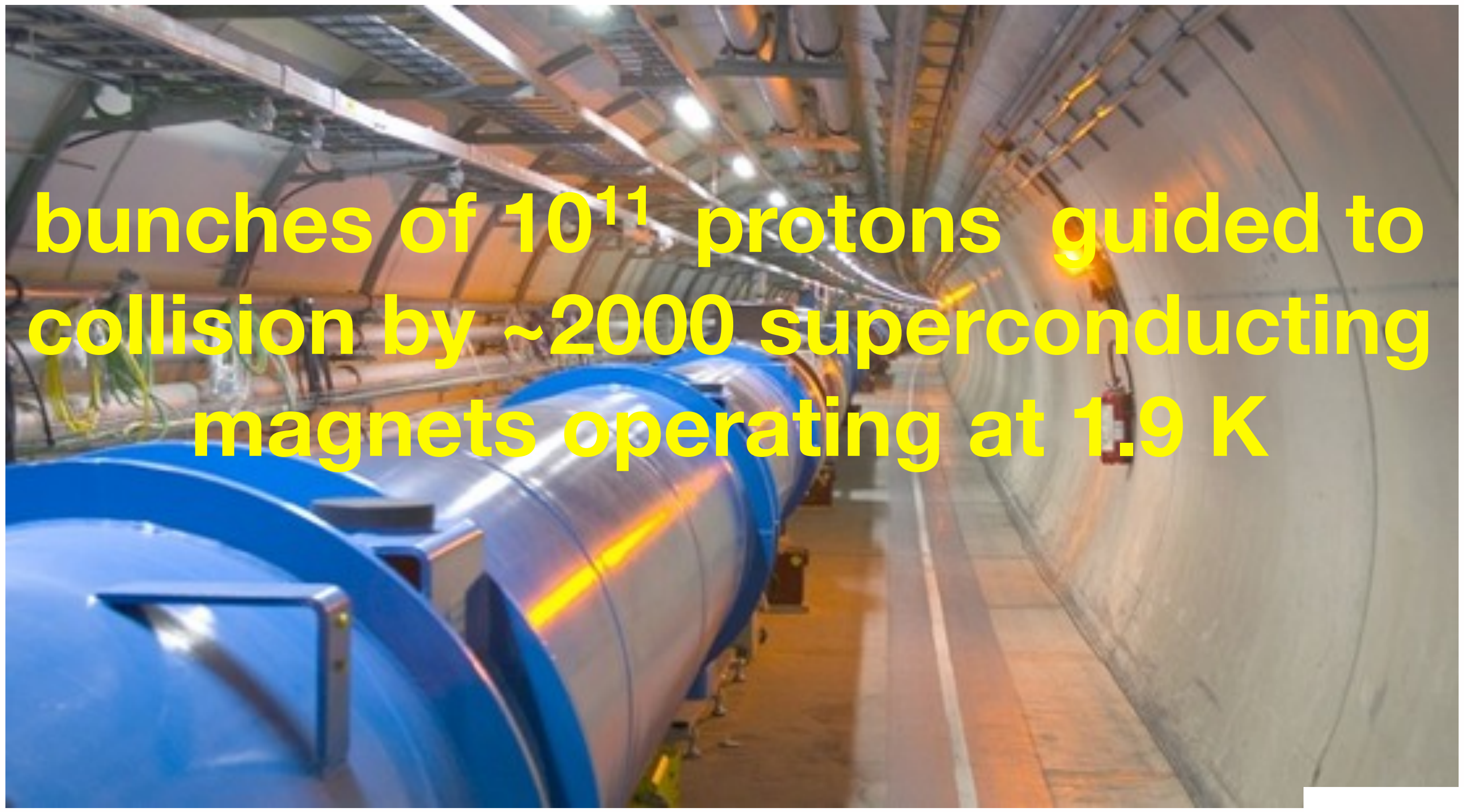


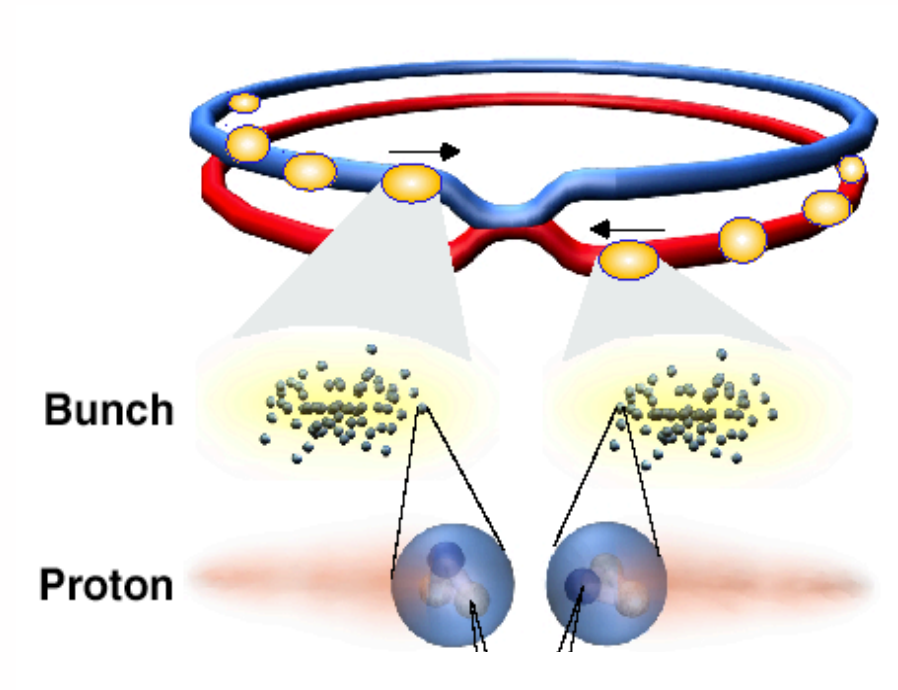


LHC : a *Top* producer i.e. providing the luminosity

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm}) = 7,8,13 TeV in 27 Km tunnel

eventually: E_{CM}=14TeV (7 TeV per beam, design value)





$$\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$$

Key parameters:

- N_i = bunch intensity
- n_b = number of bunches
- σ = colliding beam size

dN_{events}/dt = ***Luminosity*** * cross section

$N_{events}(\Delta t)$= ***∫Ldt*** * cross section

LHC : a *Top* producer i.e. providing the luminosity

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm} or $\sqrt{s}$) = 7 TeV in 27 Km tunnel

E_{cm}*(Tevatron)= 1.96 TeV*

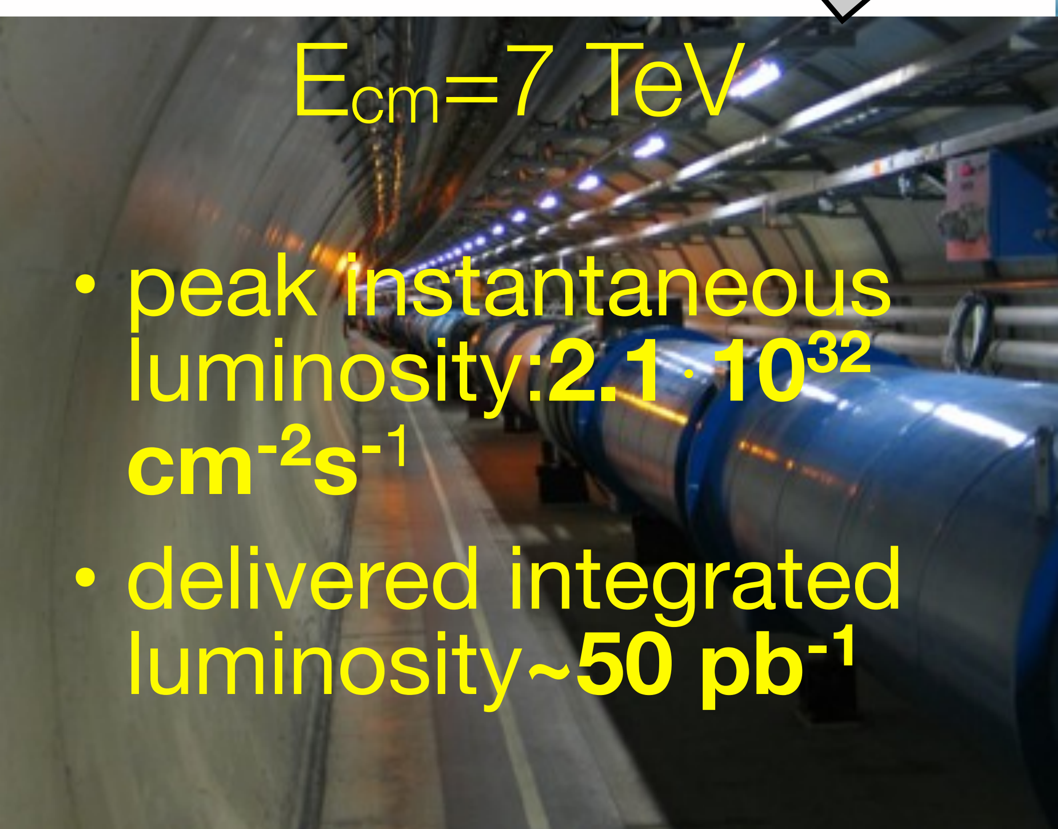
$$\mathcal{L} \propto \frac{N_1 N_2}{\sigma^2}$$

Key parameters:

- N_i = bunch intensity
- n_b = number of bunches
- σ = colliding beam size

Ad maiora..

2010



E_{cm}=7 TeV

- peak instantaneous luminosity:**2.1·10^{32} cm^{-2}s^{-1}**
- delivered integrated luminosity~**50 pb^{-1}**

design: **E_{CM}=14TeV** , lumi ***10^{34}cm^{-2} s^{-1}***

(~30 times Tevatron pp collider)

RUN2 (start)

2015 **E_{cm} =13 TeV *at start***

(14 to be decided later)

peak lumi: 1.6·10^{34} cm^{-2} s^{-1} ± 20%

∫Ldt ~40-45 fb^{-1} /exp per year

RUN1

2012 **E_{cm} =8 TeV**

peak lumi: 7.7·10^{33} cm^{-2} s^{-1}

∫Ldt ~22 fb^{-1} /exp

2011 **E_{cm} =7 TeV**

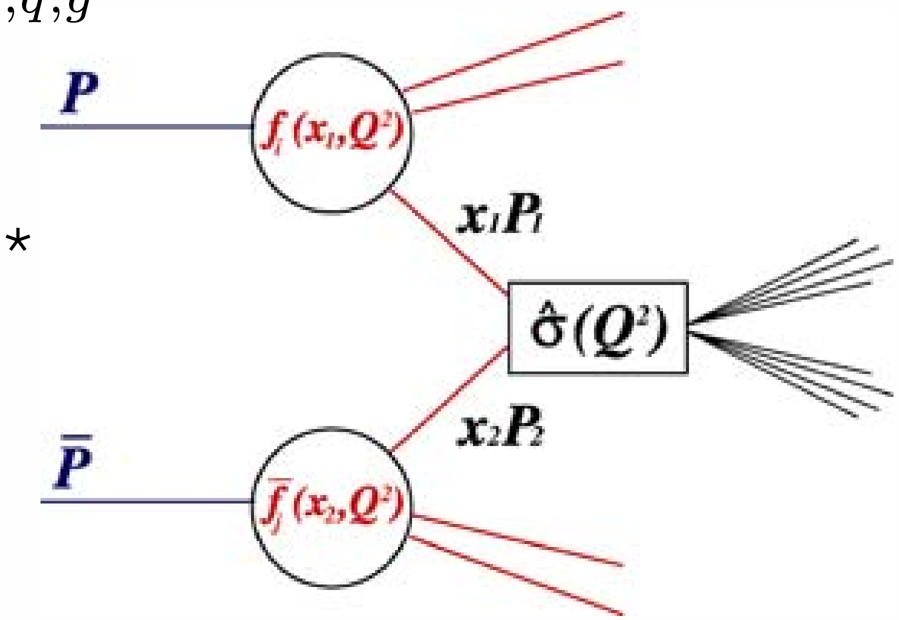
peak lumi 2·10^{33} cm^{-2} s^{-1}

∫Ldt ~5.6 fb^{-1} /exp

$N_{events}(\Delta t)$= ***∫Ldt*** * cross section

Top quark @ LHC: the cross section(I)

$$\sigma^{t\bar{t}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int \mathrm{d}x_i \mathrm{d}x_j f_i\left(x_i, \mu^2\right) \bar{f}_j\left(x_j, \mu^2\right) \quad \hat{\sigma}^{ij\to tt}\left(\rho, m_t^2, x_i, x_j, \alpha_s(\mu^2), \mu^2\right)$$



	LHC(14)	LHC(7)	Tev(1.9)
gg	~90%	~85%	~10%
qq	~10%	~15%	~90%

N

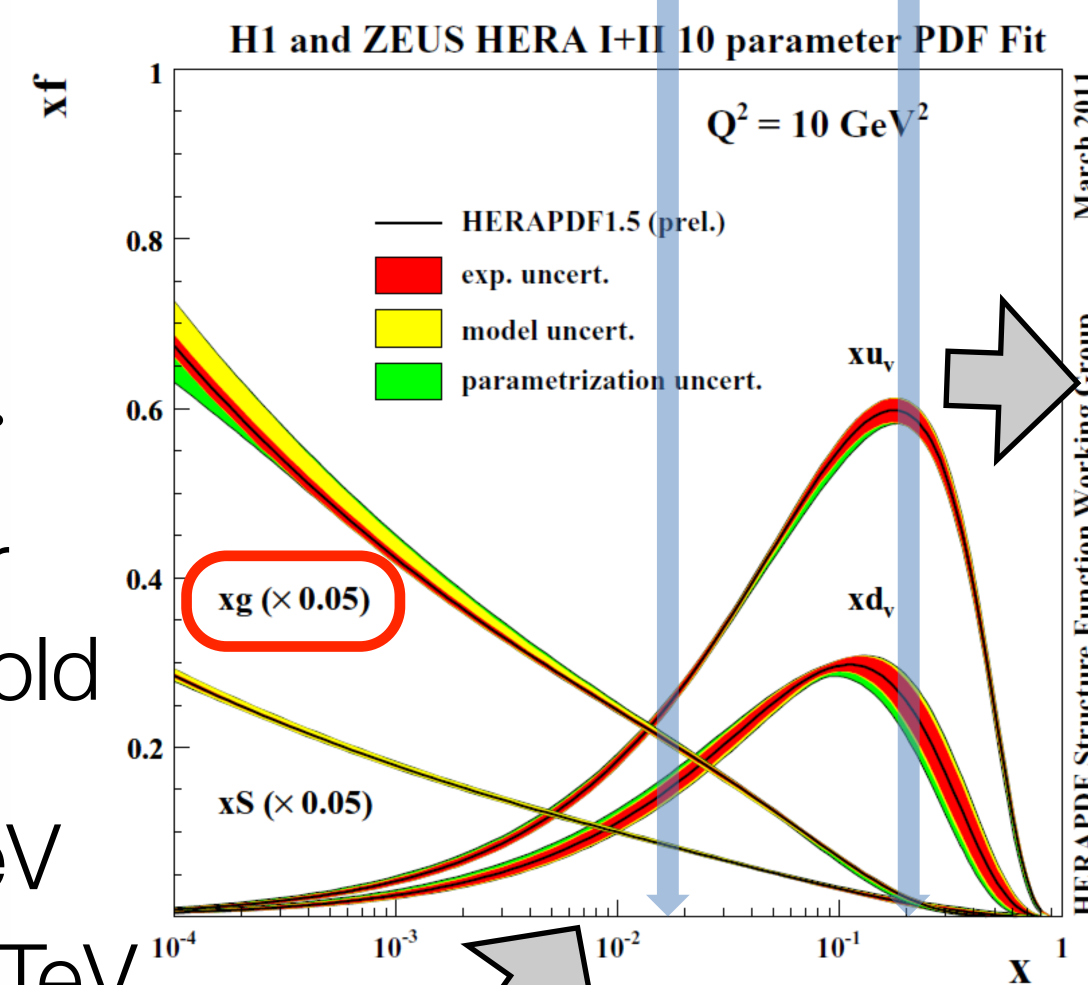
$N_{events}(\Delta t) =$ ***∫Ldt*** * cross section

To produce $t\bar{t}$

~massless partons

$\hat{s} \geq 4m_t^2$ ⇒ $x_i x_j = \hat{s}/s \geq 4m_t^2/s.$

$f_i(x)$ falls with larger x ⇒ typical $x_i x_j$ near threshold



⇒ $x \approx \frac{2m_t}{\sqrt{s}} =$ 0.19 @ Tevatron √s=1.8 TeV

0.18 @ Tevatron √s=1.96 TeV

(0.048, 0.043, 0.025) @ LHC with √s=(7, 8,14) TeV

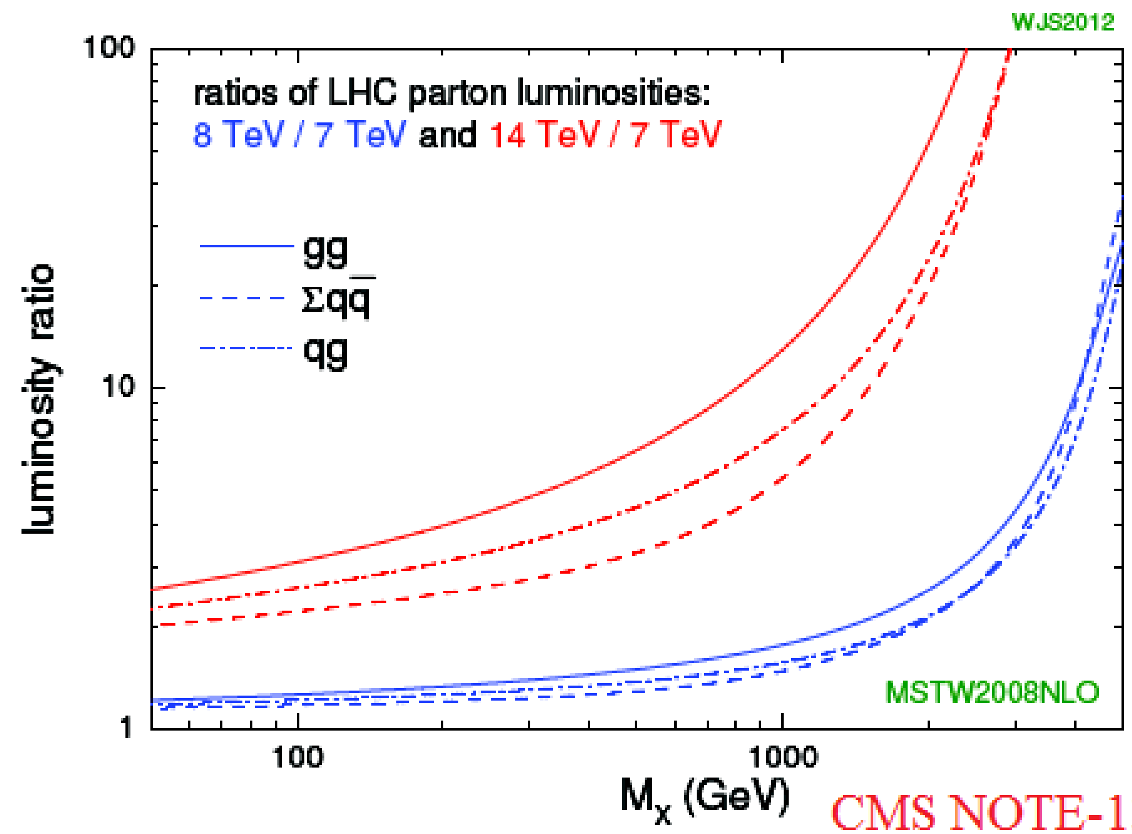
Top quark @ LHC: production (III)

(formulas from Campbell et al, hep/ph 0611148)

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij} = \sum_{i,j} \int \left(\frac{d\hat{s}}{\hat{s}}\, dy\right) \left(\frac{dL_{ij}}{d\hat{s}\, dy}\right) (\hat{s}\, \hat{\sigma}_{ij}) \sim \sum_{i,j} \frac{\Delta\hat{s}}{\hat{s}} \left(\frac{dL_{ij}}{d\hat{s}}\right) (\hat{s}\, \hat{\sigma}_{ij})$$

$$\frac{dL_{ij}}{d\hat{s}\, dy} = \frac{1}{s} \frac{1}{1+\delta_{ij}} [f_i(x_1,\mu) f_j(x_2,\mu) + (1 \leftrightarrow 2)]$$

- Different **x-range and center of mass** dependence incorporated in **Parton luminosities**→
  - **gg→X** dominated processes **grow more than qq →X** ones
  - **larger gains at high multi-TeV masses** ~up to O(100)



CMS NOTE-13-002

$R^{th,nnpdf}$ = *14TeV to 8 TeV xsec ratios*

JHEP{1208},2012

Cross Section	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}$(%)	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar{t}/Z$	2.12	$\pm$ 1.3	$-0.8-0.8$	$-0.4-1.1$
$t\bar{t}$	3.90	$\pm$ 1.1	$-0.5-0.7$	$-0.4-1.1$
Z	1.84	$\pm$ 0.7	$-0.1-0.3$	$-0.3-0.2$
W^+	1.75	$\pm$ 0.7	$-0.0-0.3$	$-0.3-0.2$
W^-	1.86	$\pm$ 0.6	$-0.1-0.3$	$-0.3-0.1$
W^+/W^-	0.94	$\pm$ 0.3	$-0.0-0.0$	$-0.0-0.0$
W/Z	0.98	$\pm$ 0.1	$-0.1-0.0$	$-0.0-0.0$
ggH	2.56	$\pm$ 0.6	$-0.1-0.1$	$-0.9-1.0$
$t\bar{t}(M_{tt} \geq 1$ TeV$)$	8.18	$\pm$ 2.5	$-1.3-1.1$	$-1.6-2.1$
$t\bar{t}(M_{tt} \geq 2$ TeV$)$	24.9	$\pm$ 6.3	$-0.0-0.3$	$-3.0-1.1$
$\sigma_{\rm jet}(p_T \geq 1$ TeV$)$	15.1	$\pm$ 2.1	$-0.4-0.0$	$-1.9-2.4$
$\sigma_{\rm jet}(p_T \geq 2$ TeV$)$	182	$\pm$ 7.7	$-0.3-0.2$	$-5.7-4.0$

- **Cross sections in "tails" increase differently** from the inclusive value

thanks to K. Suruliz, TOP2013

Top quark @ LHC: production (II)

pp collisions

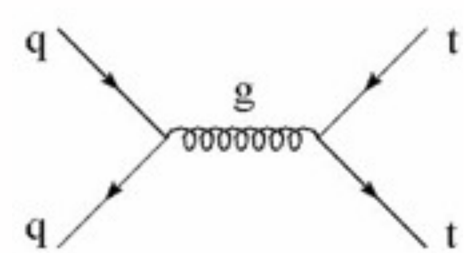
probing lower x than Tevatron → (abundant) gluon fusion dominated

	Tevatron	LHC(7)	LHC(14)
gg	~10%	**~85%**	~90%
qq	~90%	**~15%**	~10%

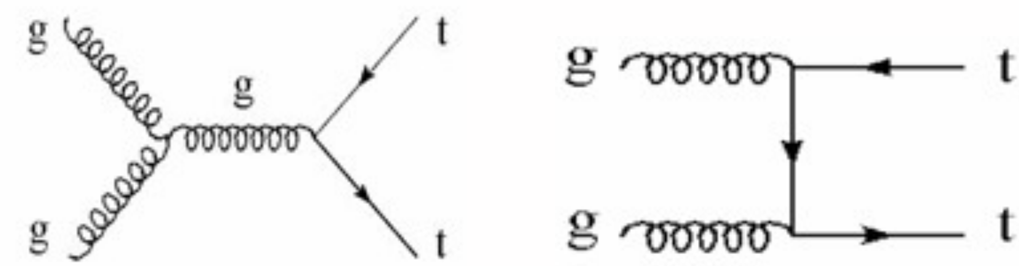
m_{top}= 172.5

top pairs: strong

qq annihilation



gluon fusion



At Tevatron

$\sigma_{t\bar{t}} \sim 7$ pb
$\sigma_t \sim 3.5$ pb

Czakon,Mitov,Fiedler 2013

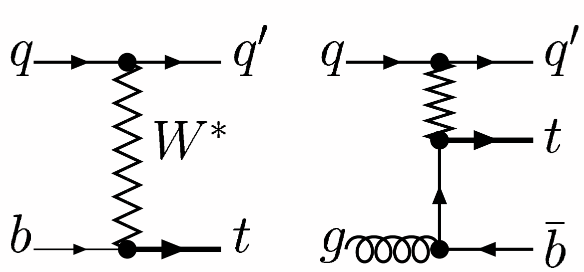
NNLO+NNLL accuracy

$\delta\sigma_{tt}/\sigma_{tt}$ ~4%

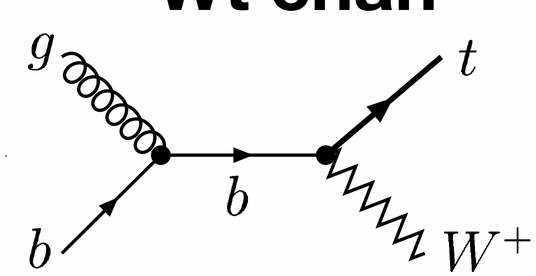
σ_{7TeV} (pb)	$172^{+4.4}_{-5.8}{}^{+4.7}_{-48}$
σ_{8TeV} (pb)	$245^{+6.2}_{-8.4}{}^{+6.2}_{-6.4}$
σ_{13TeV} (pb)	~741

single top: electroweak

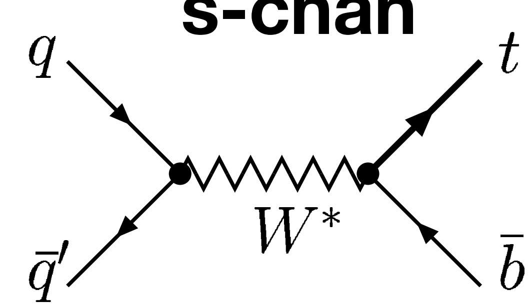
t-chan



Wt chan



s-chan



	t-chan	Wt chan	s-chan
σ_{7TeV} (pb)	64.6±2.4	15.7±1.1	4.6±0.2
σ_{8TeV} (pb)	87.8±3.4	22.4±1.5	5.6±0.2
σ_{13TeV} (pb)	~213	~71.7	~10.9

Kidonakis 2010,2011

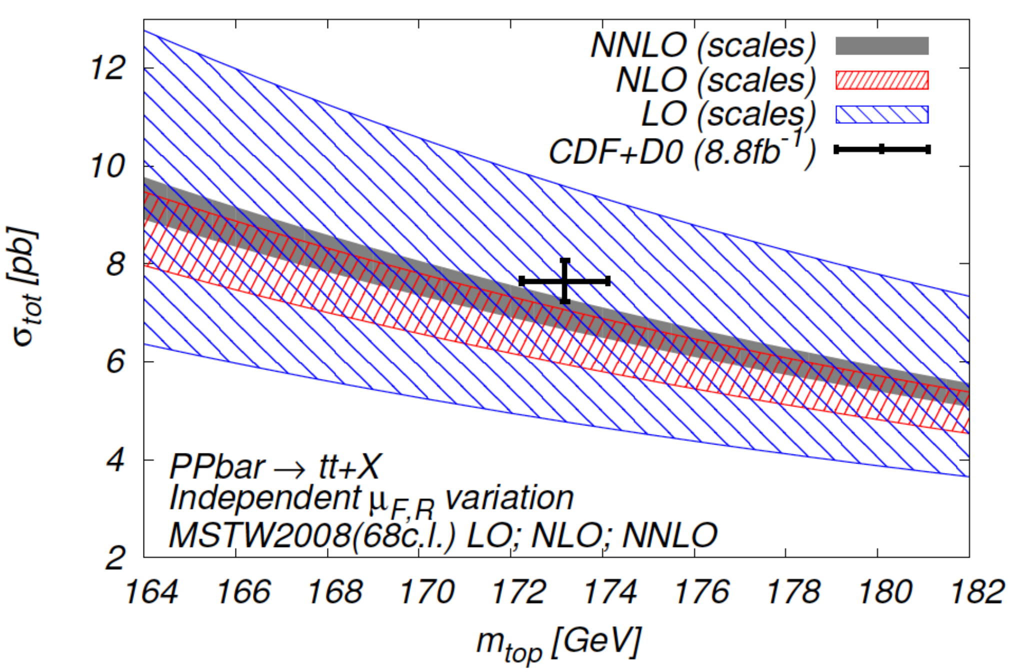
approx NNLO

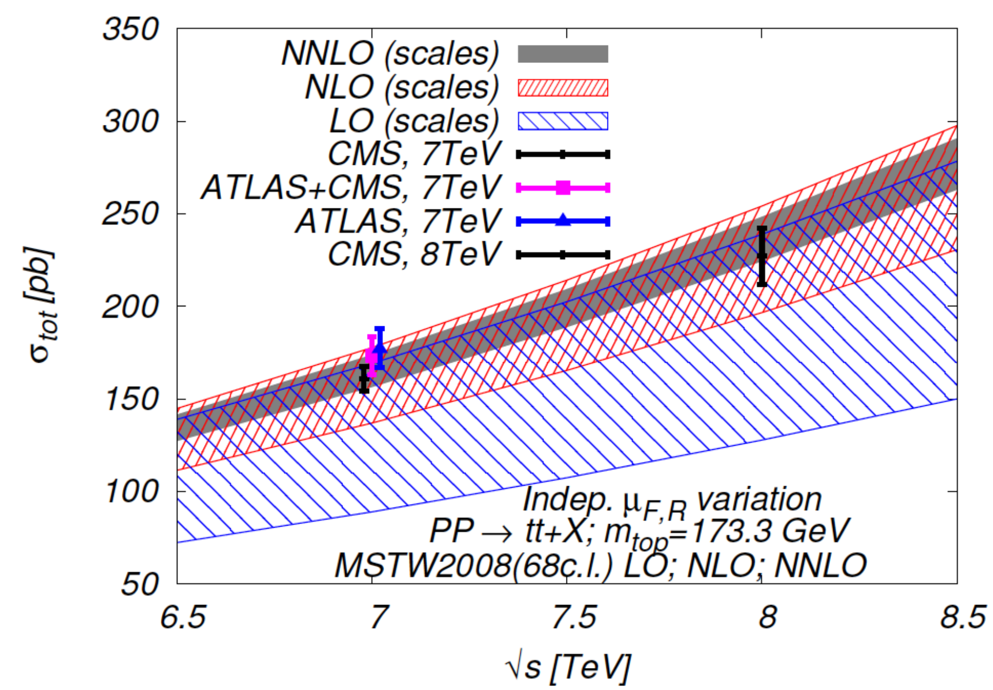
$\delta\sigma_t/\sigma_t$ ~2 to 7%

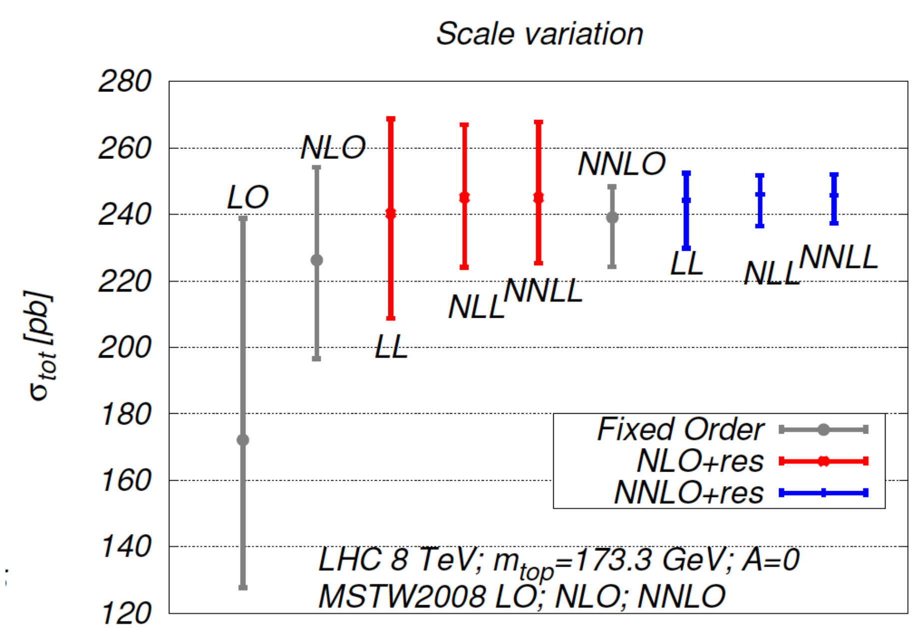
Impressive theory progress: the NNLO revolution

- NNLO for $t\bar{t}$ is available now *M. Czakon @ TOP2014*

Perturbative convergence







Concurrent uncertainties:

Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_S (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

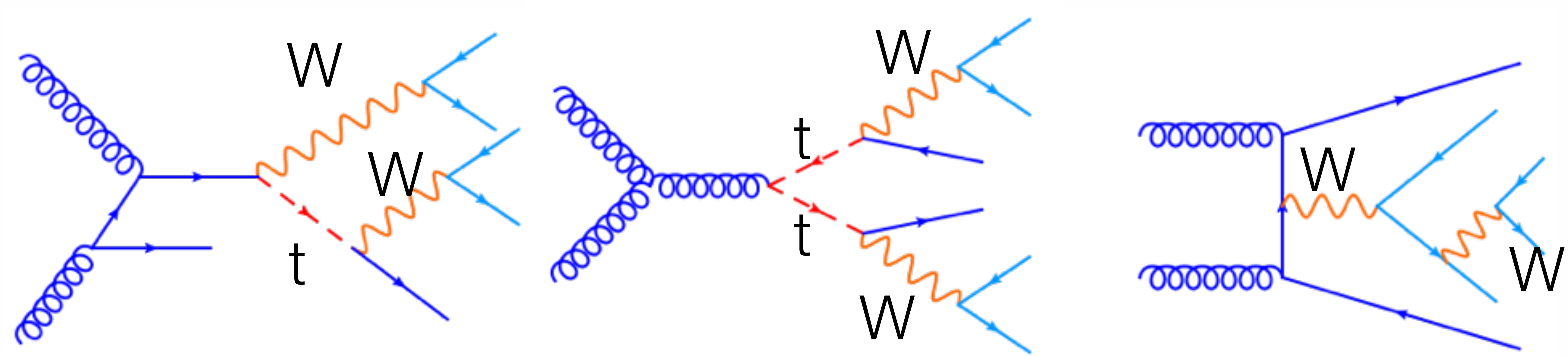
Soft gluon resummation makes a difference:

5% -> 3%

Impressive theory progress: NLO for top pairs and single top

- **At NLO tt, Wt and WW share the same initial final state so one needs WWbb @NLO**

(graphs by F Caola, CERN)



it is there now!!

- results provided recently by two groups:

  [FREDERIX, ARXIV:1311.4893] [CASCIOLI, KALLWEIT, MAIERHÖFER, POZZORINI, ARXIV:1312.0546]

Future @ NLO

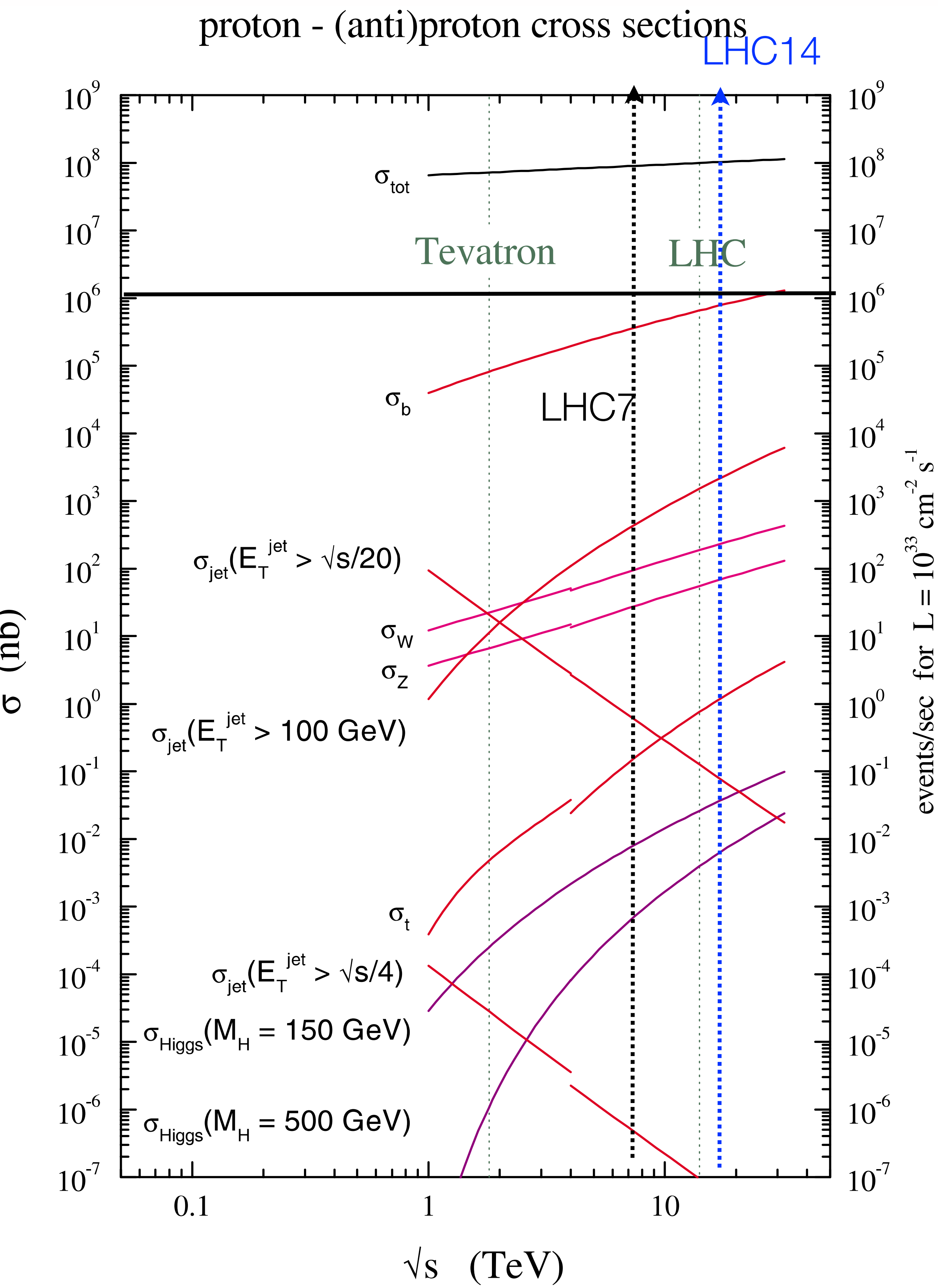
WWbb final state with doubly resonant (tt), singly resonant (Wt) and non resonant interfering contrib

single top t-channel

check description by Rikkert

Top @ LHC: in the context

(W.J Stirling, private communication)



t and $t\bar{t}$ cross section

√s(TeV)	σ_{tt}(pb)	σ_t(pb)	$t\bar{t}$(t) Rate at L= $10^{33}cm^{-2}\ s^{-1}$
1.96(pp)	~7		
7(pp)	~172	~85	0.17 (0.08)Hz
8(pp)	~245	~115	0.24 (0.12)Hz
13(pp)	~740	~296	0.74 (0.30)Hz
14(pp)	~900	~338	0.90 (0.33)Hz

~5.4M (~0.96 M) $t\bar{t}$ events produced by LHC in 2012 (2011)

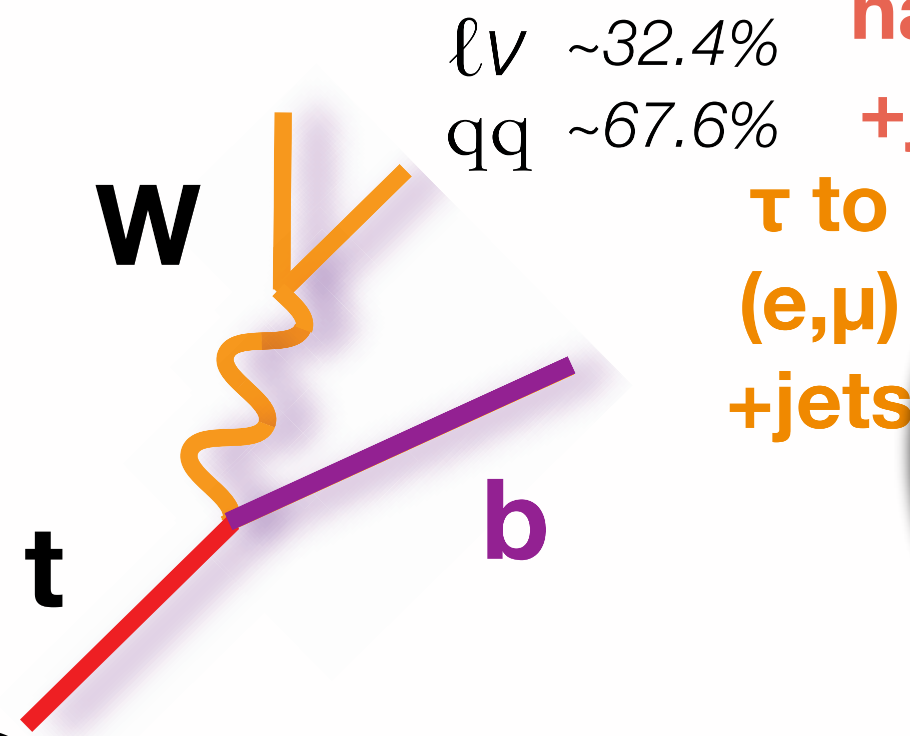
~2.5M (0.47 M) single top events produced by LHC in 2011 (2012)

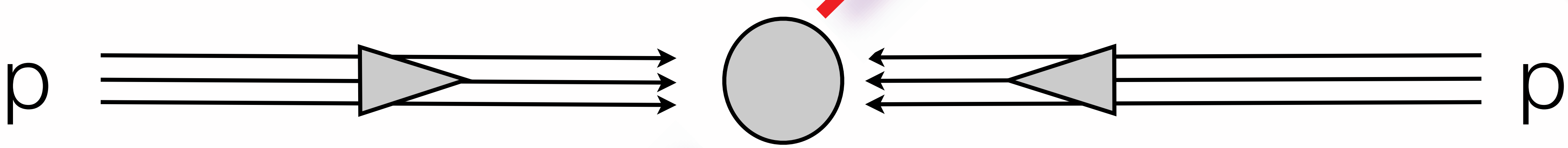
LHC is a TOP FACTORY

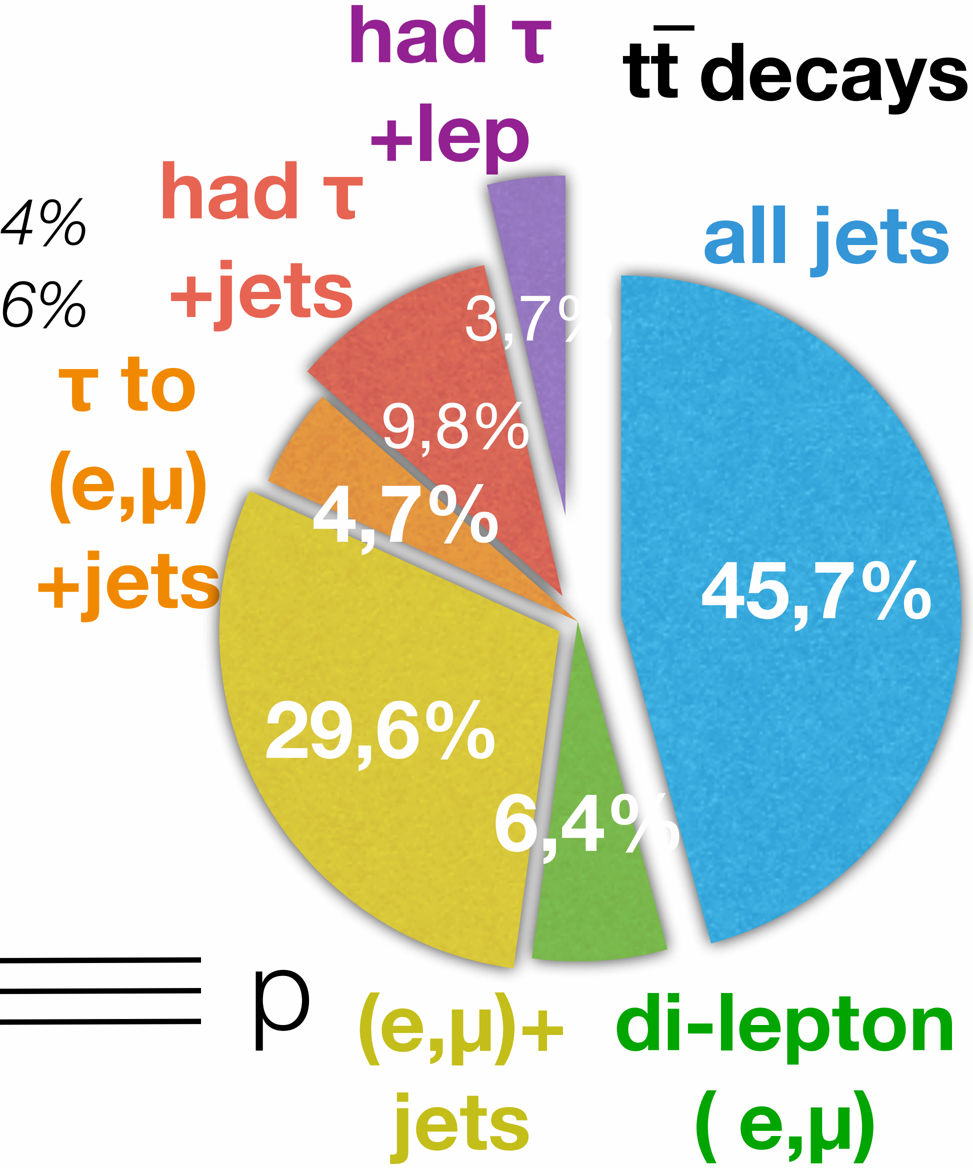
Tevatron (lower energy collider): $\int Ldt$ =9.4 fb^{-1} on tape, expect ~ $6.6\cdot10^4$ events

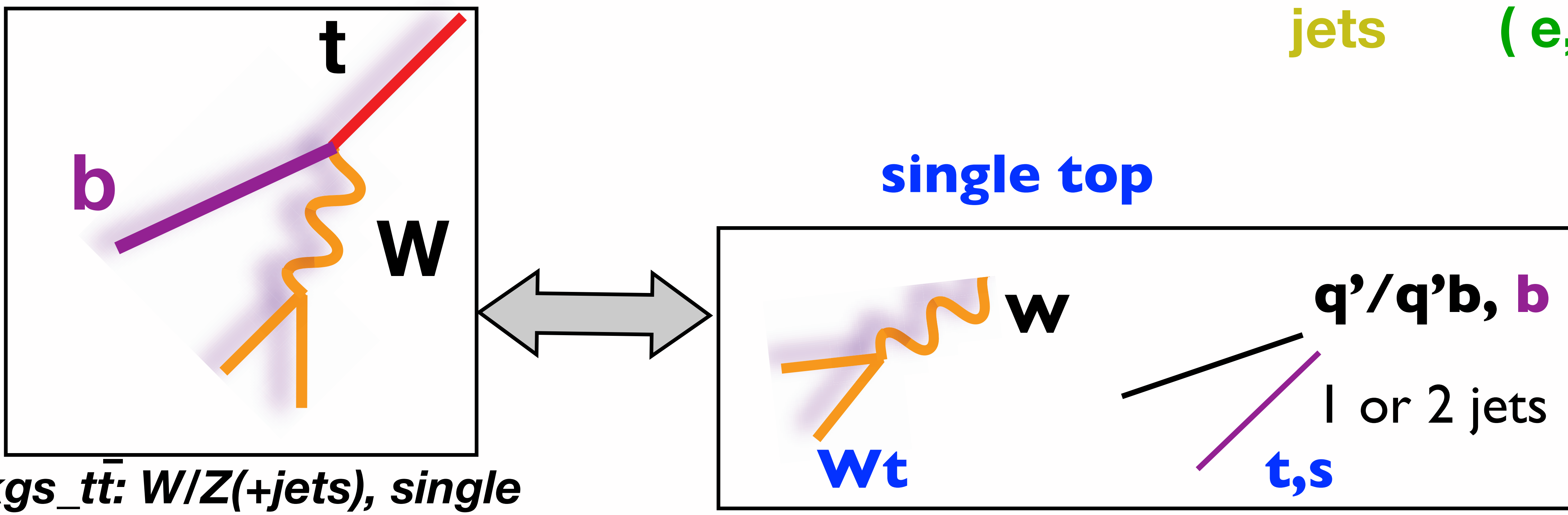
Final state signatures

- **High P_T jets of hadrons**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**









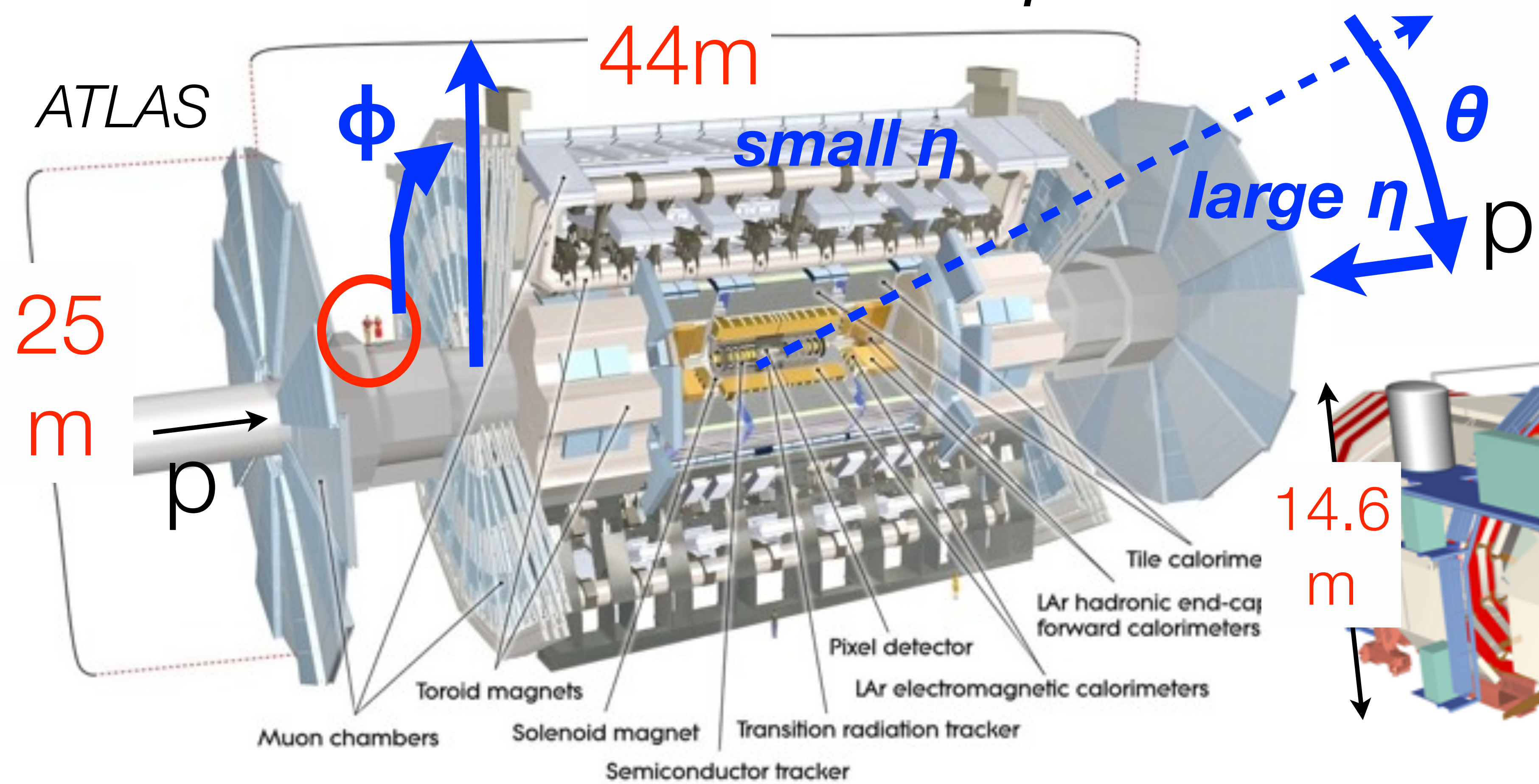
bkgs_tt̄: W/Z(+jets), single top, QCD, Di-bosons

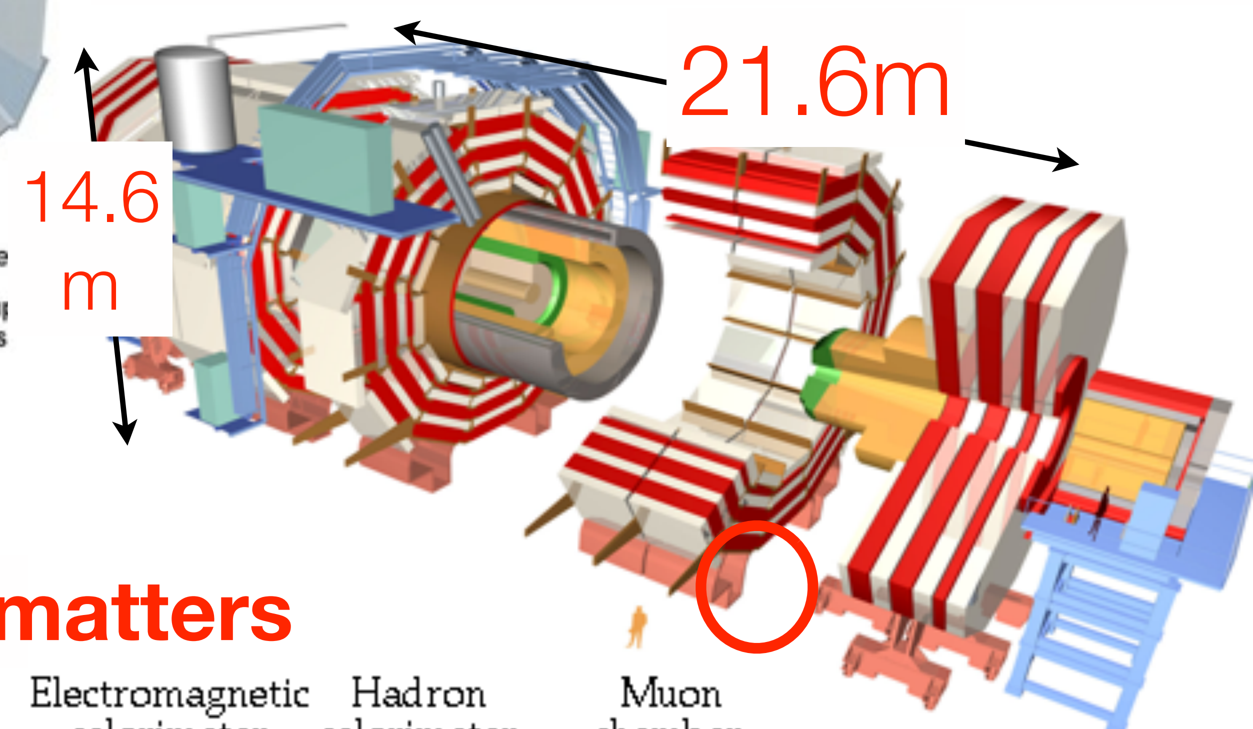
bkgs_single_t: tt̄ + same bkgs_tt̄

ATLAS & CMS: *Top* observers

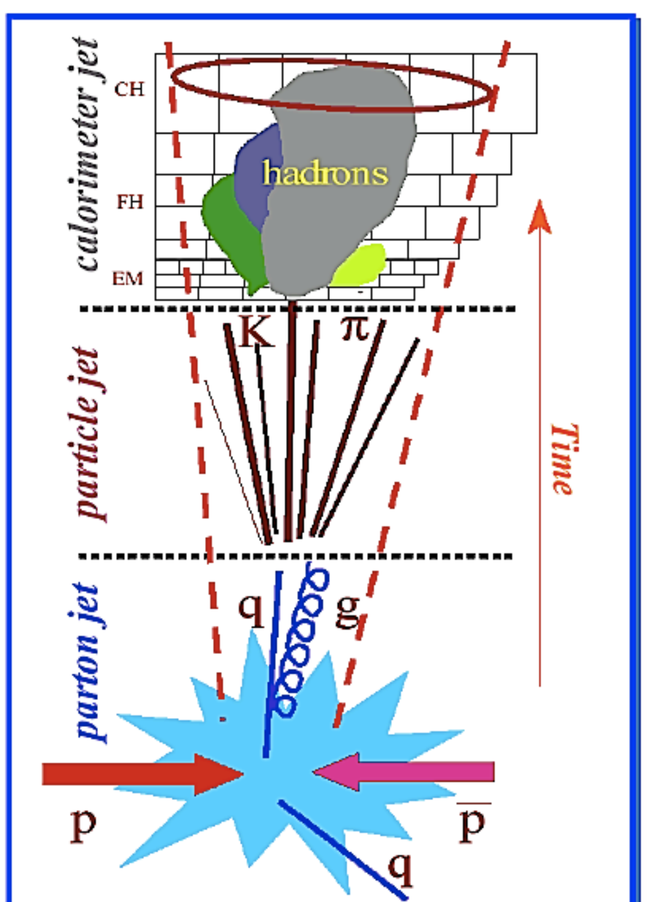
3 (ATLAS) or 2(CMS) trigger levels for event selection

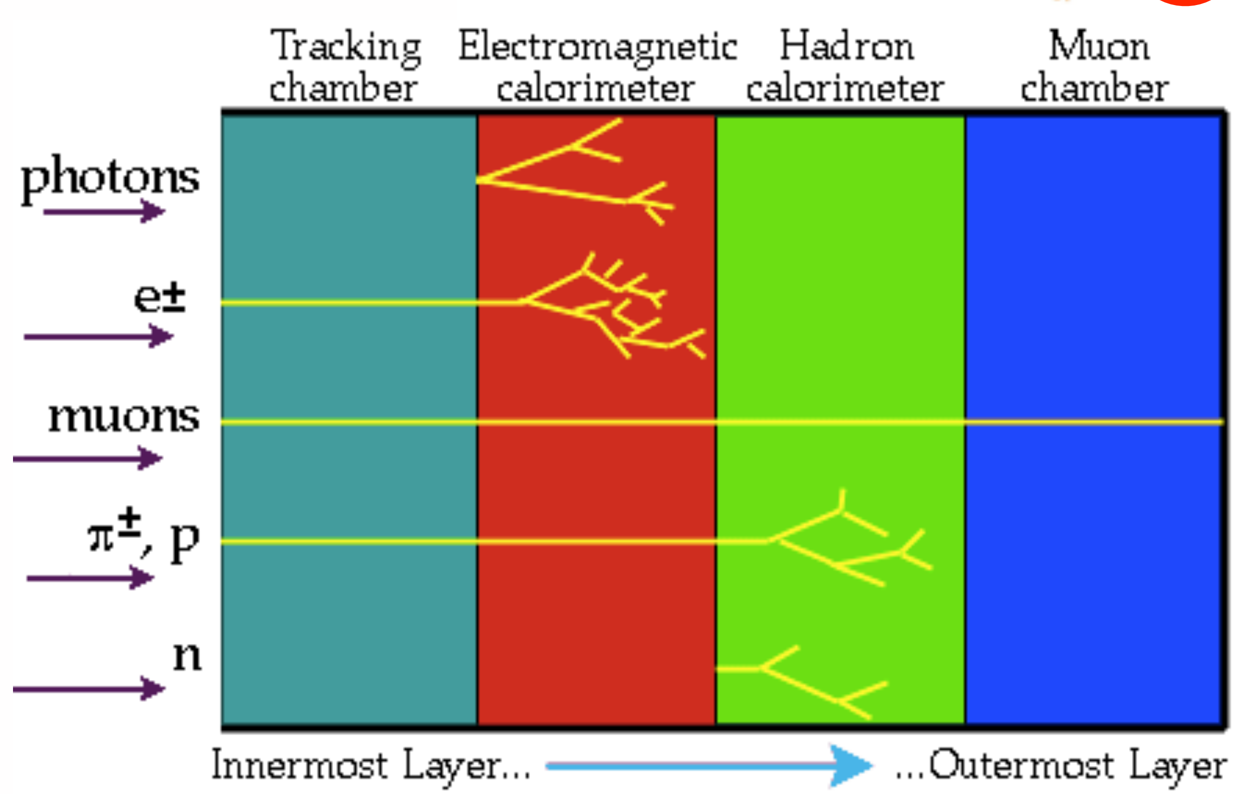
η = pseudorapidity =-ln (tan(θ/2))





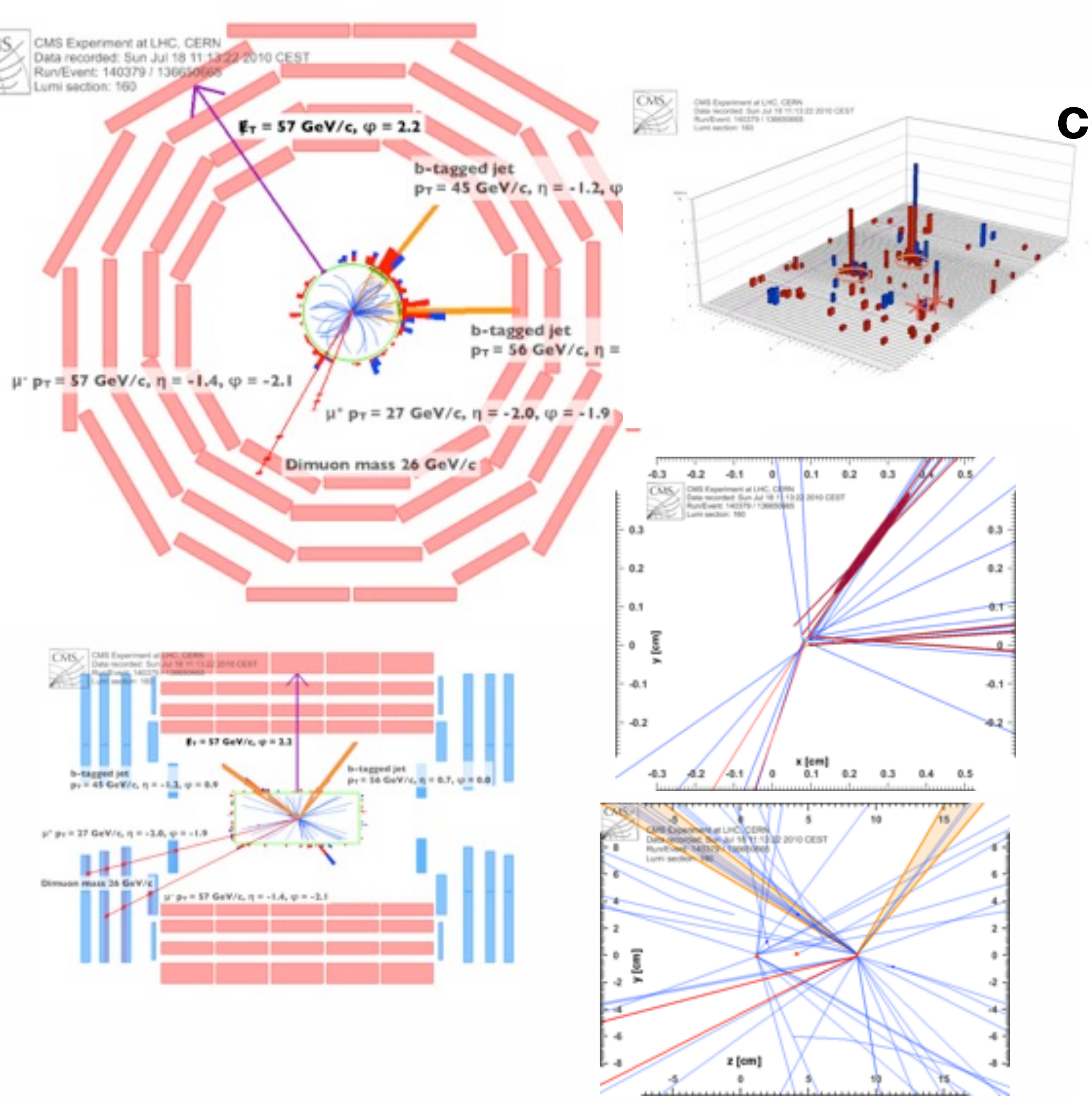
size matters





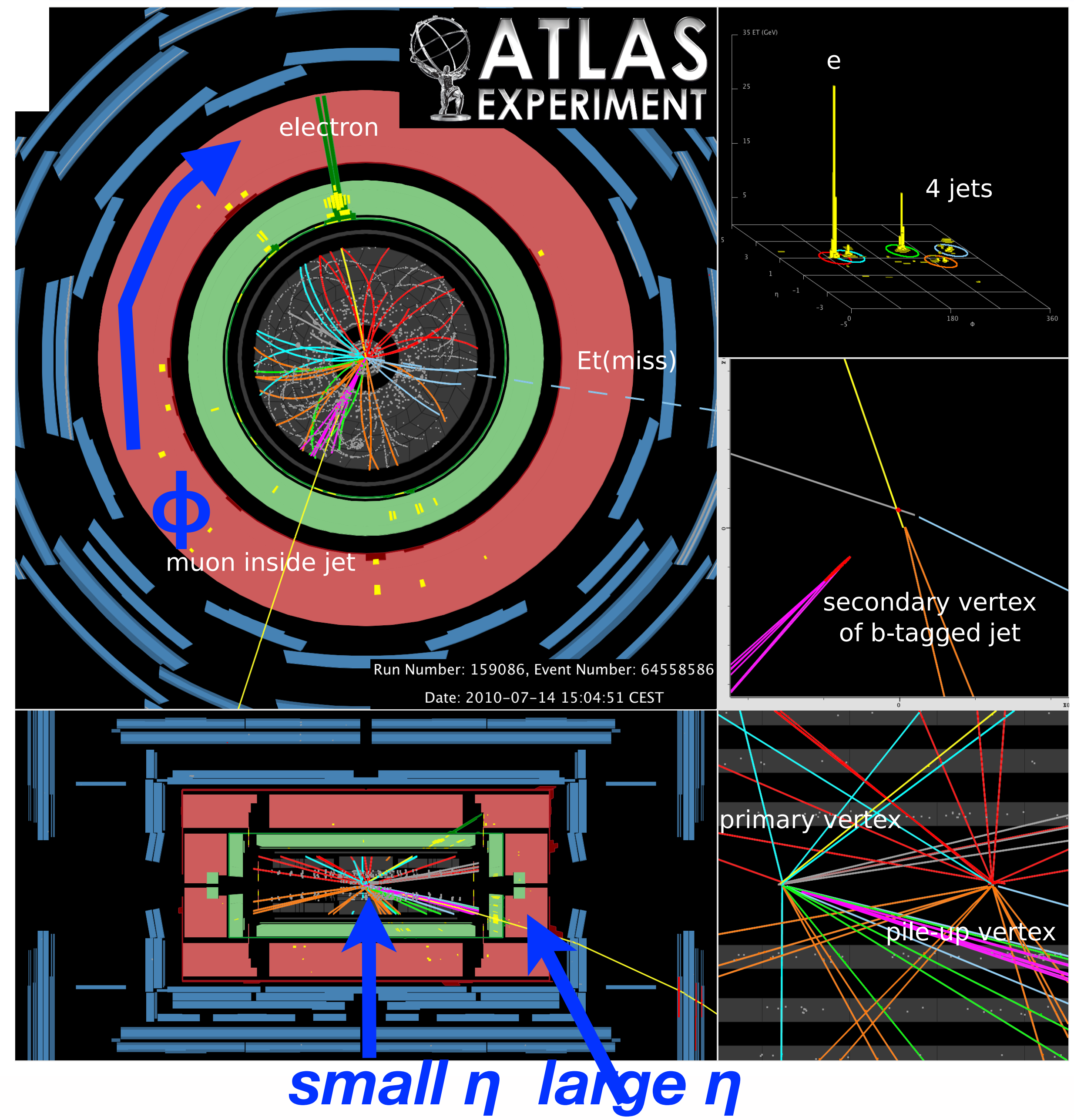
ATLAS and CMS: *Top observers.....*

Top quark events are real commissioning tool: full detector at play!!



di-lepton (μμ+jets) candidate

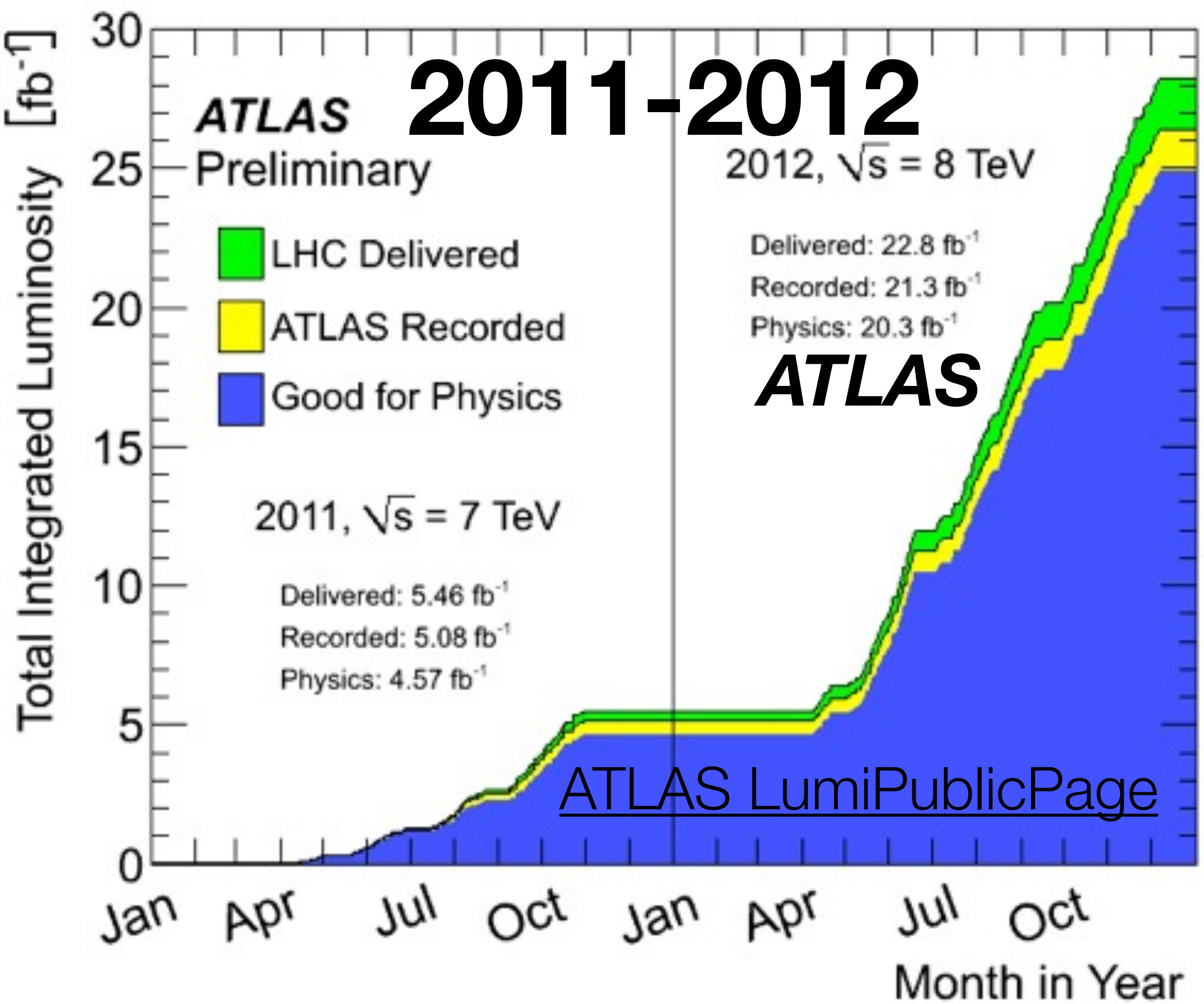
e+jets candidate

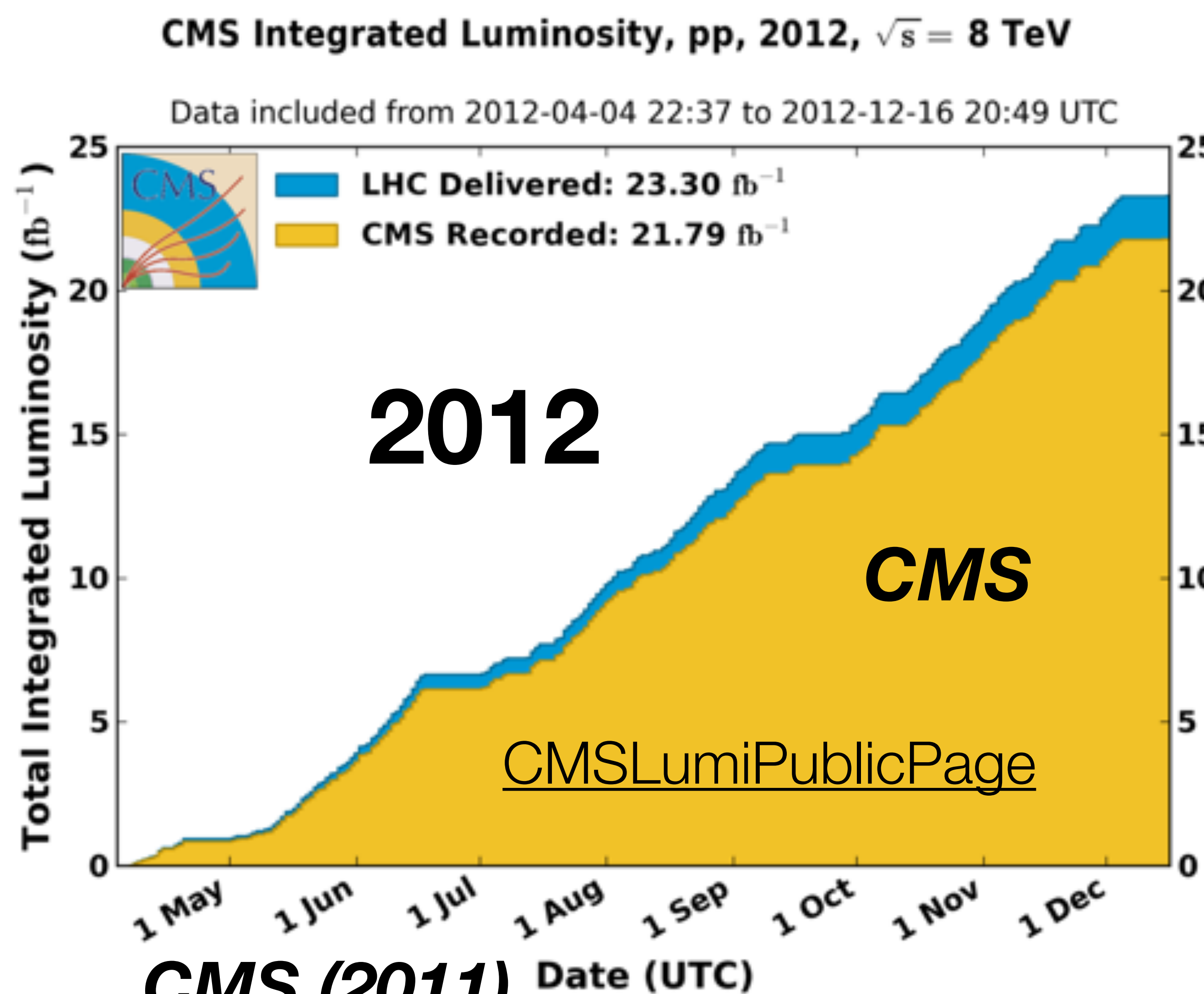


...with excellent data taking performance

Analyses use : ~4.5-5 fb^{-1} (2011) to ~20-21 fb^{-1} (2012)

$N_{events}(\Delta t) = \int L dt$ * cross section





Lumi uncertainty ~1.8% (2011) and 2.8% (2012)

ATLAS (2010)

Total Recorded (Delivered) Lumi: **45.0 (48.1) pb^{-1}**

Lumi uncertainty~3.4%

Data sample for first top paper~3 pb^{-1}

CMS (2011)

Total Recorded (Delivered) Lumi:

5.41(5.51) fb^{-1}

Lumi uncertainty~4.6%

CMS (2010)

Total Recorded (Delivered) Lumi:

40.76 (44.22) pb^{-1}

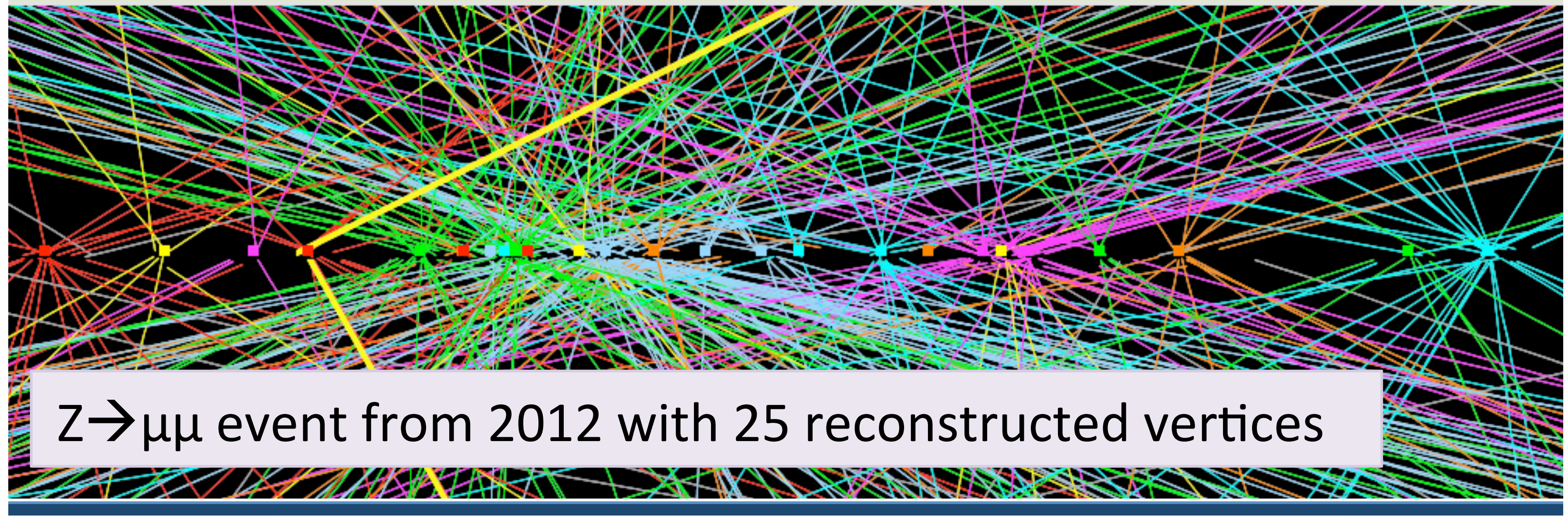
Lumi uncertainty~4%

…In a harsh environment

Number of Interactions per Crossing

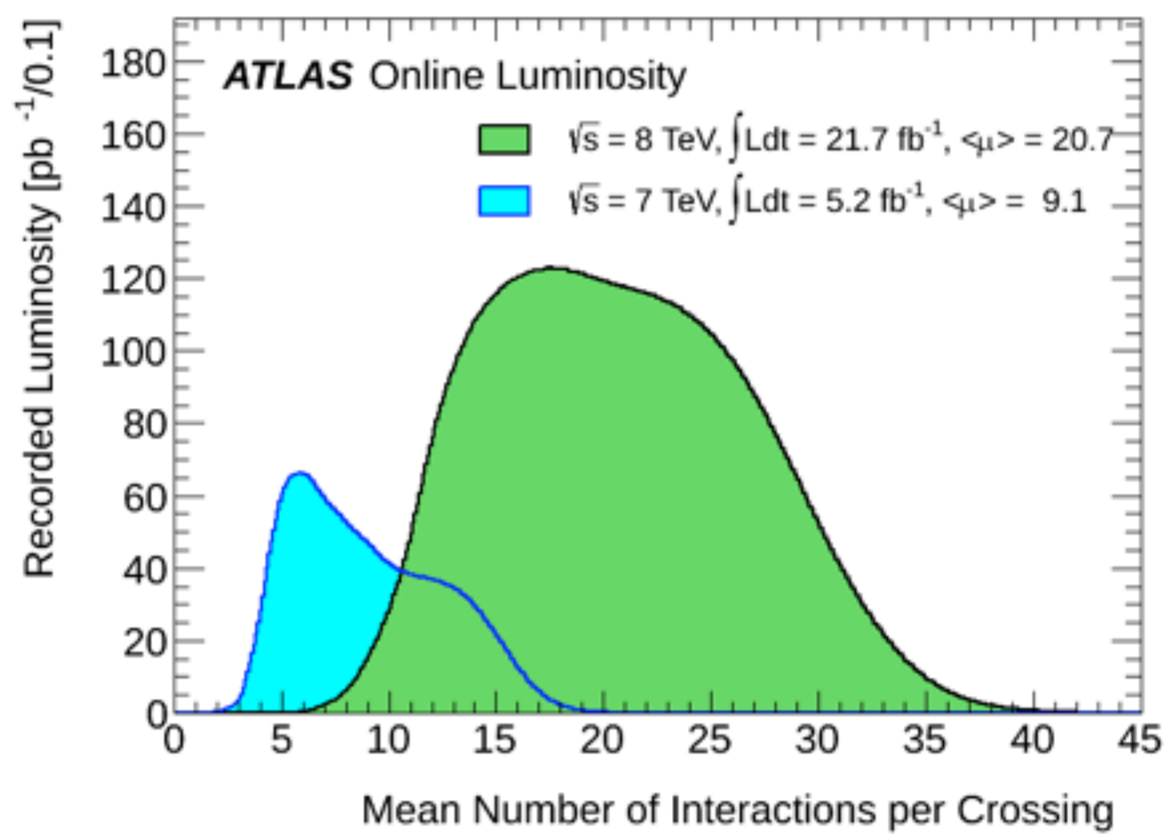
- Running with 50ns bunch spacing (instead of 25ns)
  - → double pile-up for same luminosity
- Has to be fought and mitigated at all levels:
  - Trigger, reconstruction of physics objects, isolation cuts, etc.
  - Data processing: CPU time for reconstruction…

M. Aleksa TOP2012



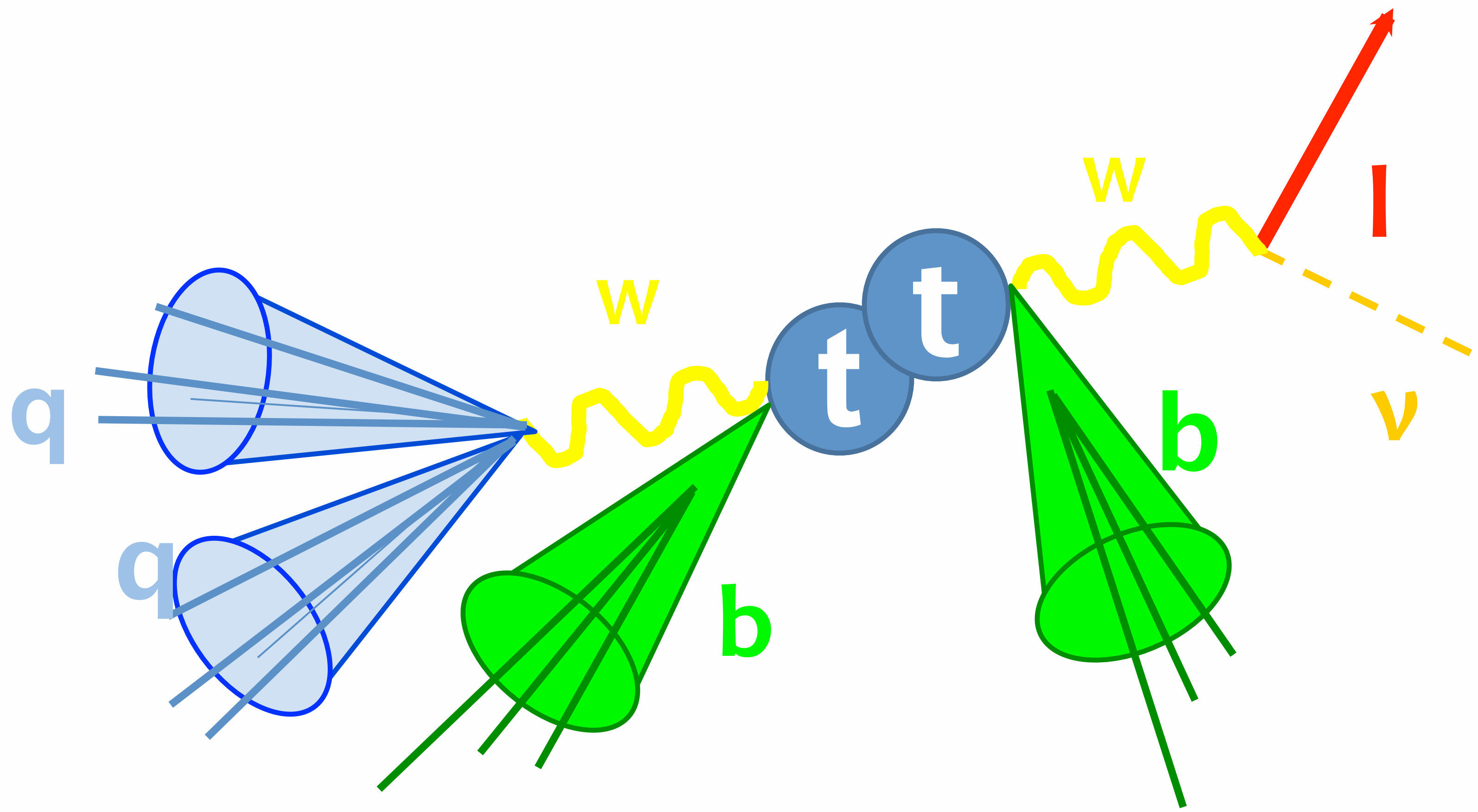
*Shown is **the luminosity-weighted distribution of the mean number of interactions per crossing for the 2011 and 2012 data.***

*This shows the full 2011 run and 2012 data taken between April 4th and Novemebr 26th The integrated luminosities and the mean mu values are given in the figure. The mean number of interactions per crossing corresponds **the mean of the poisson distribution on the number of interactions per crossing calculated for each bunch.** It is calculated from the instantaneous per bunch luminosity as $\mu = L_{bunch} \times \sigma_{inel} / f_r$ where L_{bunch} is the per bunch instantaneous luminosity, σ_{inel} is the inelastic cross section which we take to be 71.5 mb for 7TeV collisions and 73.0 mb for 8TeV collisions, n_{bunch} is the number of colliding bunches and f_r is the LHC revolution frequency. More details on this can be found in arXiv:1101.2185.*



Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)

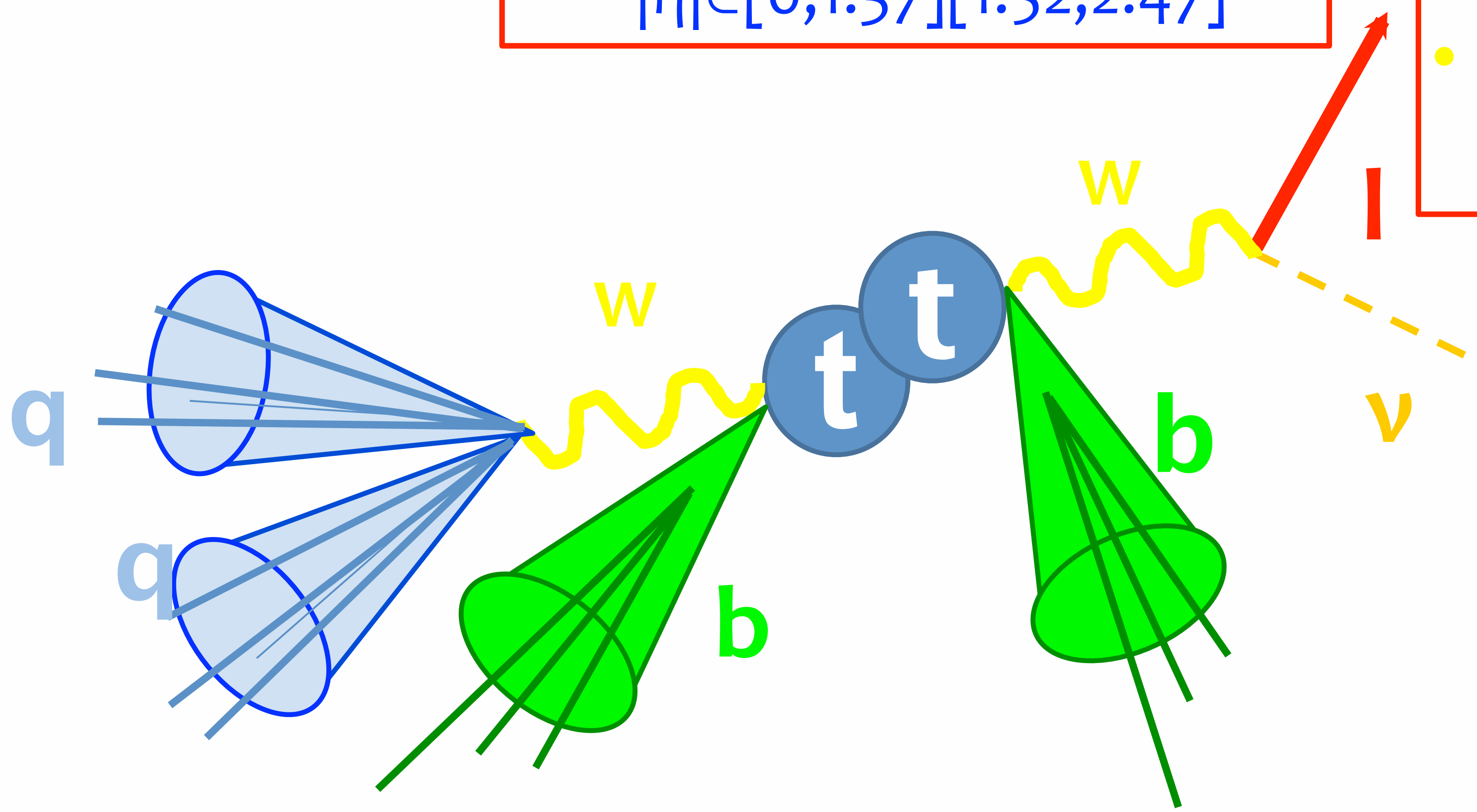


Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)

Electron
- Good isolated calo object
- Matched to track
- E_T>25 GeV
- $|\eta|\in[0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Calo and track isolation
- $p_T > 20$ GeV $|\eta| < 2.5$ (2.1 for CMS)



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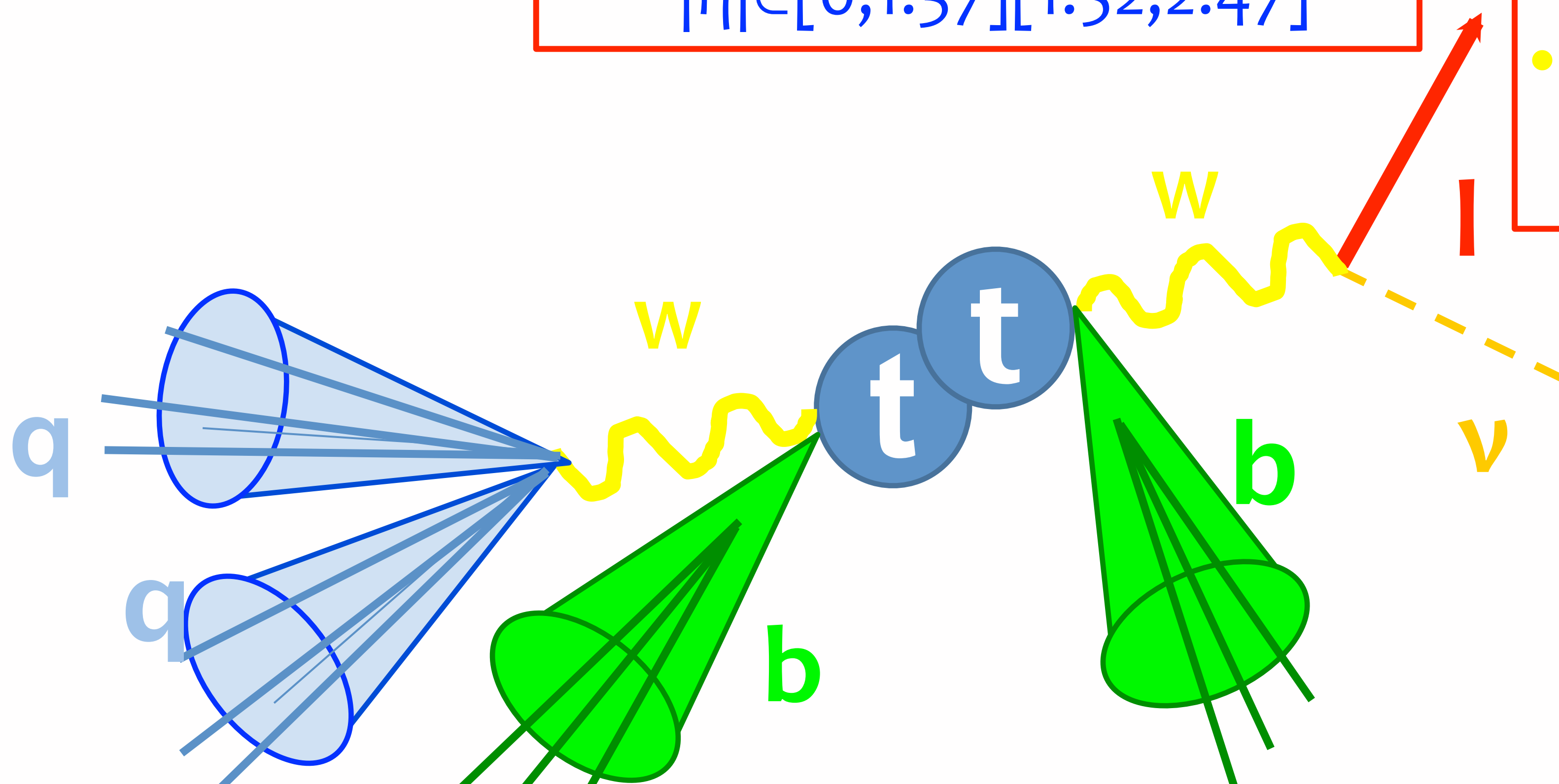

Jet
- Topological clusters, Anti-k_T (R=0.4)
- MC Calibration checked w/data
- $p_T > 25$ (20) GeV (30 for CMS), $|\eta| < 2.5$
- (large JVF $=\sum_{\text{jet trk in PV}} p_T/\sum_{\text{jet trk}} p_T$ vs pile-up jets, CMS: use particle flow to remove charged hadrons not from prim vertex)

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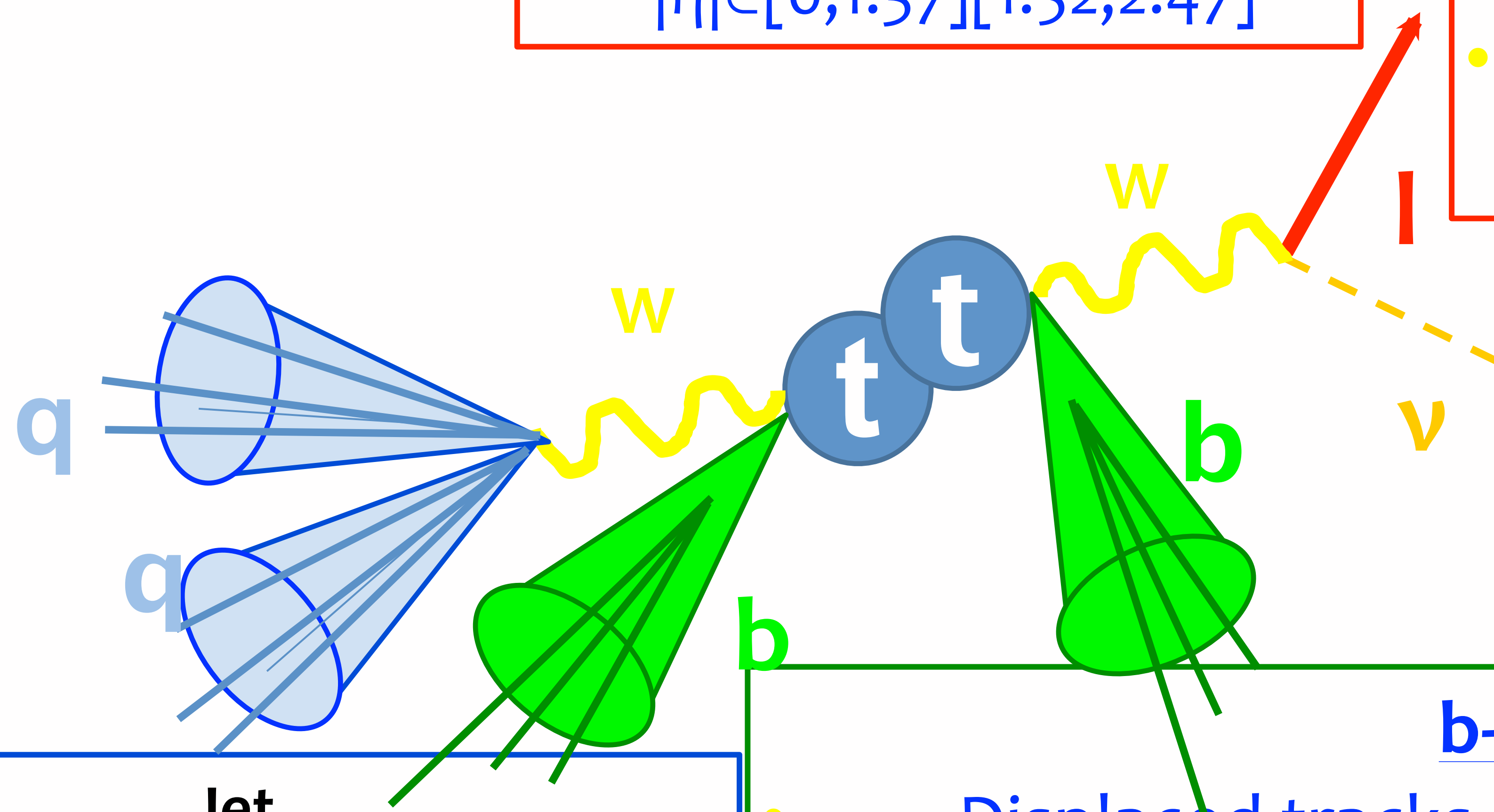

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b-Jet

- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with prim. vertex
- IP3D+SV1 +/or JetFitter: advanced lkl/NN taggers

Selection/Ingredients for top quark pairs/single-top

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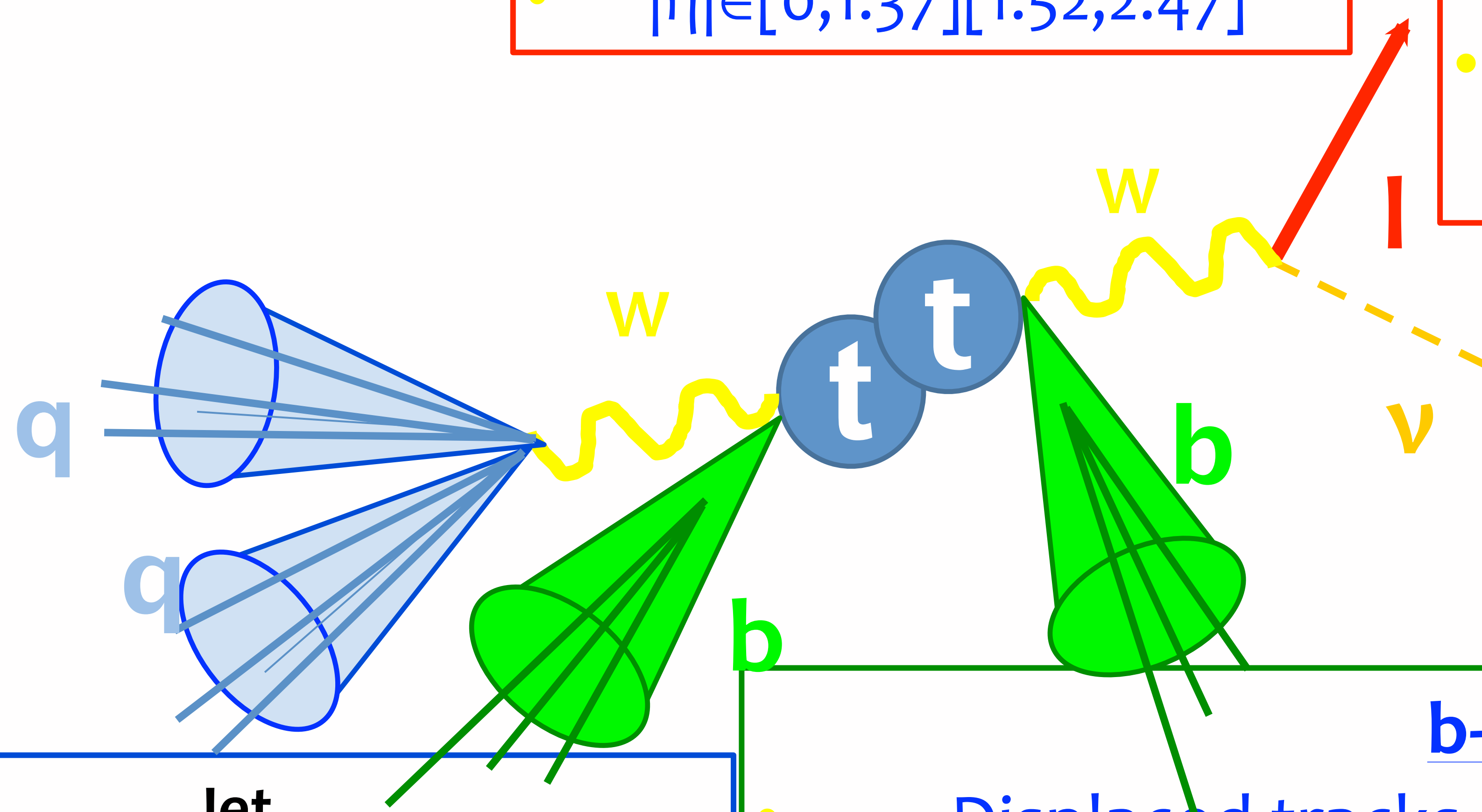

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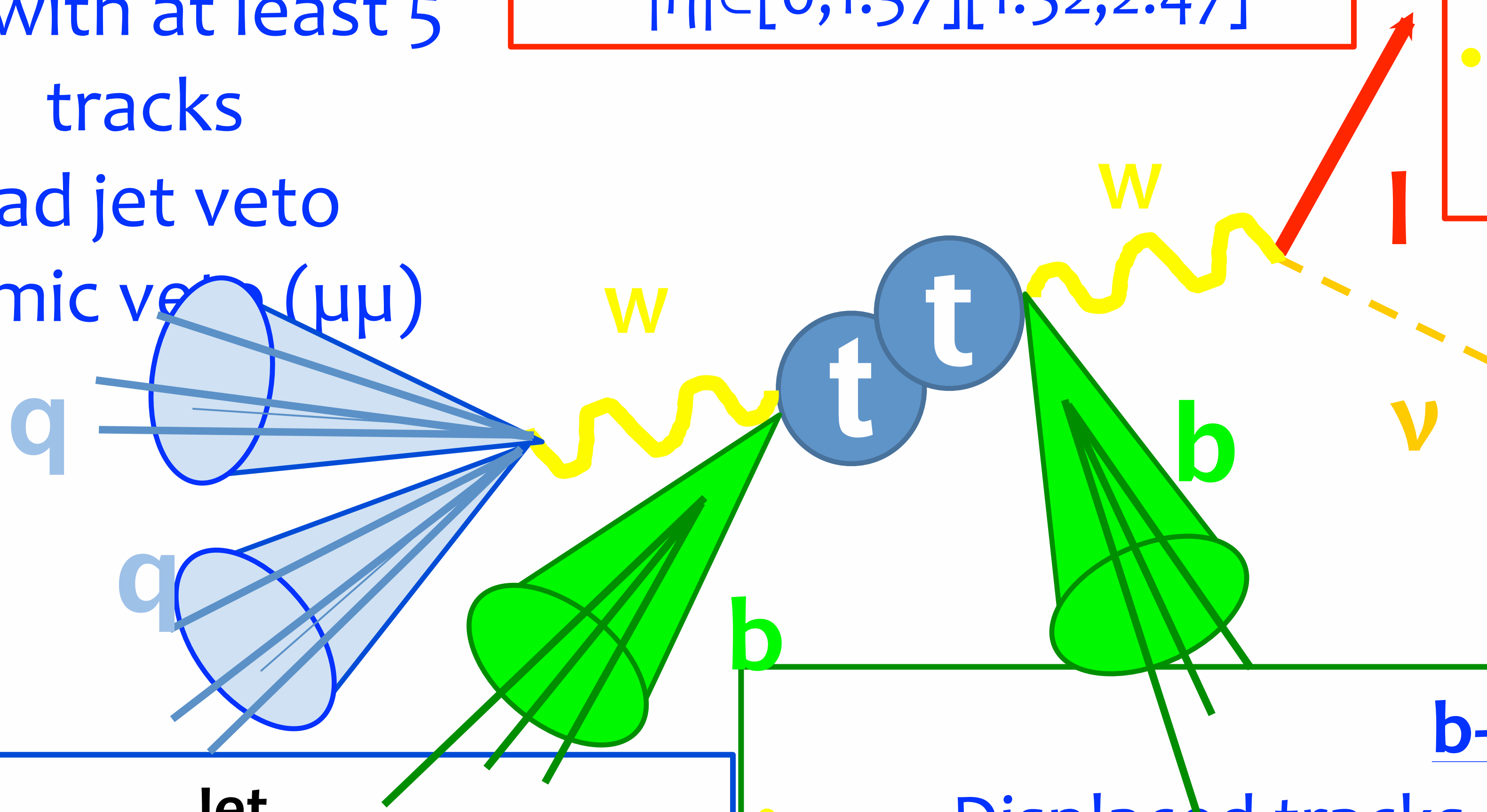
Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)

Event cleaning
- Good run conditions
- Primary vertex (PV)with at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

Electron
- Good isolated calo object
- Matched to track
- E_T>25 GeV
- $|\eta| \in [0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Calo and track isolation
- $p_T > 20$ GeV $|\eta| < 2.5$ (2.1 for CMS)



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Backgrounds: what are they ? How are they estimated?

Definition

- Background: **events that look like the signal, but have different nature** i.e *pass same requirements as signal* either because of *same final state & kinematics* or because of *detection imperfection*

essential clues

Techniques

Goal: estimate and *subtract*

Simulation: usually for shape (dN/dx)

Data: to constrain normalization & sometimes shape

Points of attention

Top specific!

Large number of tt or t events allows tight selection with (often) large Signal/ Background→ ***test bkg modelling (shape and normalization) in bkg dominated regions***

→ ***syst effect in precision measurements & searches***

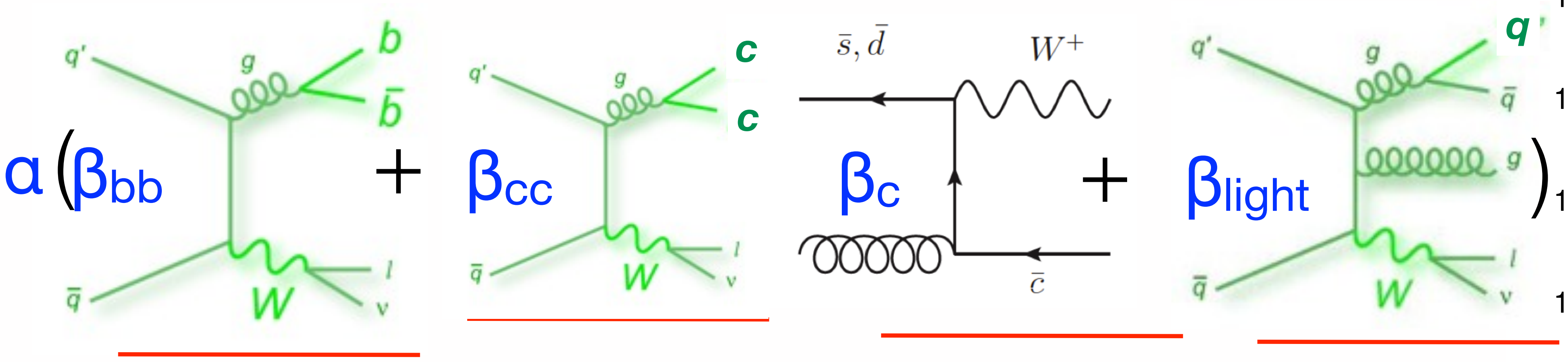
Backgrounds - single lepton+jets - **full scale example**

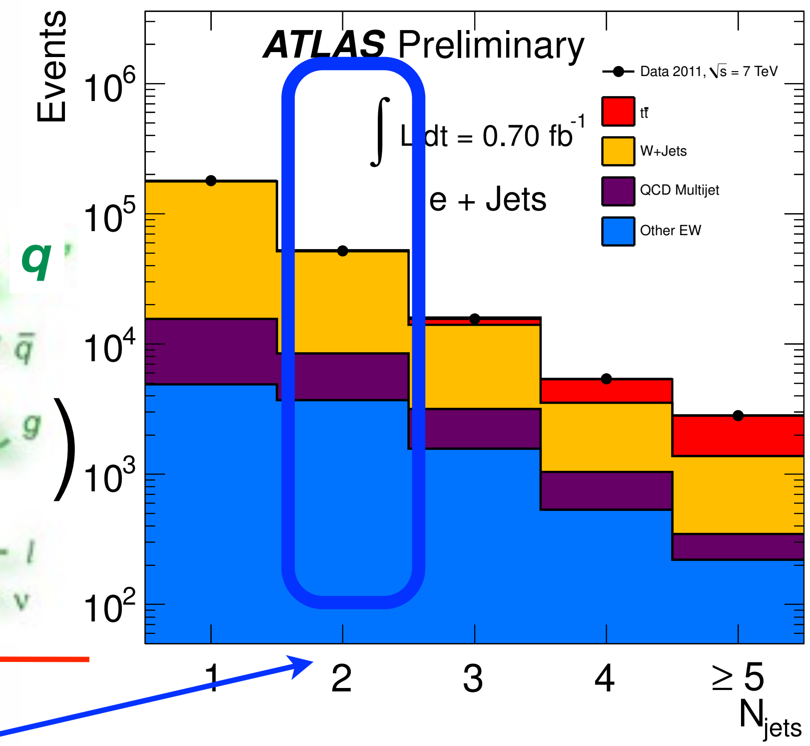
ATLAS-CONF-2011-121

- ***W+jets***

simulated shapes

data-driven overall norm and flavour fractions





- Iterate: **use events with 1lep + large E_T^{miss} +2 jets to derive α and β_{xx} before b-tagging**
  1. *Derive* α ***as ratio of asymmetric production of W^+ and W^- is well known*** *(more u-quarks than d-quarks) in W+2jets events, no b-tag*

$$N_{W^+} + N_{W^-} = \frac{(N^{MC}_{W^+} + N^{MC}_{W^-})}{(N^{MC}_{W^+} - N^{MC}_{W^-})}(D^+ - D^-) = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^+ - D^-),$$

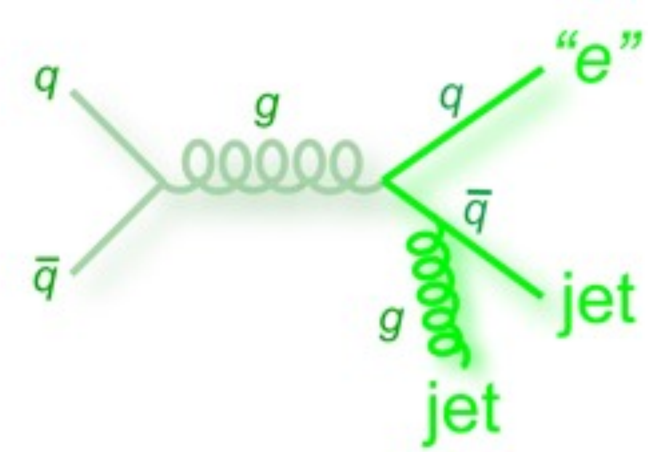
  2. *Derive* β_{xx} *from 3 equations using 2 data samples with positive and negative leptons in W+2 jet bin with standard sel & no b-tag + 1 normalization condition*
  3. *Derive* α *as in 1, but in r_{MC} use* β_{xx} *from step 2*

- Extrapolate shape and norm from 2 jets channel to **any jet multiplicity b-tagged** channel with

$$W^n_{\geq 1tag} = W^n_{pretag} \cdot f^{2j}_{tag} \cdot f^{2\to n}_{tag}$$

Backgrounds estimates *(tt single lepton+jets, single top t,s-char*

- **Fake leptons**



"Fake" leptons: mis-id jets, $\gamma \to e^+e^-$, non-prompt leptons (b/c-decays), punch-through had

- *Matrix method* ***(J Boudreau, Top2012)***

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}},$$
$$N^{\text{std}} = r N^{\text{loose}}_{\text{real}} + f N^{\text{loose}}_{\text{fake}}$$

r is the marginal efficiency of standard cuts.
f is the same, for background sources

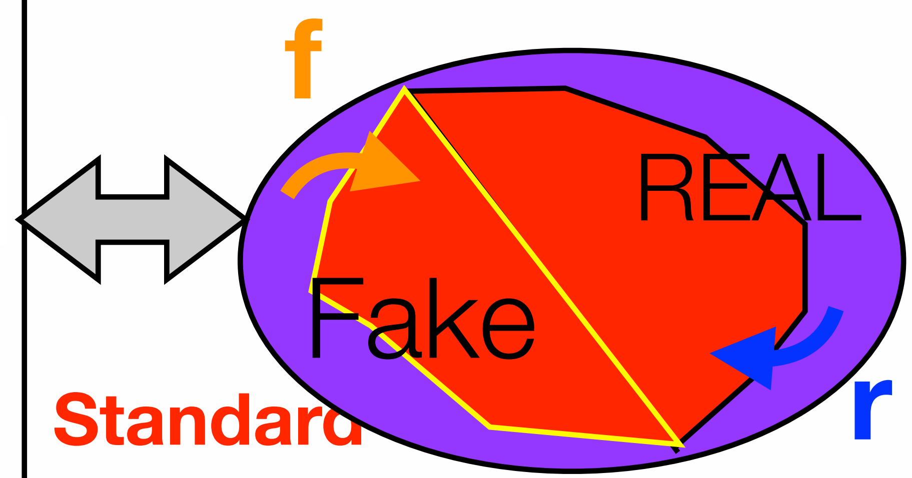
Both can be measured in pure or background event subtracted samples

- *Jet template*

Shape from jet triggered events with 1 high em. content jet.

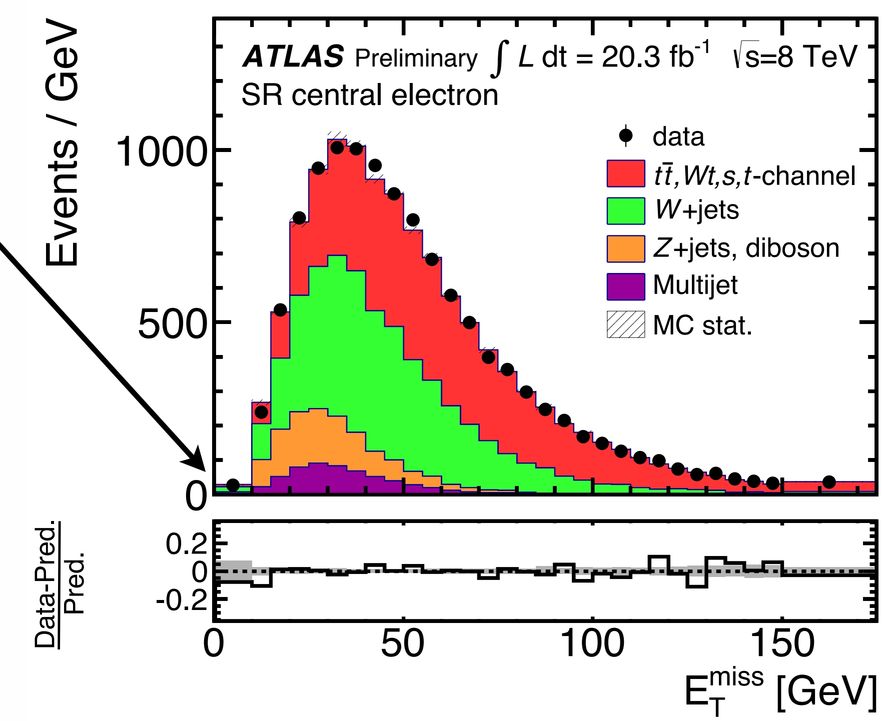
Normalize by fitting low E_T^{miss} shape to data and extrapolate

Loose selection=relax lepton isolation & identification

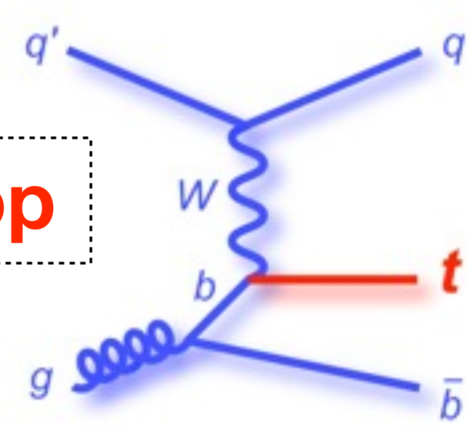


Standard selection

ATLAS-CONF-2014-007

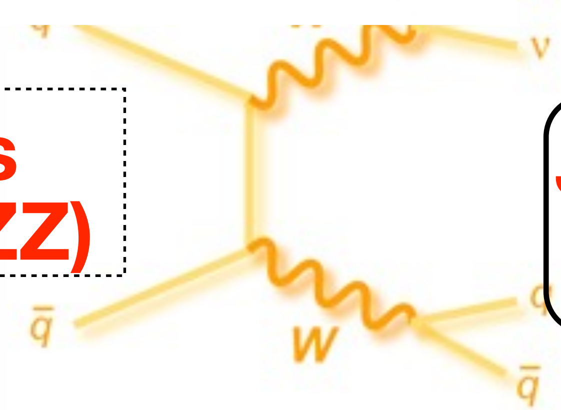


- **Single top**



Simulated shape+ rate set to approx NNLO

- **Di-bosons (WW,WZ,ZZ)**



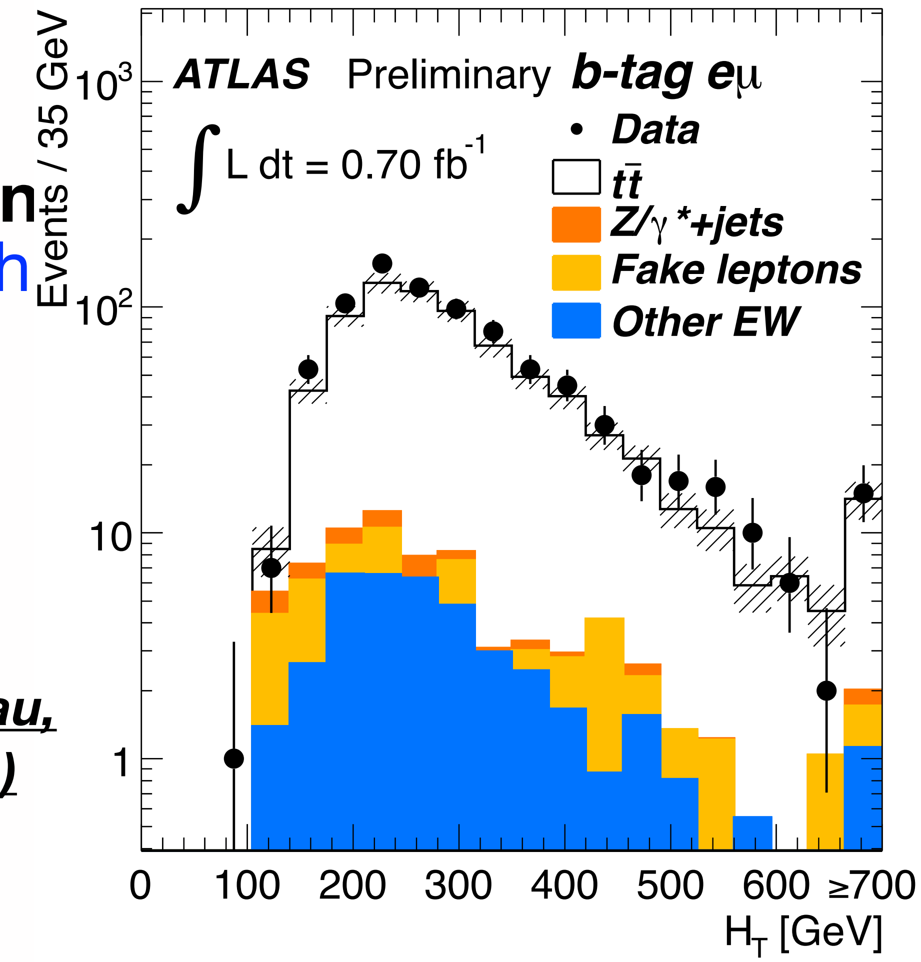
Simulated shape+ rate set to SM

normalizations=fit parameters, estimates are starting points for fit

Backgrounds *(tt di-lepton, Wt single top)*

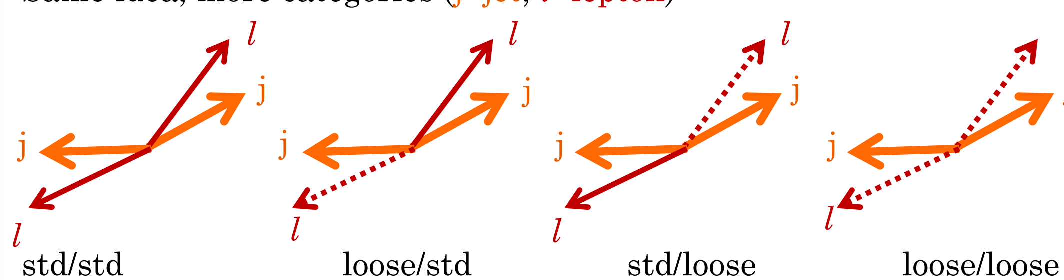
- ***Fake leptons** : generalize single lepton estimate*
  - Get **r** and **f** : **probability** for **loose** "fake" and real **lepton *to pass standard sel.*** ← **control samples** enriched with real (in Z window) or **"fake" (low E_T^{miss})** leptons
  - **Combine** with **N(di-lep)** for **all loose "fake" & real** pairs→**fake standard lepton content**

ATLAS-CONF-2011-100



di-lep topologies

Same idea, more categories (j=jet, *l*=lepton)



(J Boudreau, Top2012)

loose, standard

$$\begin{pmatrix} N^{l,l} \\ N^{l,s} \\ N^{s,l} \\ N^{s,s} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ r_2 & f_2 & r_2 & f_2 \\ r_1 & f_1 & r_1 & f_1 \\ r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \end{pmatrix} \circ \begin{pmatrix} N^{l,l}_{r,r} \\ N^{l,l}_{r,f} \\ N^{l,l}_{f,r} \\ N^{l,l}_{f,f} \end{pmatrix}$$

real,fake in loose

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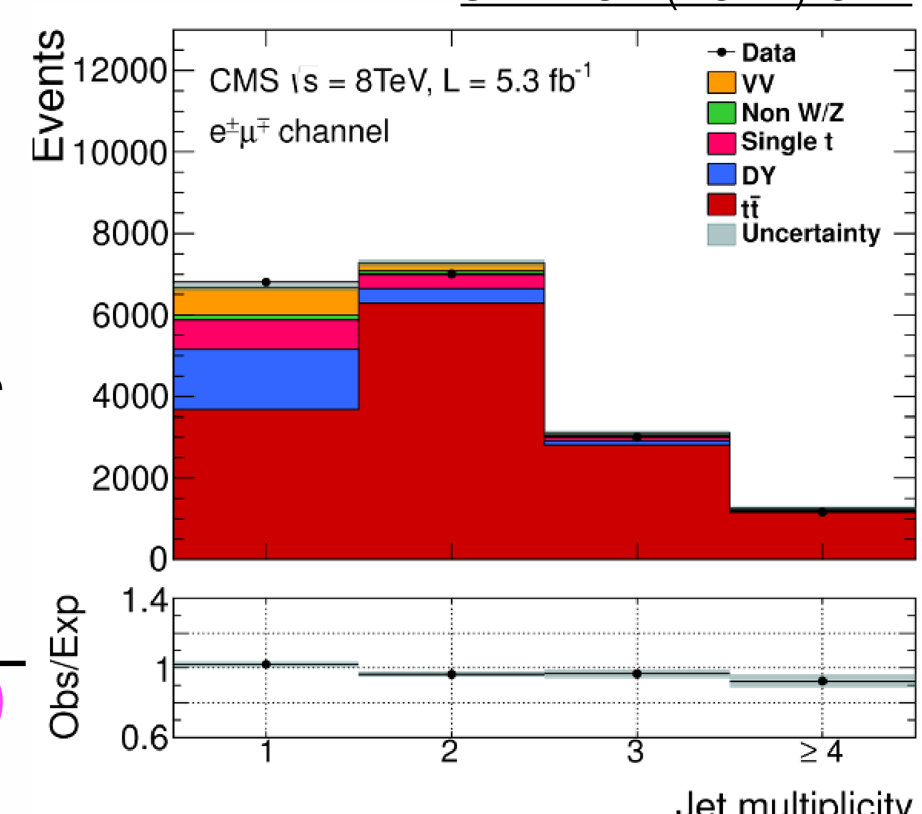
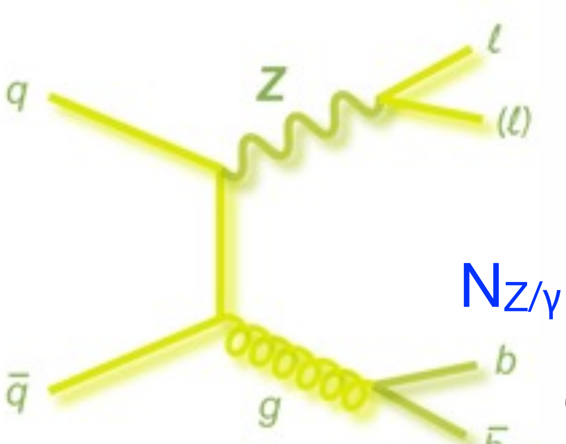
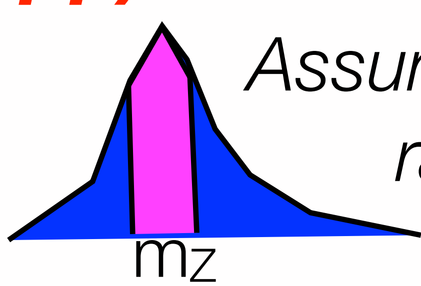


- ***Z/γ* bkg (ee, μμ)***





Assume constant Zdata/Z MC ratio in/out Z window

$$N_{Z/\gamma}(SR) = [\mathbf{Data}(CR) - \text{NonZBkg}(CR)] \frac{MC_{Z/\gamma}(SR)}{\mathbf{MC_{Z/\gamma}(CR)}}$$

CR (SR)=in (out of) Z mass window

What we study about the top quark

inspired by figure
by D Chakraborty

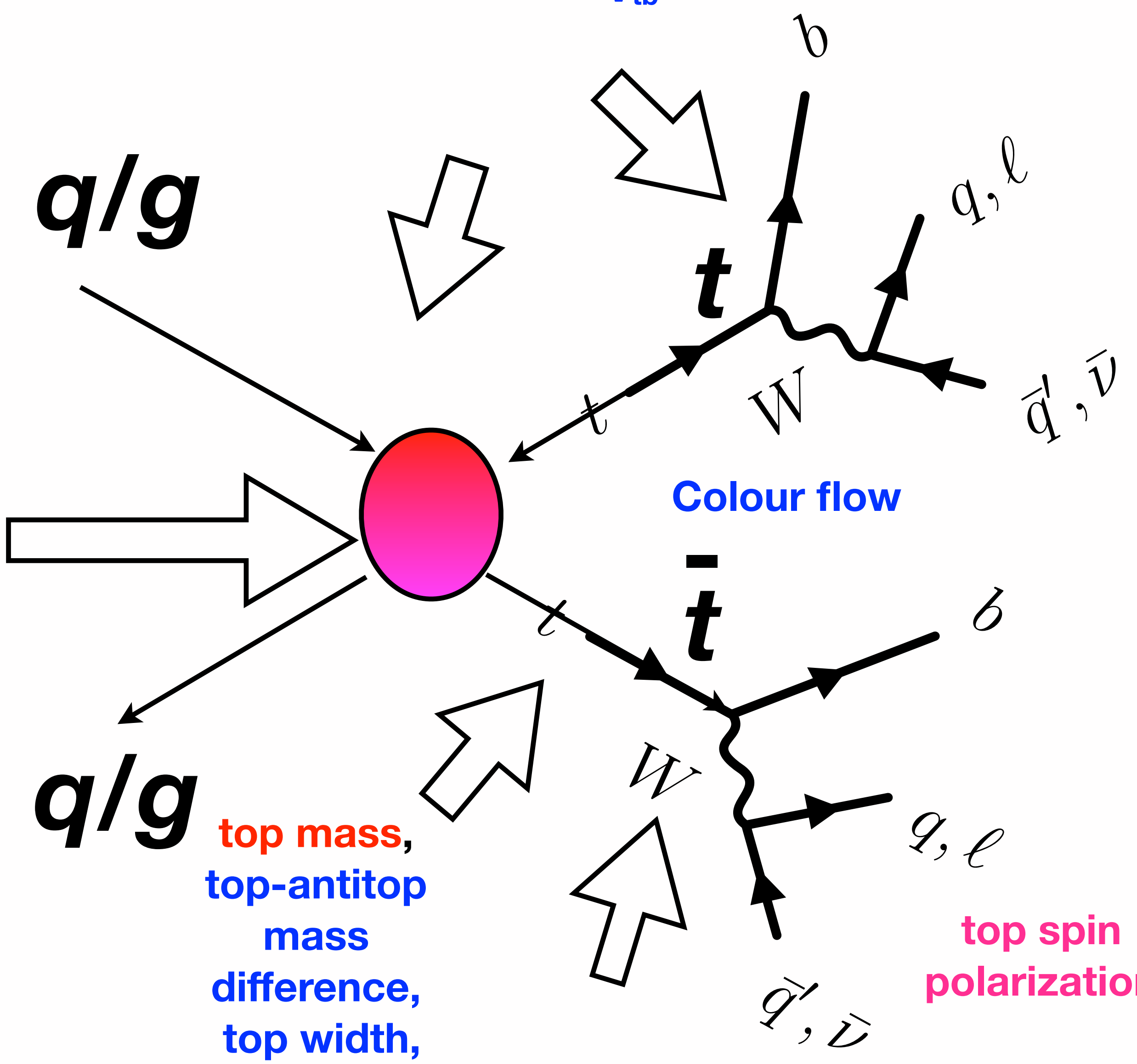
Discuss Today

Branching Fractions
V_{tb}

Production cross section double and single top

Resonant production & New phys

Production kinematics



Colour flow

Spin correlation

Charge asymmetry

top spin polarization

top mass, top-antitop mass difference, top width, spin, charge lifetime

W helicity
Wtb coupling,V(tb)

How is an analysis flowing

essential clues

- Select sample(s) enriched in top quark events with requirements on the characteristic kinematic objects or functions of them
- Reconstruct $t\bar{t}$ event kinematics
- Extract measured variable/distribution by technique that involves
  - subtracting/accounting for the effect of the background
  - correcting for detector effects
  - accounting for efficiencies/acceptances
- **Assess statistics and systematic uncertainties on the measured quantity**
- Combine the results from different samples (if necessary)
- Compare with prediction(s)

Measurement of top cross sections: $\sigma_{t\bar{t}}$ and σ_t

or

how many top quarks have we got?

Start to combine results at the LHC...

How is cross section (sigma) measured?

essential clues

Definition

$N_{observed} = N_{bkg} + \int L dt \, ^* \, \sigma_{tt \text{ or } t} \, ^*$ **detection/extrapolation efficiency**

Counting: Poisson distributed

$$f(n;\nu) = \frac{\nu^n}{n!} e^{-\nu}$$

- ***Cut and Count*** i.e. **invert formula above** = maximum likelihood solution for poisson hypothesis
- Cut and ***Use shapes:*** measure variable that is sensitive to cross section to separate signal from bkg:
  - fit number of signal events and correct
  - fit cross section directly

Top specific!

- Measured in variety of final states
  - confirm lepton universality
- **Systematics dominated**
- Define sigma at particle level
- Many top quarks: going differential!

dilepton	low bkg, low prob
l+jets	compromise between, prob & bkg
fully hadronic	large prob, large bkg

How is cross section (sigma) measured?

essential clues

NEW Definition

$$\sigma_{t\bar{t}}^{fid/total} = \frac{N_{evt}}{\mathcal{E}\times\mathcal{A}\times Br\times\mathcal{L}} \Rightarrow \sigma_{t\bar{t}}^{total} = \frac{\sigma_{t\bar{t}}^{fid}}{\mathcal{A}\times Br}$$

$$\mathcal{A} = \frac{N_{GEN}^{Cuts}}{N_{GEN}} = \frac{1+3}{1+2+3+4}$$

$$\mathcal{E} = \frac{N_{RECO}}{N_{GEN}^{Cut}} = \frac{1+2}{1+3}$$

Reco

Pass Reco, Pass PL	**Pass Reco**, Fail PL	Fail Reco Pass PL	Fail Reco, Fail PL
1	2	3	4

to correct to

- ***Fiducial particle level (PL) cross section:*** measurement in terms of physical **observable objects** (jet of **stable hadrons, leptons) in** kinem phase space close to detector acceptance
    - ❖durable connection with theory
    - ❖usually reduced modelling uncertainties
- ***Parton level cross section:*** in terms of quarks
- Save PL analyses results in toolkit to be compared with evolving theory predictions
    - see **R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory

Top specific!

- ***Dilepton e channel: emerging as the most precise***
    - ***low bkg , reduction of syst uncertainties from jets***

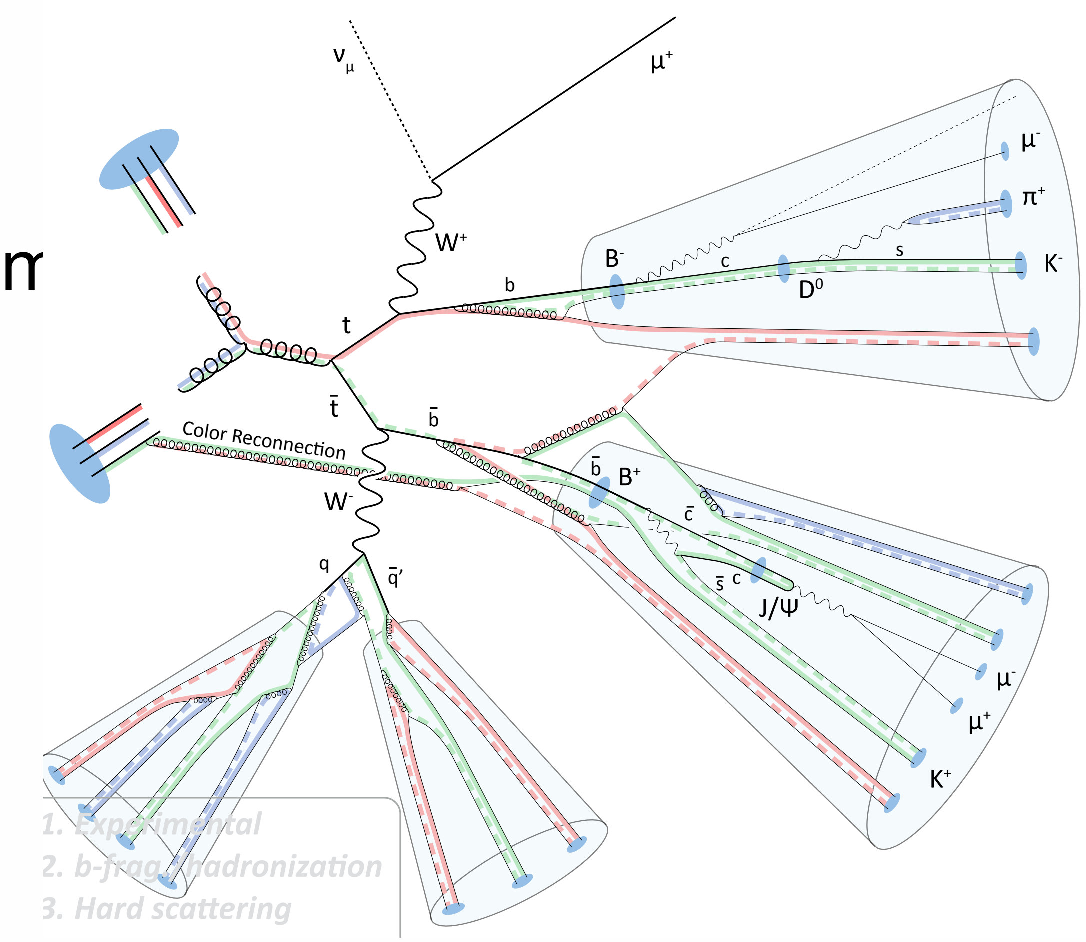


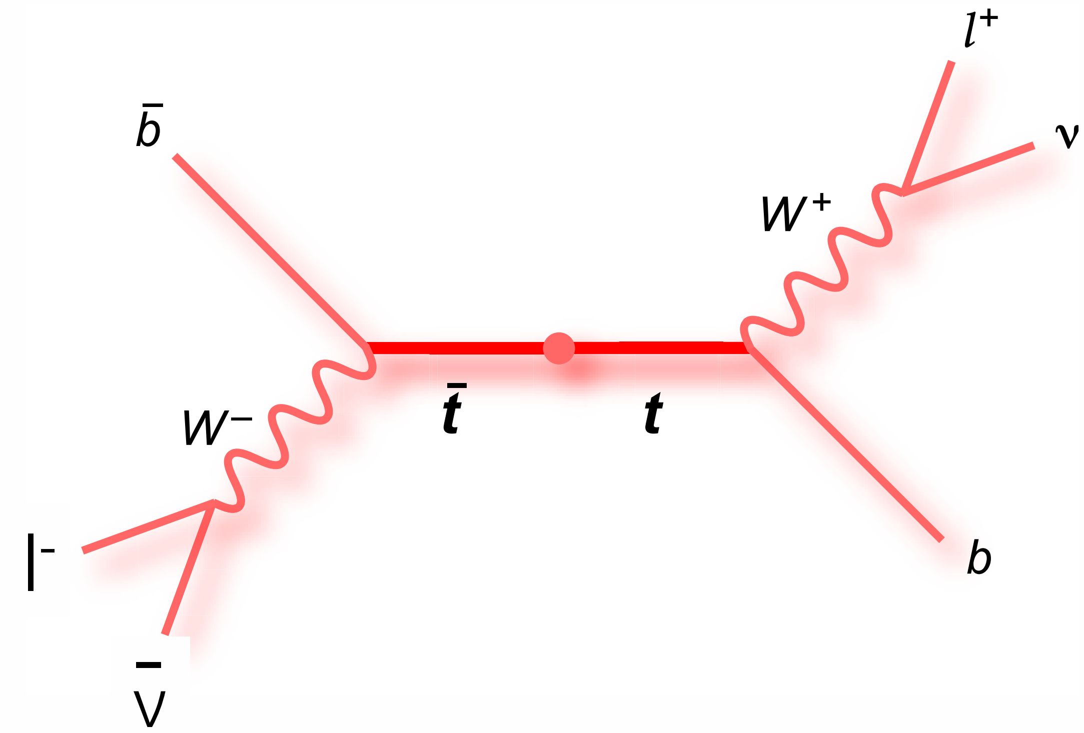
Figure by B Stieger (CERN)

Cut and count: σ_{tt} @ $\sqrt{s}$ = 8 TeV - *di-lepton channel*

- Vertex and quality cuts
- After dilep “trigger” require **exactly two opposite sign** high p_T isolated central **leptons (ee, eμ, μμ)**
- **≥ 2 central** high p_T **jet**
- High $\mathbf{E_T^{miss}}$ **for (ee, μμ)** *(>40 GeV)*
- **For (ee, μμ) veto low di-lep mass** *(<20 GeV, from heavy flavour resonances)* & **Z-like** *(15 GeV mass window)* **events**
- **≥ 1 b-tagged jet**

∫Ldt = **5.3 fb^{-1}** *(2012)*

CMS JHEP02 (2014) 024



- Data-driven **Fake leptons** (*extended matrix method*), **Z**+γ*+jets (*extrapolate from Z window*) . *Di bosons and single lepton from simulation.*

- *small corrections to simulated events efficiencies derived from data*

Cut and count: σ_{tt} @ $\sqrt{s}$ = 8 TeV - *di-lepton channel*

JHEP02 (2014) 024

- **Subtract background and get N_{tt}** $$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A} \cdot \mathcal{L}}$$
- **Extract cross section by correcting with lumi and efficiency**
  - combining channels with **best linear unbiased estimator** including correlations and systematics *(assume 100% correlation across channels)*

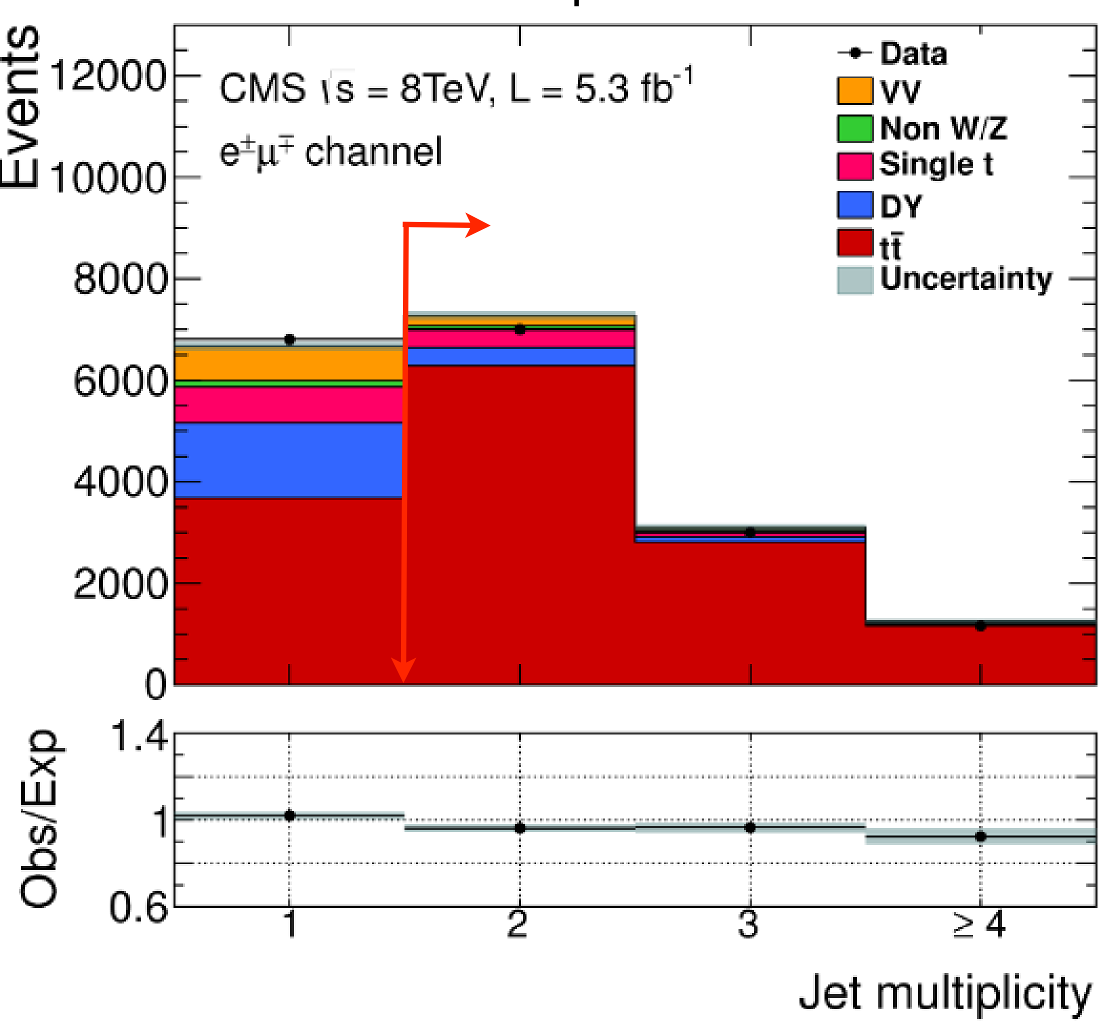
assume m_{top}=172.5

$$\sigma_{t\bar{t}} = 239 \pm 2\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 6\,(\text{lum.})\,\text{pb}$$ **δσ/σ~5.3%**

"cut and count" equivalent to maximizing lkl with Poisson Dist

uncertainty band is statistical +b-jet syst uncertainty

after dilep sel



syst dominated!

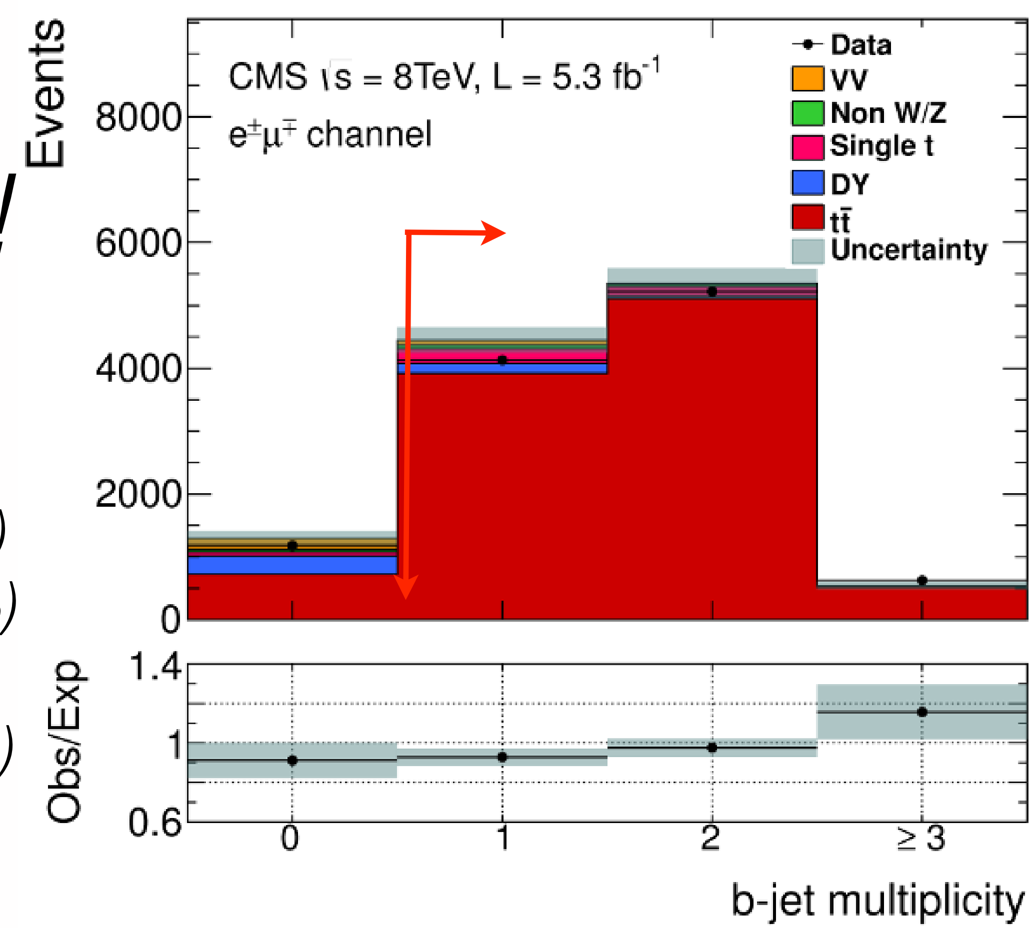
Jet En Scale (JES) *O(2.2%) in eμ and O(4%) in ee,μμ*

luminosity *O(2.6%)*

Drell Yan Bkg *O(4%) in ee,μμ*

tt modelling *(scales) ~O(2.4%) in eμ*

after dilep,no b-jet req.



(L Shabalina @ TOP2012)

BLUE for multiple measurements

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

BLUE 101: method

L.Lyons, D.Gibaut, P.Clifford, NIM A270 (1988), A.Valassi, NIM A500 (2003)

- BLUE = Best Linear Unbiased Estimate

- Inputs

input measurements

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{pmatrix} \qquad M = \begin{pmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 & \cdots & \rho_{1N}\sigma_1\sigma_N \\ \rho_{12}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 & & \\ \rho_{13}\sigma_1\sigma_3 & \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 & & \\ \vdots & & & \ddots & \\ \rho_{1N}\sigma_1\sigma_N & & & & \sigma_N^2 \end{pmatrix}$$

uncertainties on input measurements

correlations of uncertainties on input measurements

essential clues

- Output

combined measurement

$$\hat{x} = \sum_{i=1}^{N} w_i x_i \qquad \sigma_{\hat{x}}^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} M_{ij} w_i w_j$$

find set of weights that minimize the variance

- where

$$w = M^{-1}U/(U_T M^{-1}U) \qquad \chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} (\hat{x}-x_i)(\hat{x}-x_j)M_{ij}^{-1}$$

method of Lagrangian multipliers

equivalent to χ^2 method

Inclusive σ_{tt} : dilepton - $\sqrt{s}$ =7 & 8 TeV

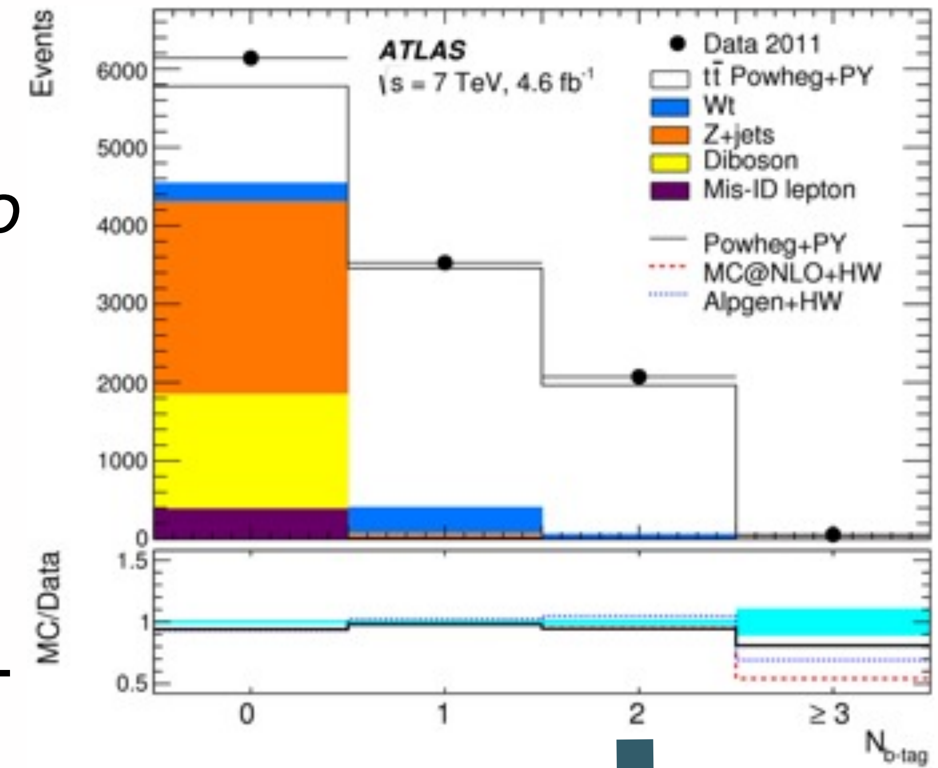
$\int Ldt \sim$ **20.3 fb^{-1}** *(2012)*

$\int Ldt \sim$ **4.6 fb^{-1}** *(2011)*

[Eur.Phys.J. C74 (2014) 3109](#)

ℓνℓνbb

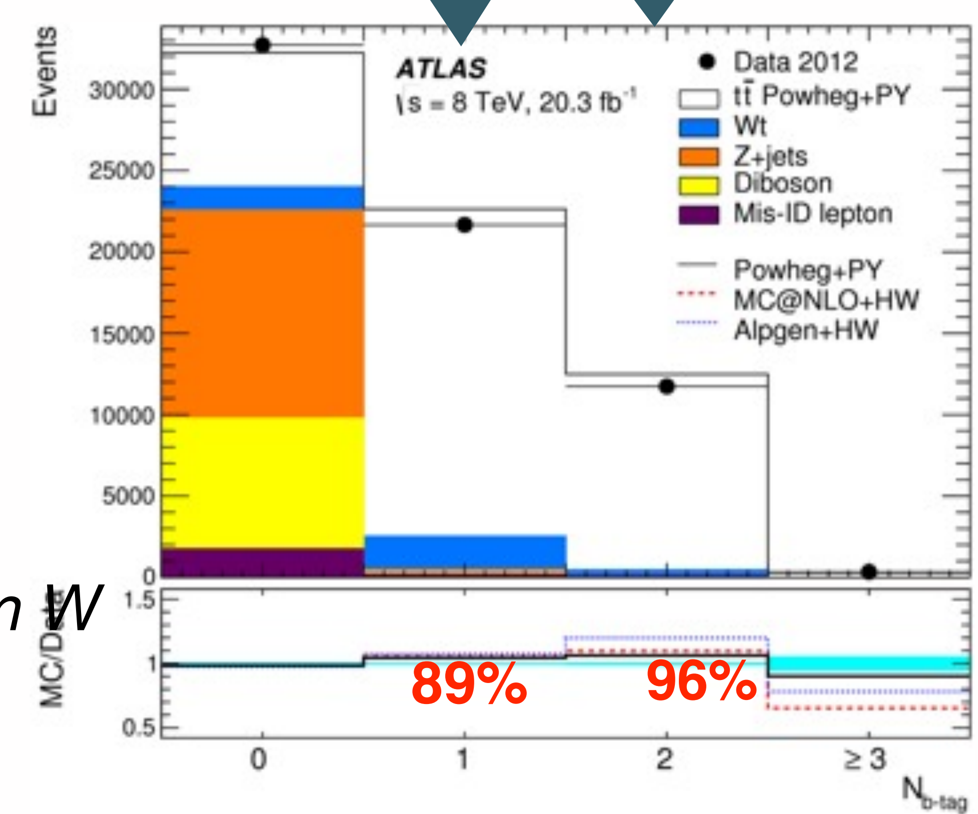
- **Require opposite sign (OS) eμ,** no H_T,E_T^{miss} cuts, no lep isolation *minimal use of jet/E_T^{miss} info*
- **Bkg: single top** (Wt) *(from simul.)*, **data-driven fake leptons** *(extrapolated from same sign lep. sample)*, **Z +jets** *(extrapolated from Z→μμ sample)*
- **Simultaneous fit for σ_{tt} and ε_b, efficiency to select, reco and b-tag a jet in** 1-b-tag and 2-b-tag samples→**minimize jet & b-tag syst**



from simulation

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg}$$

$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$



tt purity

Measure σ_{tt} (parton level) & σ_{fid} (particle level)

$$\epsilon_{e\mu} = A_{e\mu}G_{e\mu} \qquad C_b = \epsilon_{bb}/\epsilon_b{}^2$$

$A_{e\mu}$ = *fraction of tt ev. with 1* **eμ** *brem-corrected pair from W*

b-jet is tagged with b-hadron

$G_{e\mu}$= **eμ** *reco efficiency*

$$\sigma^{\rm fid}_{t\bar{t}} = A_{e\mu}\sigma_{t\bar{t}},$$

$$\sigma_{t\bar{t}}\epsilon_{e\mu} \longrightarrow \sigma^{\rm fid}_{t\bar{t}}G_{e\mu}$$

Inclusive σ_{tt} : dilepton - $\sqrt{s}$ =7 & 8 TeV

(summary by J Brochero (TOP2014))

Total Cross Section

$$\sigma^{\mu e}_{t\bar{t}}(\sqrt{s}{=}7\,\mathrm{TeV}) = 182.9 \pm 3.1(\mathrm{stat.}) \pm 4.2(\mathrm{syst.}) \pm 3.6(\mathcal{L}) \pm 3.3(\mathrm{beam})\,\mathrm{pb}$$

$$\sigma^{\mu e}_{t\bar{t}}(\sqrt{s}{=}8\,\mathrm{TeV}) = 242.4 \pm 1.7(\mathrm{stat.}) \pm 5.5(\mathrm{syst.}) \pm 7.5(\mathcal{L}) \pm 4.2(\mathrm{beam})\,\mathrm{pb}$$

$$R_{t\bar{t}} = 1.326 \pm 0.024(\mathrm{stat.}) \pm 0.015(\mathrm{syst.}) \pm 0.049(\mathcal{L}) \pm 0.001(\mathrm{beam})$$

p_T^ℓ (GeV)	$\lvert\eta^\ell\rvert$	Fiducial cross section (including $W \to \tau \to \ell\nu$) $\sqrt{s} = 7$ TeV (pb)	$\sqrt{s} = 8$ TeV (pb)
> 25	< 2.5	$2.615 \pm 0.044 \pm 0.056 \pm 0.052 \pm 0.047$	$3.448 \pm 0.025 \pm 0.069 \pm 0.107 \pm 0.059$
> 30	< 2.4	$2.029 \pm 0.034 \pm 0.043 \pm 0.040 \pm 0.036$	$2.662 \pm 0.019 \pm 0.054 \pm 0.083 \pm 0.046$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~3.9%

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~4.2%

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
$\sqrt{s}$	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b-tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

- **Dominated by "External" Syst:**
  Lumi and E_b, then tt modelling & scales

$$R^{Theory}_{t\bar{t}}(7/8\,\mathrm{TeV}) = 1.430 \pm 0.013(\mathrm{PDF} + \alpha_s) + \pm 0.001(\mathrm{scale})$$

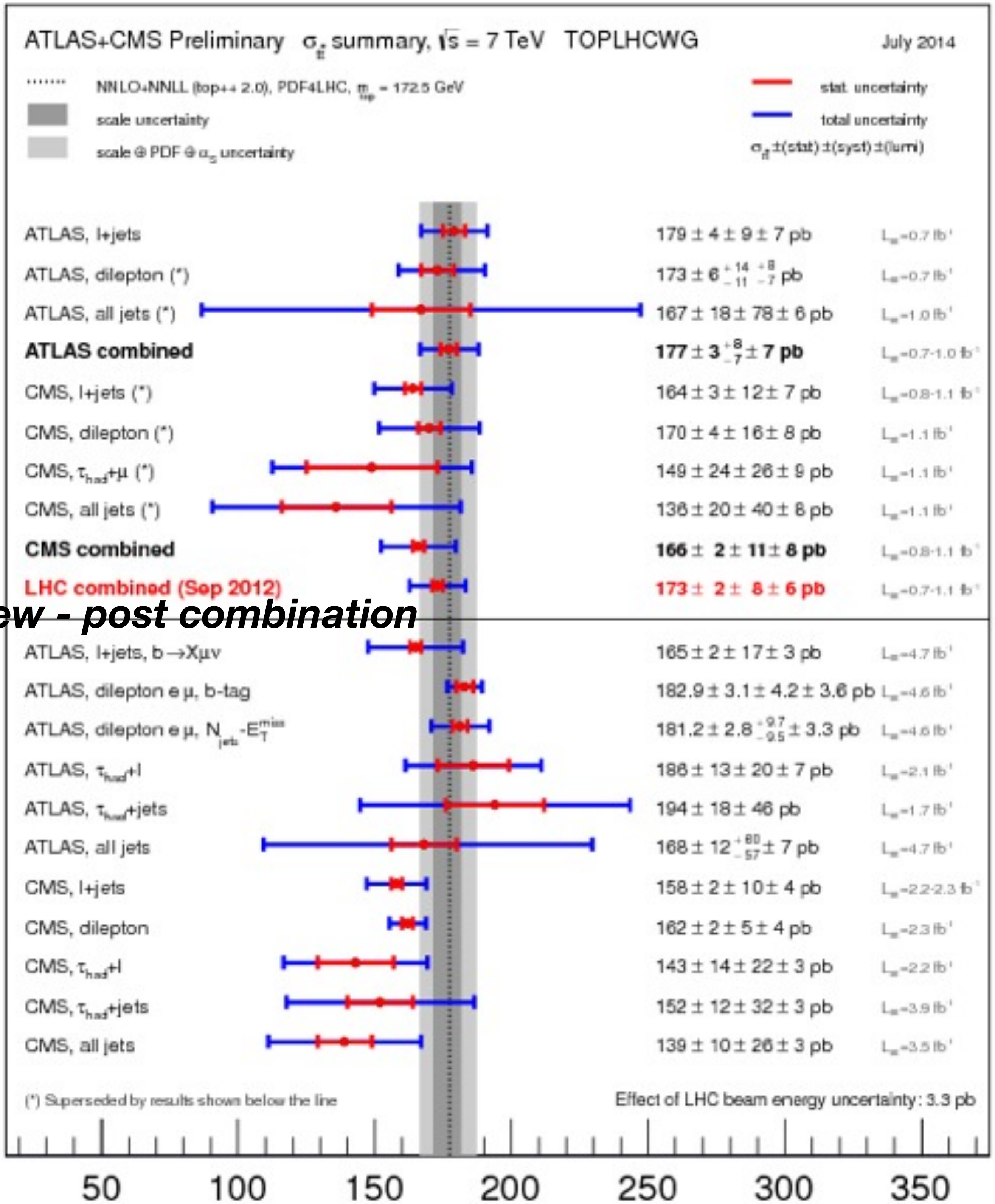
$$\frac{d\sigma_{t\bar{t}}}{dm_t} = -0.28\%\ \mathrm{per\ GeV}$$

← *useful to compare with theory*

Inclusive $\sigma_{t\bar{t}}$ - Summary at $\sqrt{s}$ = 7 & 8 TeV

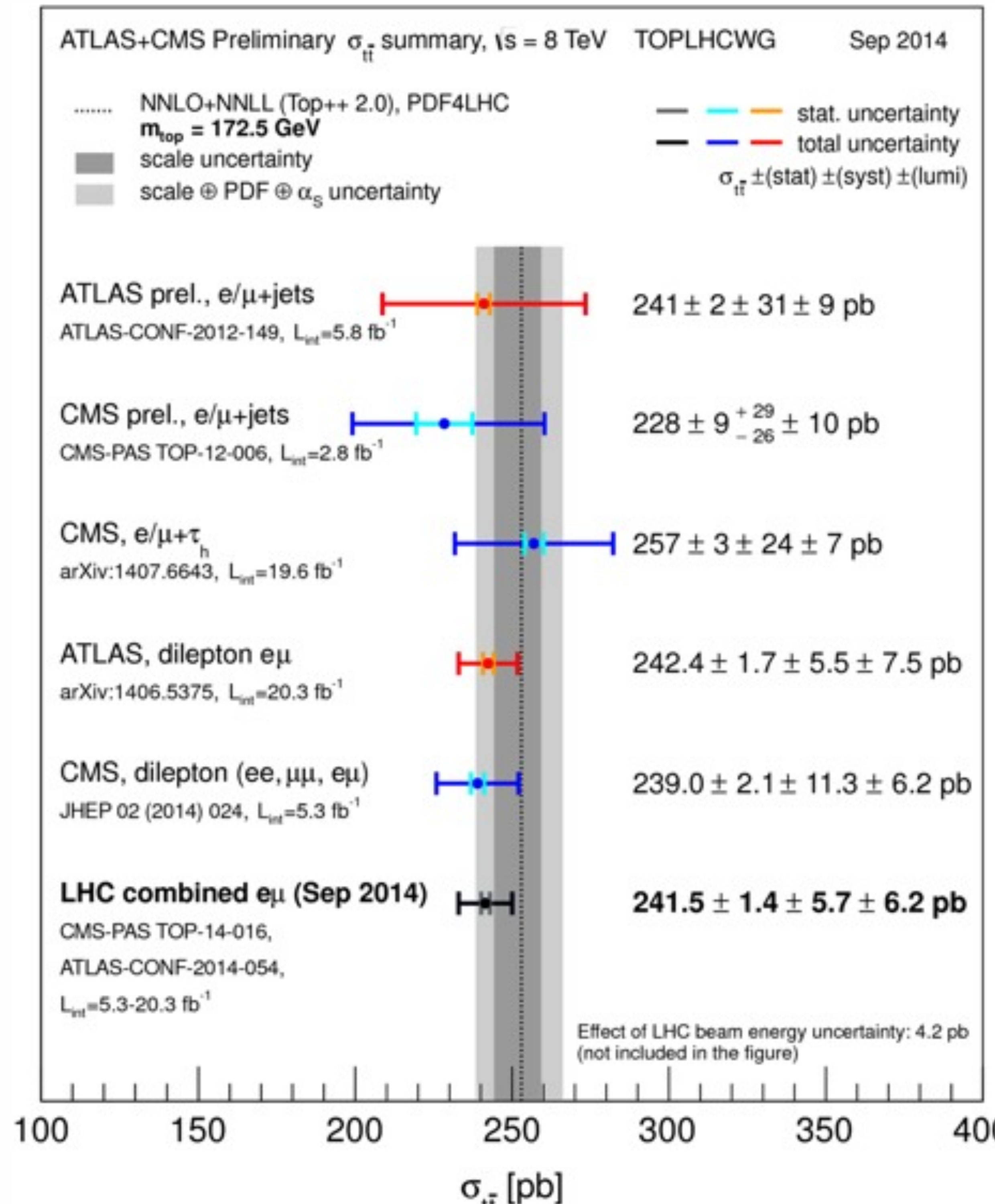
Systematics dominated, similar to/smaller than theory uncertainty

ATLAS & CMS Public summary plots



New - post combination

7 TeV **LHC combination** achieves **$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~5.8%**



at 8 TeV **LHC combination** achieves **$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~3.5% (E_{beam} 1.7%)**

How is combination of results carried out?

The simplest combination: weighted average for uncorrelated meas.

for differet distr and known variances

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \qquad \sigma(\bar{x}) = \sqrt{\sum_{i=1}^{n} w_i^2 \sigma_i^2}. \qquad w_i = \frac{1}{\sigma_i^2}.$$

essential clues

- Generalized to Best Linear Unbiased Estimator

J.Donnini, L Lista TOPLHCWG 28th-29th Nov 2013

- Find linear combination of available measurements $x = \sum_i w_i x$ with weights minimizing the variance of x, including correlations

- Equivalent to least squares minimization or max lkl for Gaussian uncertainties

Simple example:

L.Lyons et al. NIM A270 (1988) 110

- Two measurements: $x_1 \pm \sigma_1$, $x_2 \pm \sigma_2$ with correlation ρ
- The weights that minimize the χ^2:

Cov. matrix

$$\chi^2 = \begin{pmatrix} x_1 - x & x_2 - x \end{pmatrix} \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}^{-1} \begin{pmatrix} x_1 - x \\ x_2 - x \end{pmatrix}$$

are: $$w_1 = \frac{\sigma_2^2 - \rho\sigma_1\sigma_2}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2} \qquad w_2 = \frac{\sigma_1^2 - \rho\sigma_1\sigma_2}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2} \qquad (w_1+w_2=1)$$

- The uncertainty of the combined value is: $$\sigma_x = \sqrt{\frac{\sigma_1^2\sigma_2^2(1-\rho^2)}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2}}$$

- Generalized to Likelihood maximization ATLAS-CONF-2012-024

Product of lkl, including model of constraints, use generalize Gaussian for correlations

$$L_{ll}(\sigma_{t\bar{t}}, \mathcal{L}, \vec{\alpha}) = \text{Gaus}(\mathcal{L}_0 | \mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i \in \{ee,\mu\mu,e\mu\}} \text{Pois}(N_i^{\text{obs}} \,|\, N_{i,\text{tot}}^{\text{exp}}(\vec{\alpha})) \prod_{j \in \text{syst}} \text{Gaus}(0 \,|\, \alpha_j, 1)$$

$$L_{l+\text{jets}}(\vec{\theta}) = G(\hat{\vec{\theta}} \,|\, \vec{\theta}, V) = \frac{1}{(2\pi)^{k/2}|V|^{1/2}} \exp\left(-\frac{1}{2}(\hat{\vec{\theta}} - \vec{\theta})^T V^{-1} (\hat{\vec{\theta}} - \vec{\theta})\right)$$

Going differential for σ_{tt} & σ_{t}!

major test for new force/dimension deviating from SM complementary to specific searches

test of SM QCD tt & t production & kine (generators & had scheme)

- Differential tt cross sections

test novel reconstruction techniques in uncharted phase space regions

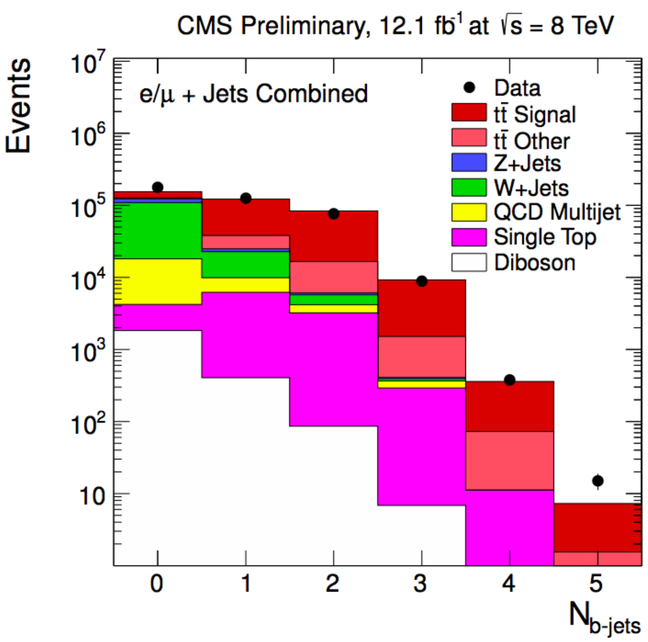
provide info on Parton Dist Functions

high energy gluons

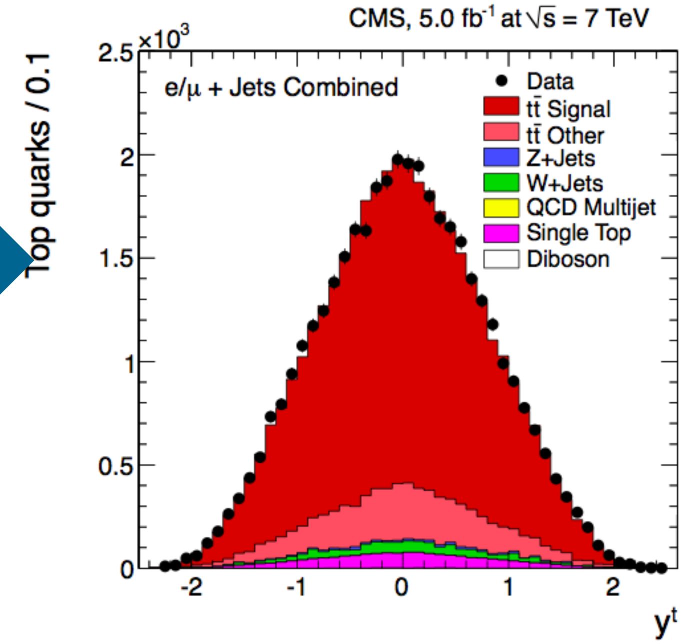
Going differential for σ_{tt} !

Measure σ(tt̄) as a function of kinematic distributions of **top, top pairs, b-jets, leptons, and lepton pairs**

(1) Event selection



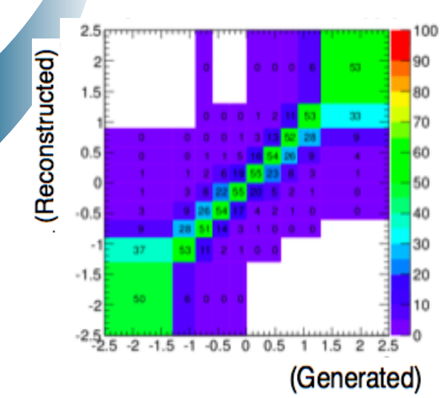
(2) tt̄ kinematic reconstruction



(3) Bin-wise cross section measurement

- Subtract background
- Unfolding: correct for detector effects and acceptance

$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\text{Data}} - N^i_{\text{BG}}}{\Delta^i_X \epsilon^i L}$$

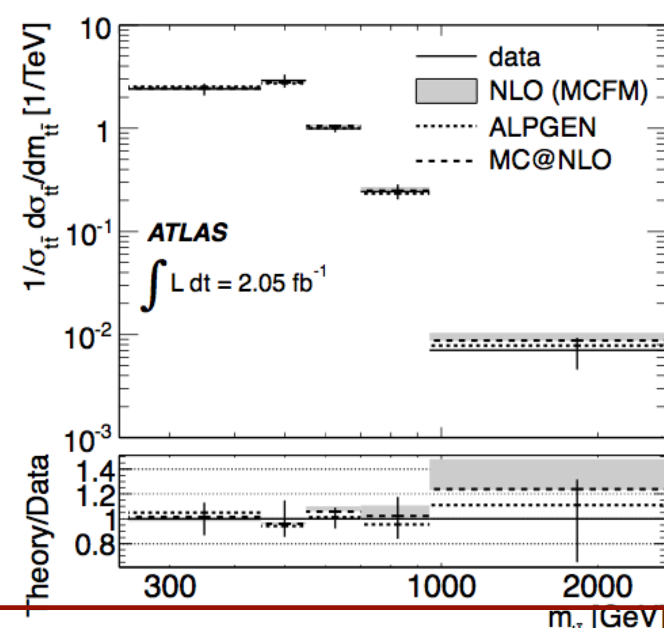


Response matrix

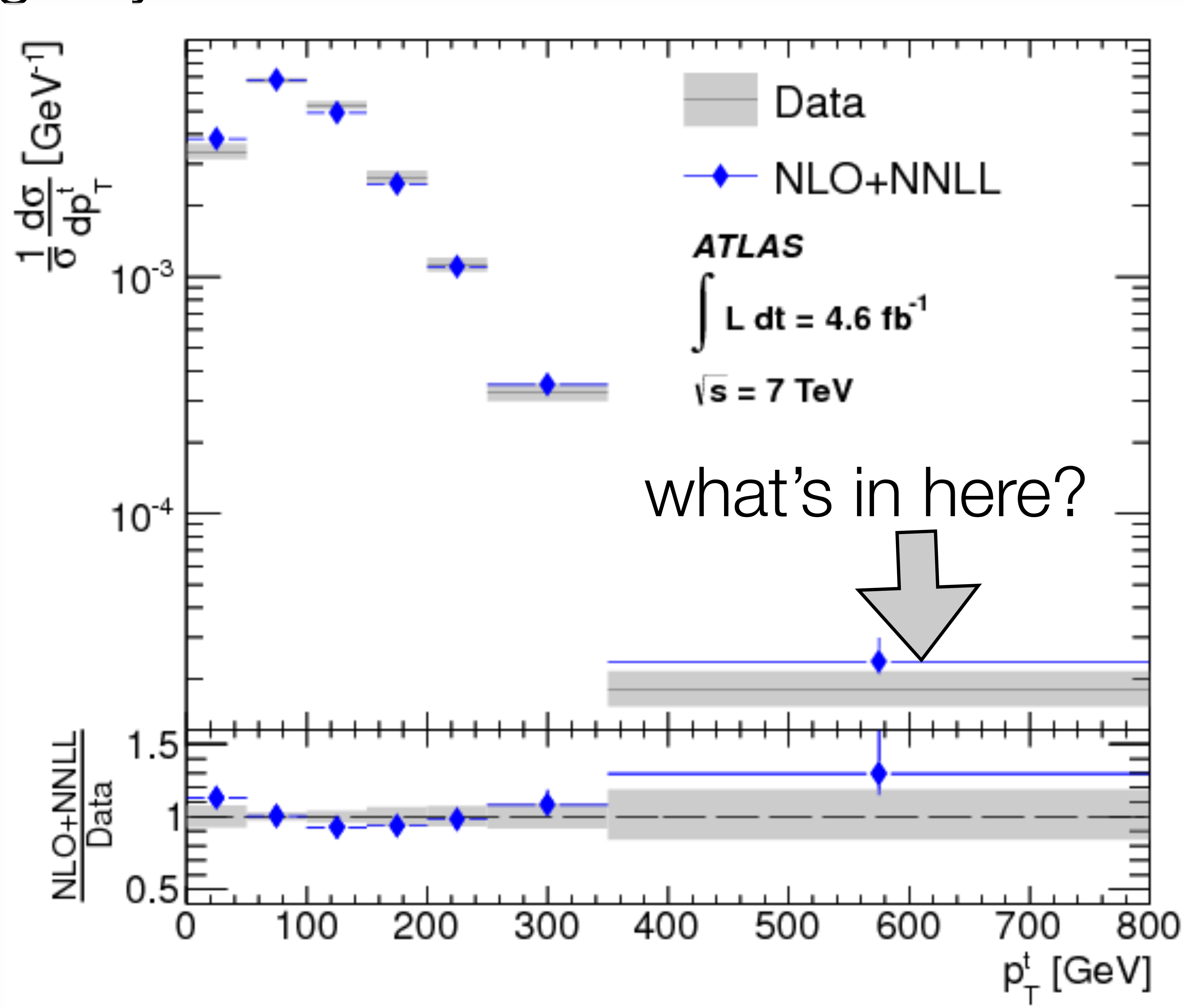
Migrations due to det resolution & biases

(4) Differential tt̄ cross sections

- Normalised to in-situ measured σ(tt̄)
- 'Visible' or extrapolated to full phase space
- Compare to theory predictions



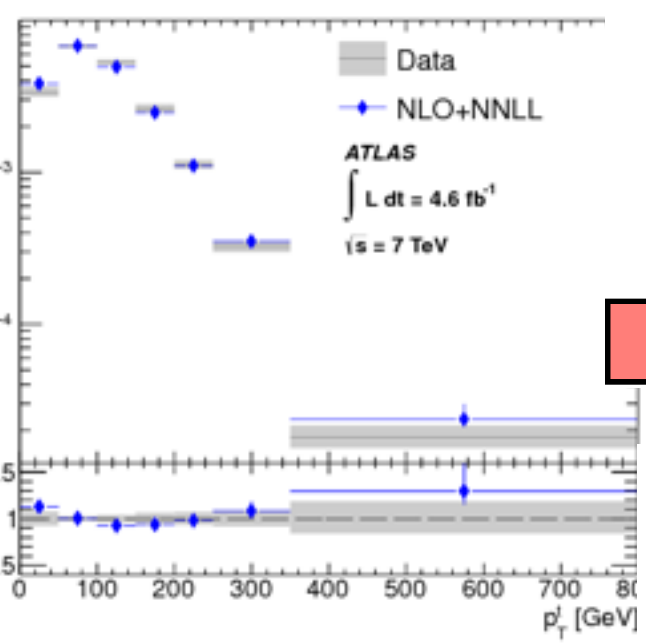
Going beyond where we are : boosted!

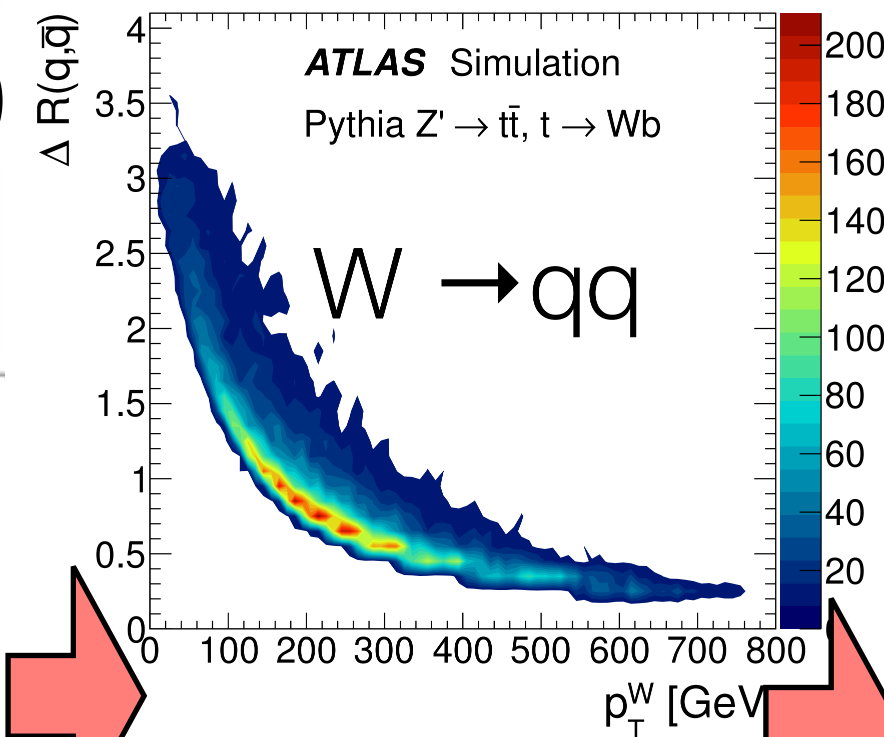


Differential in the extreme: the emergnce of boosted tops

ΔR(i,j from X→i,j) ~ 2m$_X$(i,j)/p$_{T,X}$

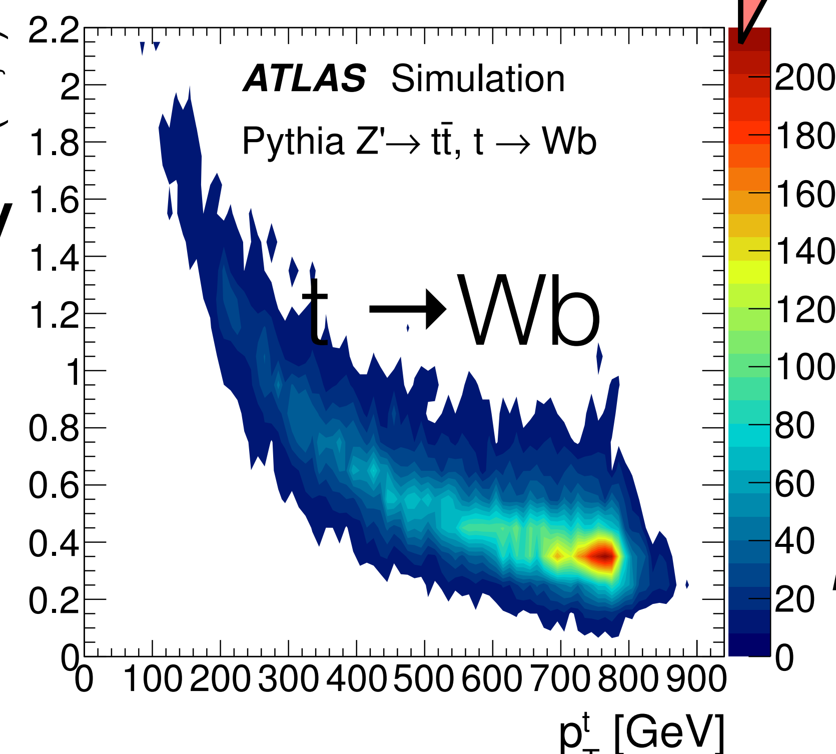
ΔR(q,q)





p$_T$>300 GeV

ΔR(W,b)

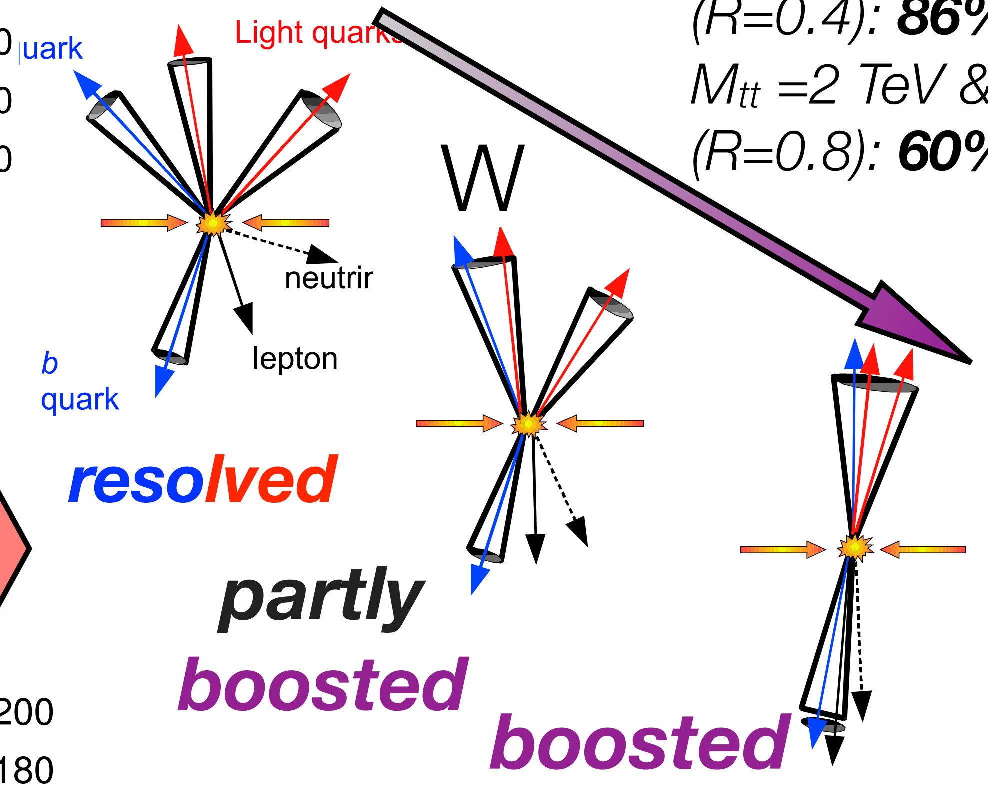


JHEP 1309 (2013) 076

Reduced efficiency for "resolved" reco

M$_{tt}$
P$_T$^{Top}

*M$_{tt}$ =1 TeV & anti-k$_T$ (R=0.4): **86% resolved***
*M$_{tt}$ =2 TeV & antikt (R=0.8): **60% boosted***



For ΔR=0.8, M$_{tt}$ ~1.7 TeV, P$_T$ ~600 GeV

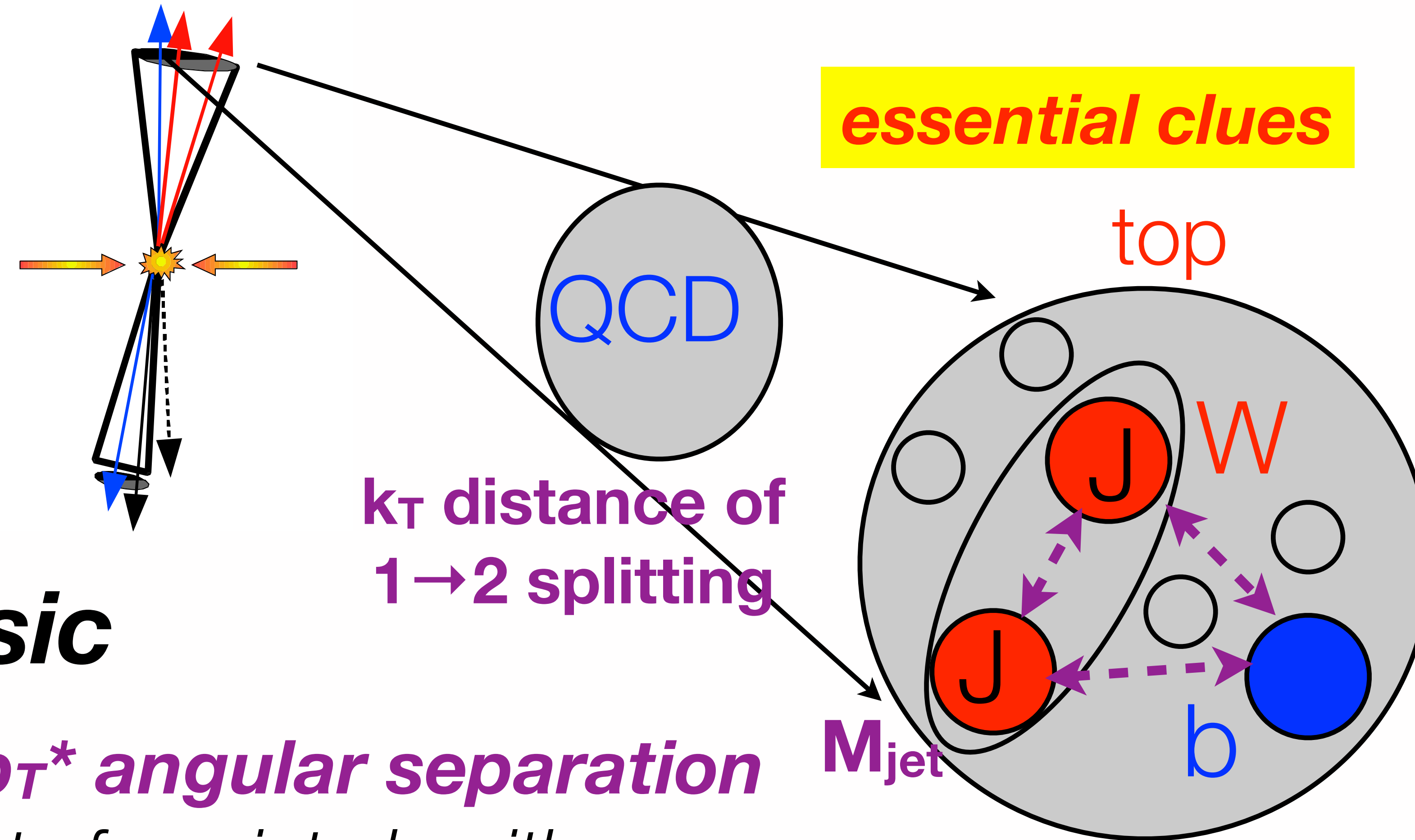
*Need to **distinguish top-jet from light q-, gluon**-initiated jets: **di-jets** bkg **overwhelming** fully had tt decays*

Pile up & soft activity degrade identification & energy estimate

How **to tag** a boosted hadronic top quark?

Look into the jet substructure

(see Jose Juknevich, TOP2013)



Basic

*Use **jet mass** and **product of p_T* angular separation** of two hardest jet constituents from jet algorithm*

- Splitting scales (ATLAS tagger) Butterworth, Cox, Forshaw (hep-ph/021098)
  - Read off k_T scales of the (next-to-)next-to-last clusterings
  - Place cuts on jet mass and splitting scales

Radiation based

Discard soft coherent radiation ("grooming") to reveal boosted objects:redefine jets

Example

- HEPTopTagger Plehn, Spannowsky, Takeuchi, Zerwas (1006.2833)
  - **Mass-drop tagger** divides jet into subjets
  - **Filtering** removes UE/Pileup contamination
  - Choose pairing based on **mass criteria**

Prong/pattern based

Recognize energy pattern in unchanged jet

Example

- Top Template Tagger Almeida et al. (1006.2035)
  - Discriminates heavy jets using their energy distributions
  - Compares the energy flow within a jet with the flow of selecte partonic decays (templates)

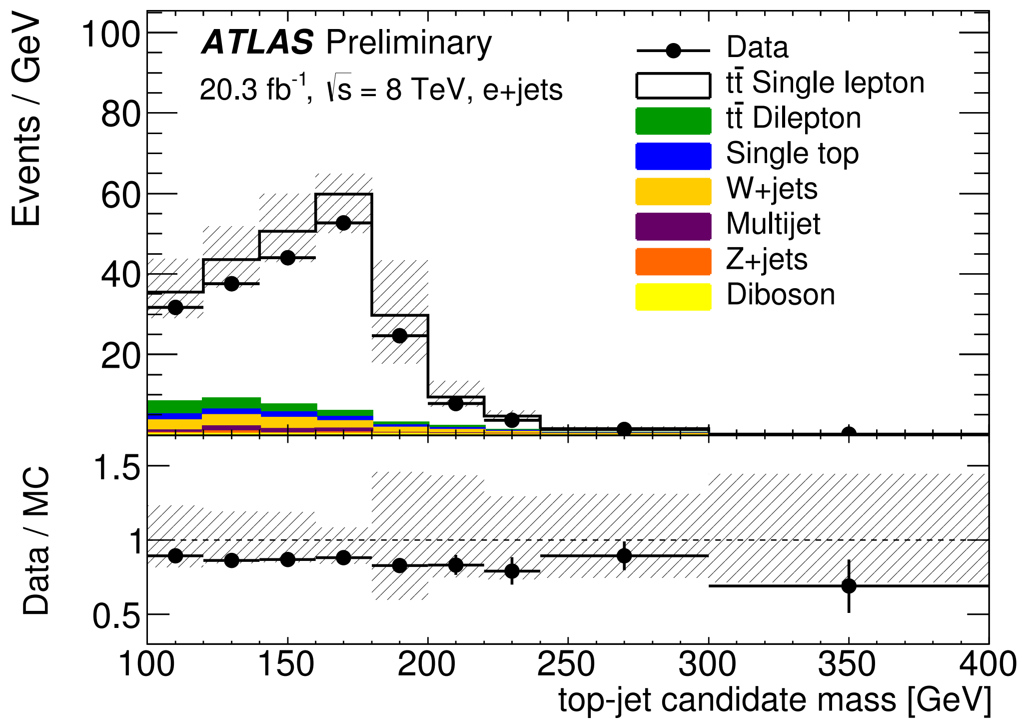
Differential $d\sigma_{t\bar{t}}/dX$: l+jets $\sqrt{s}$ = 8 TeV

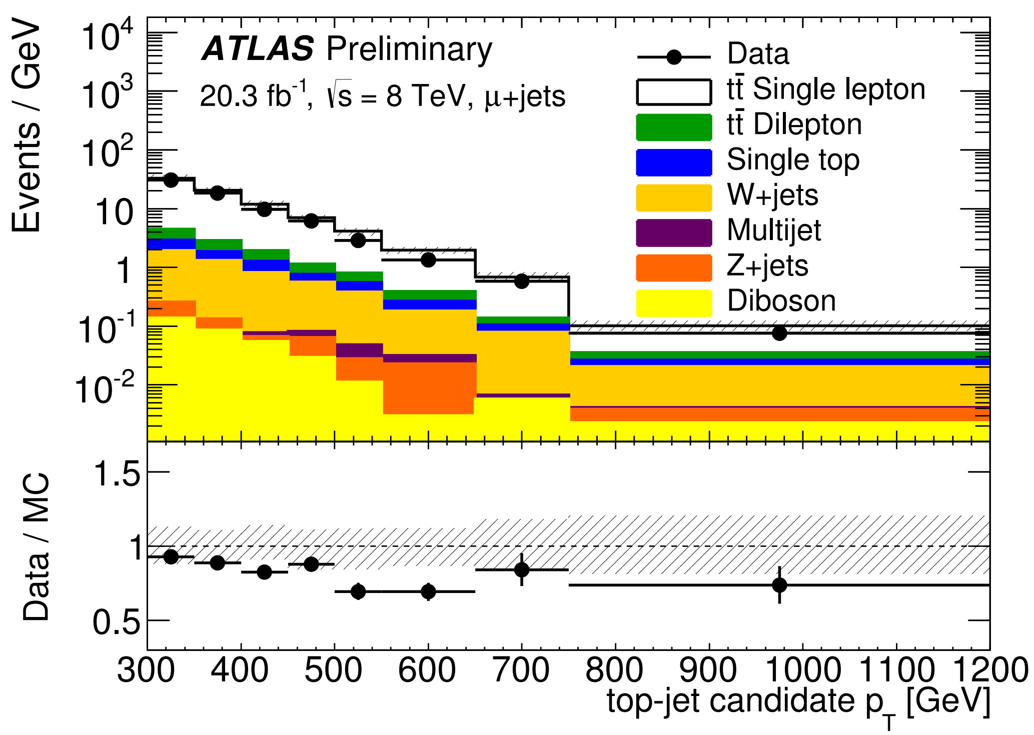
Kinematic distributions: boosted tops (ATLAS NEW!)

Lepton+jets: boosted tops

1. Lepton: p_T-dependent isolation, close to a R(=0.4) jet $\Delta R(l,jet_{R=0.4})<1.5$
2. Top jet candidate reconstructed using leading anti-k_T, R=1 jet, with $p_T > 300$ GeV, applying jet substructure cuts
3. Leptonic and hadronic candidates in opposite hemispheres
4. ≥1 b-tagged top candidate
5. E_T^{miss}, $M_{W,T}+E_T^{miss}$

- Reference MC: Powheg+Pythia
- Prediction overestimates data, shape well described
- $p_T >$ spectrum softer in data (up to approx. 50% highest bin)





Differential $d\sigma_{tt}/dX$: l+jets $\sqrt{s}$ = 8 TeV

- **Unfold to fiducial phase space** *(regularized unfolding, linearity tests)*

Reco

Pass Reco, Pass PL	**Pass Reco,** Fail PL	Fail Reco Pass PL	Fail Reco, Fail PL

Particle level same formulas for parton level

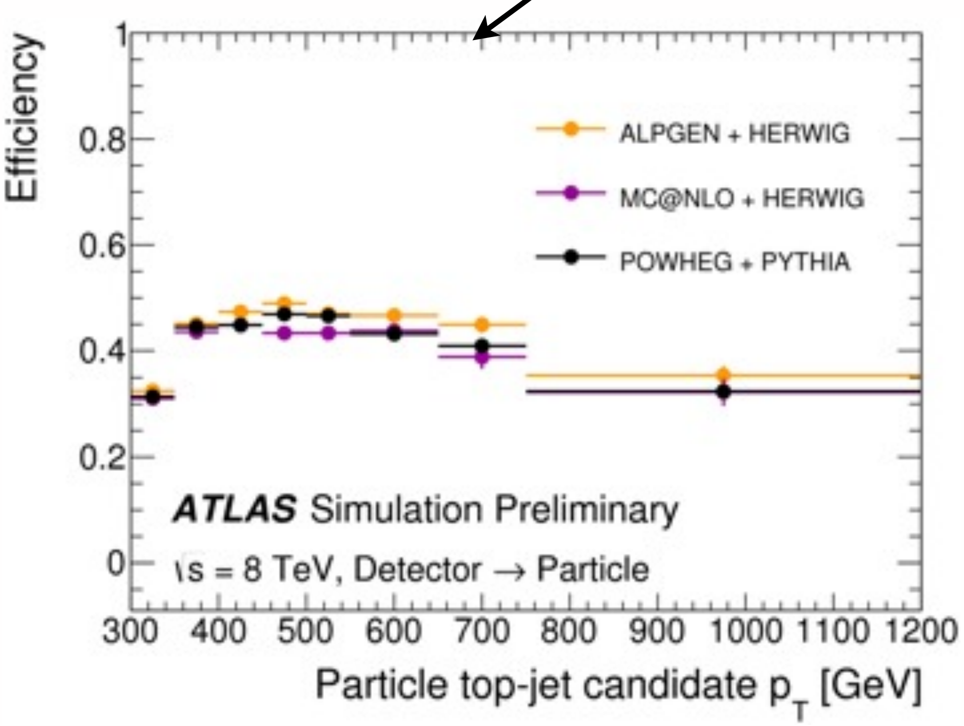
to correct to

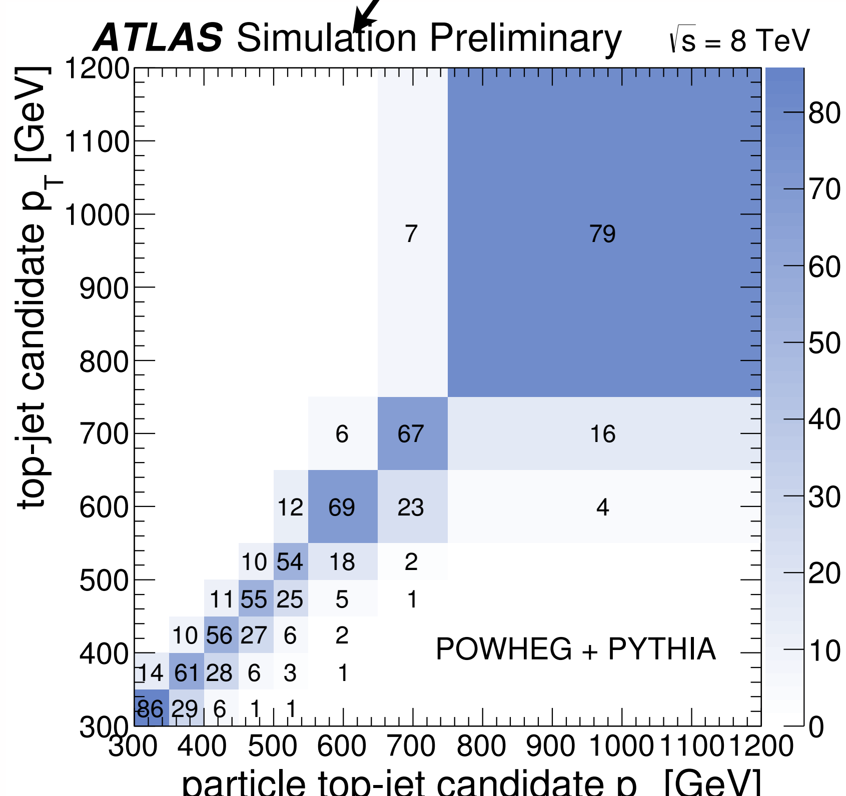
$$\frac{d\sigma_{t\bar{t}}}{dp^{i}_{T,ptcl}} = \frac{N^{i}_{ptcl}}{\Delta X^{i}\mathcal{L}} = \frac{1}{\Delta X^{i}\mathcal{L} f^{i}_{ptcl!reco}} \sum_{j} (M^{-1})^{ptcl,i}_{reco,j} f^{j}_{reco!ptcl} (N^{j}_{reco} - N^{j}_{reco,bgnd})$$

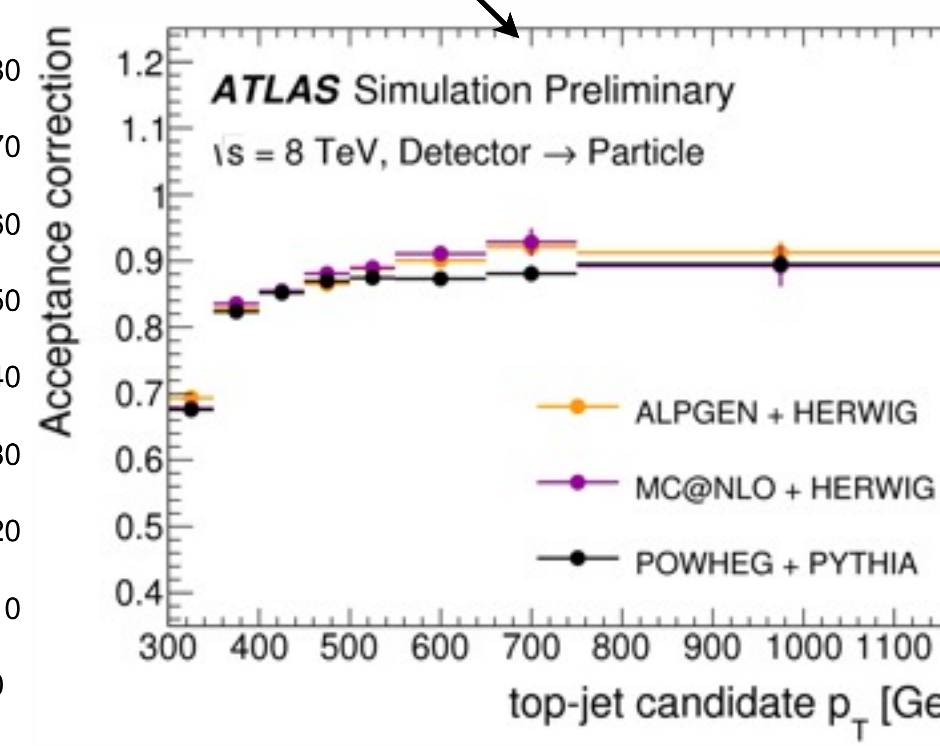
unfolding

events that pass particle & reco / events that pass particle

events that pass reco & part / events that pass reco



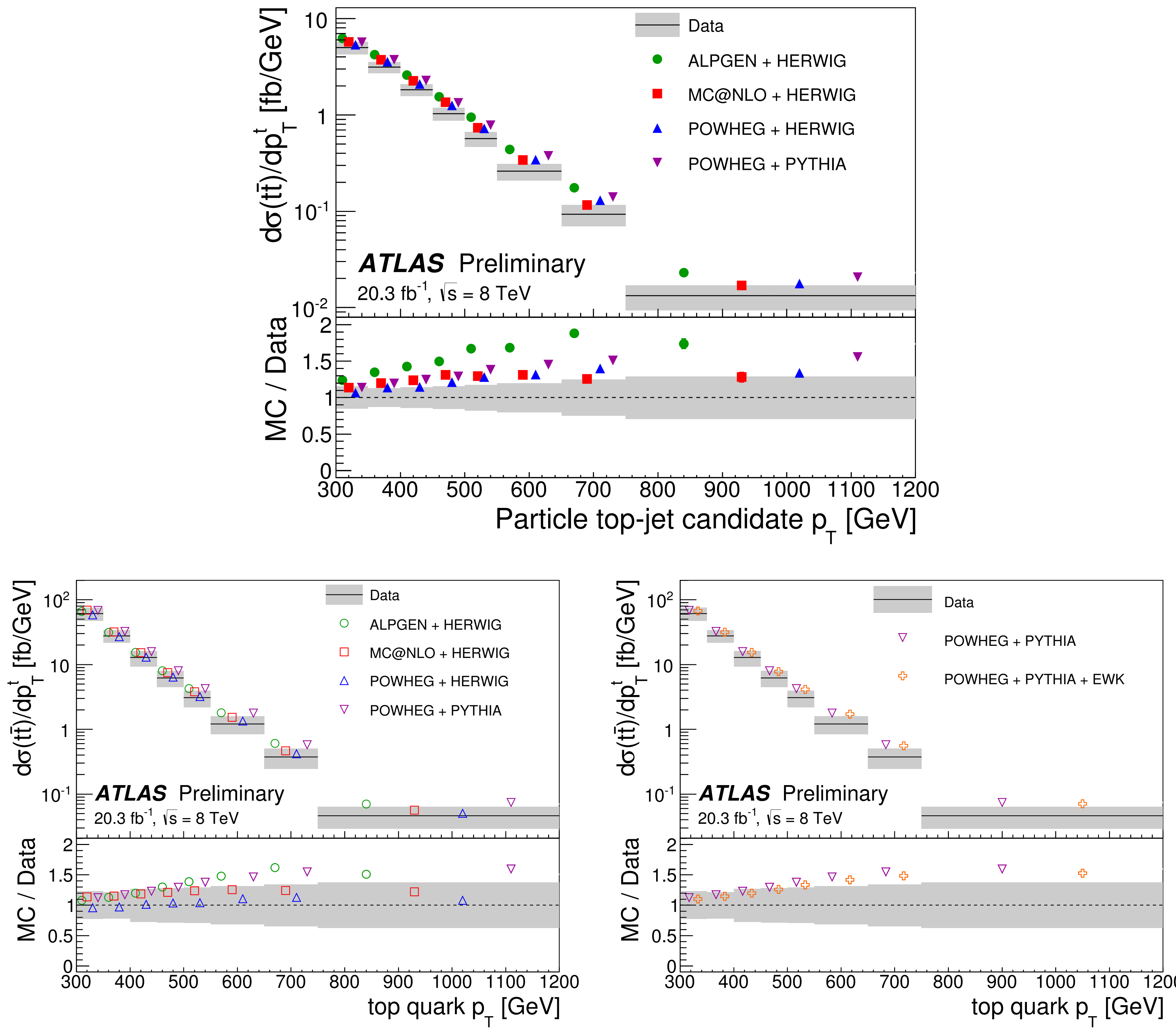




Boosted $t\bar{t}$: p_T^t (p_T^t >300 GeV)

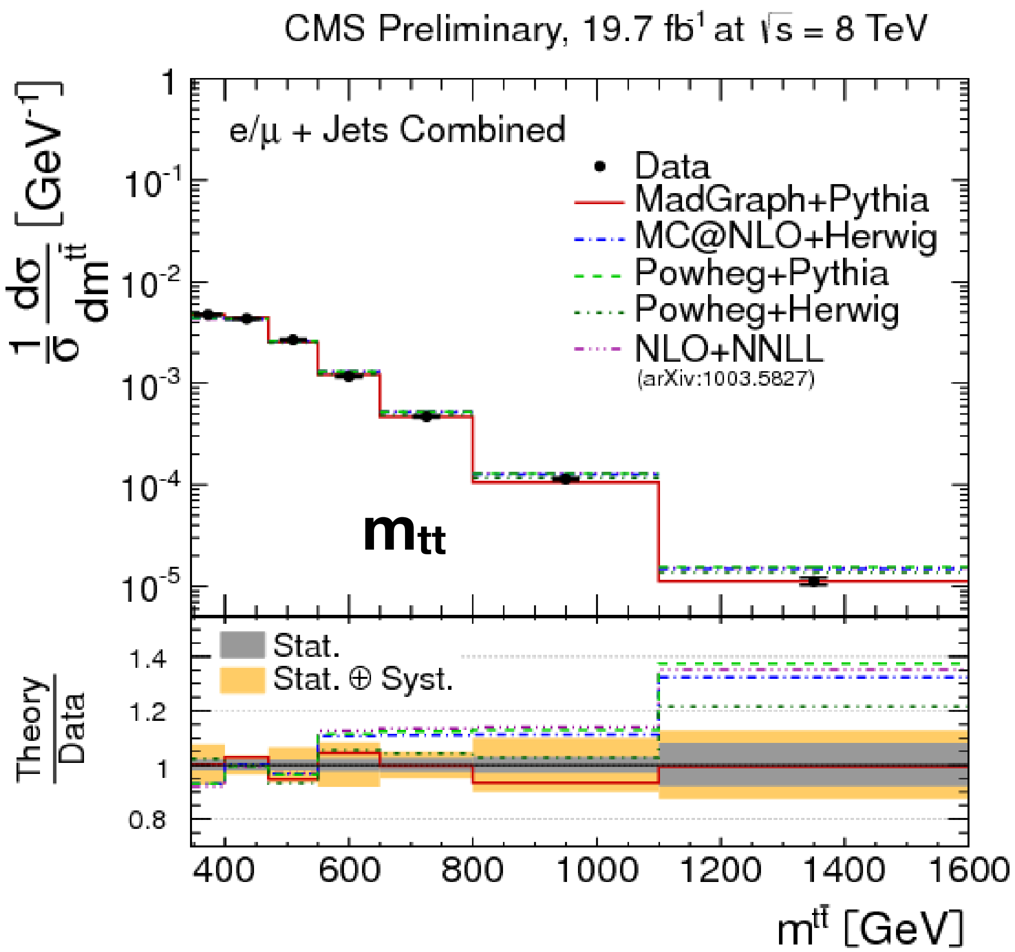
ATLAS (8 TeV) NEW!

- **Fiducial particle level and full phase space parton level, up to the TeV scale**
- Data/MC agreement: better at parton-level than at particle-level for Powheg, MC@NLO, Alpgen+Herwig
- All generators: harder spectrum, increasing with p_T (discrepancy: 30% to 70%)
- Total uncertainties ~15-30% (particle level), ~20-40% (parton level)
- Result qualitatively consistent with 7 TeV
- EW corrections: softer spectrum, not significant improvement
- Also investigated modelling radiation in Powheg (back up)



Differential σ_{tt}: growing field of action

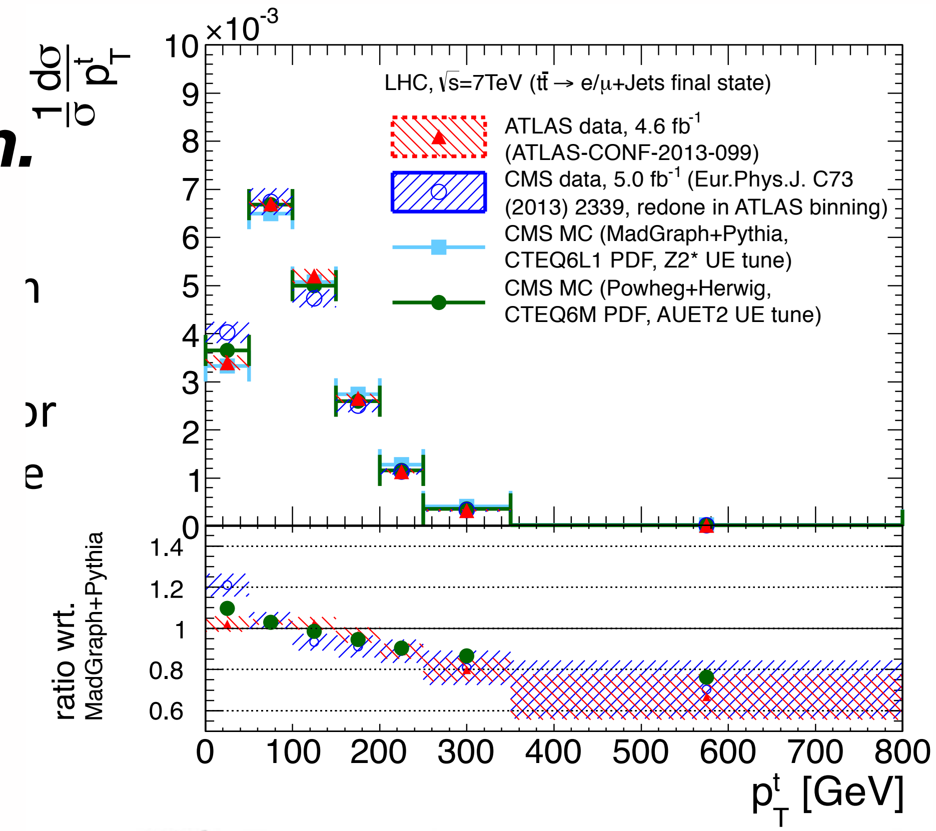
Martin Goerner (CMS-THESIS-2014-010



test SM QCD tt production & kinem.

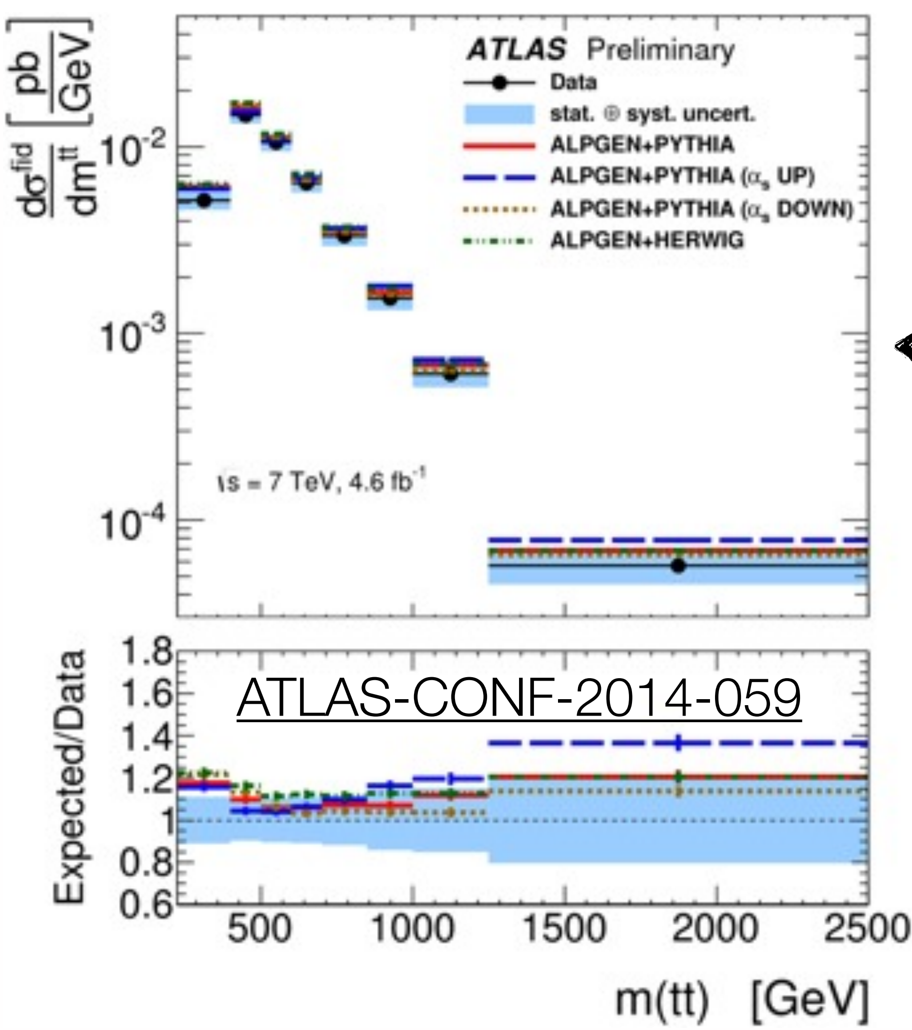
√s = 8 TeV

parton phase space

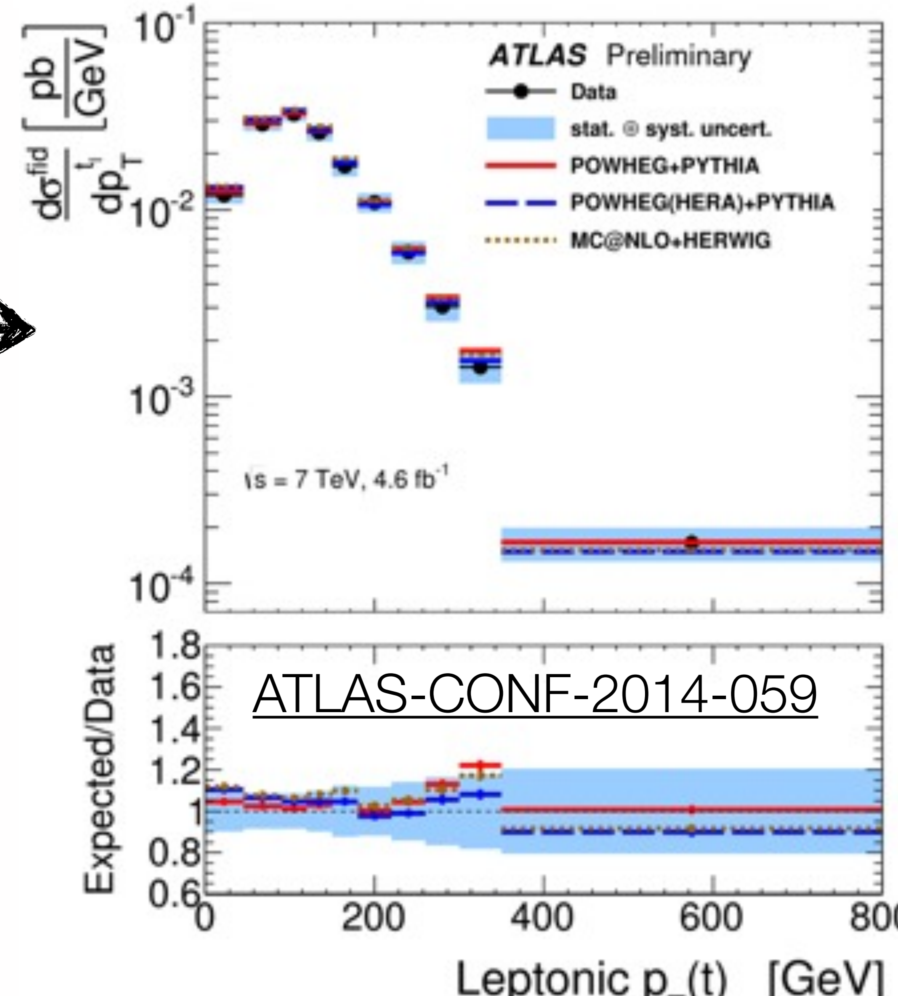


dσ/dX,

X= $p_{T,top}$ m_{tt} $p_{T,tt}$ $y_{,tt}$ 5/fb



particle level



√s = 7 TeV

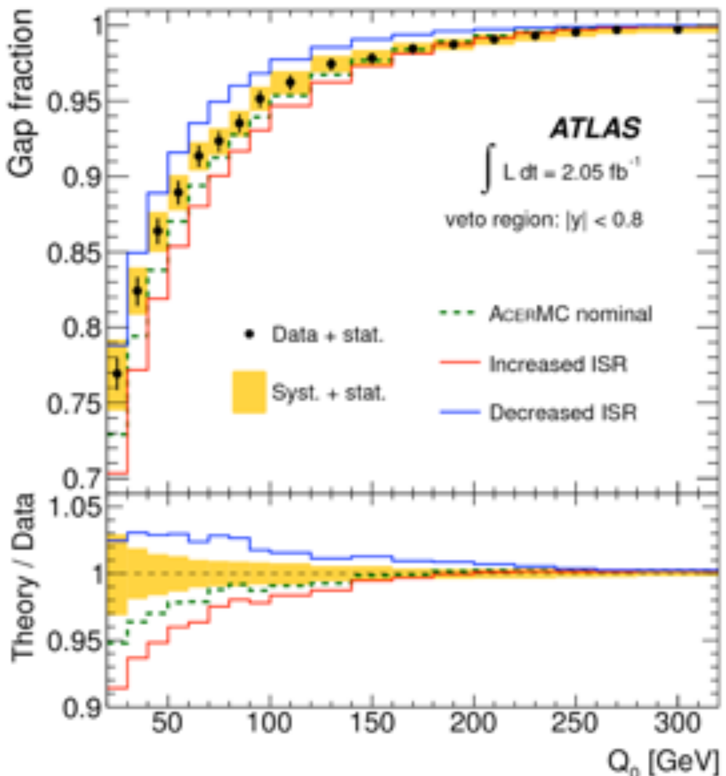
1/σ dσ/dX,

X= $p_{T,top}$ m_{tt} $p_{T,tt}$ $y_{,tt}$ 5/fb

Differential & fiducial σ_{tt}:growing field of action

arXiv:1411.5621,submitted to PLB,

$\sqrt{s}$ = 8 TeV

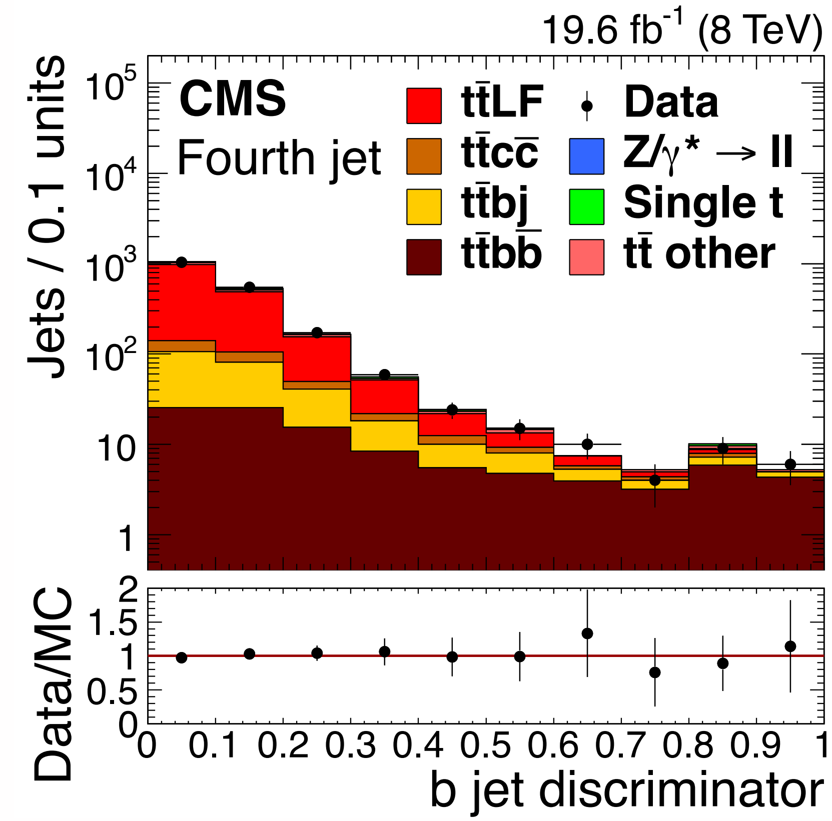


jet activity in in tt events (1/σ dσ/dQ), 2/fb

Eur. Phys. J. C (2013) 73: 2261

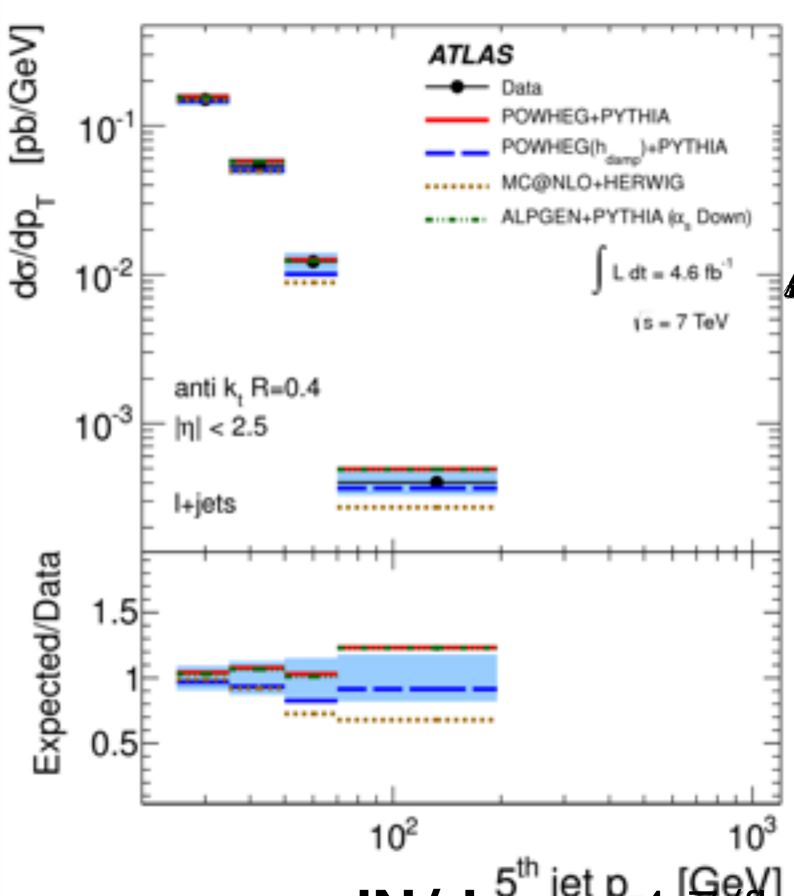
$$\sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj}$$

test of SM QCD tt production * kine



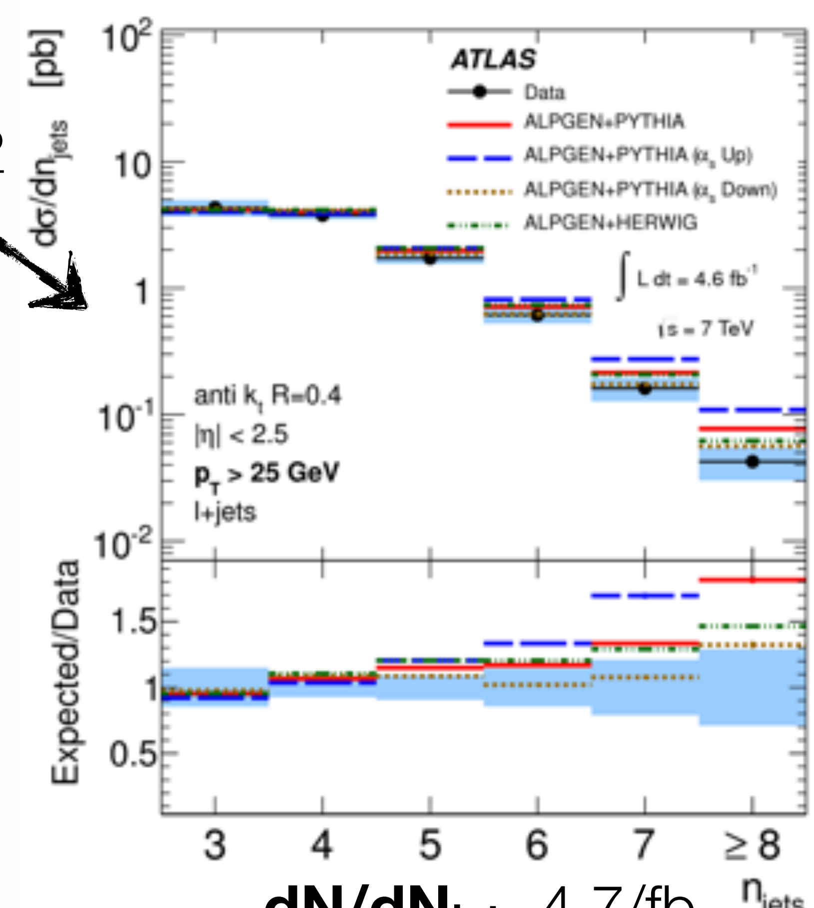
tt+heavy flavour, 19.6/fb

arxiv.org:1407.0891 submitted to JHEP



dN/dp$_{T,jets}$,4.7/fb

$\sqrt{s}$ = 7 TeV



dN/dN$_{jets}$,4.7/fb

Attention to systematic uncertainties!

essential clues

- In TOPLHC Working group harmonization in approach towards theoretical systematic uncertainties. Particularly about Monte Carlo generators and Initial/Final state radiation.
  - **Radiation**: more coherent treatment now achieved: both varying parameters of leading order generator within values set by data measurements
  - **Jet energy scale**: agreed break-down of sub-components
  - **Monte Carlo generator uncertaint**y: different strategies to be harmonized
    - ❖CMS: varies parameters within a given generator
    - ❖ATLAS; takes difefrece of generators
- The TOPLHC Working group performs combinations and comparisons of measurements
  - test simulation of one experiment in another's setup
    - ❖use the same simulated set of events to compare performance/ correlations/analyses sensitivity to syst effects.

Towards acceptance/unfolding to particle level→reduce theory extrapolation (generator dependence), more durable connection to theory

Measurement of top quark mass, m_t

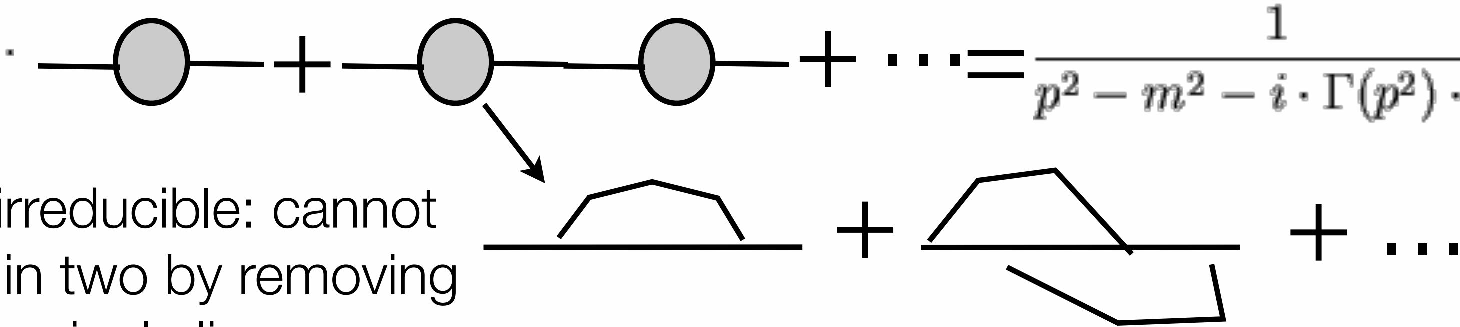
i.e.

the defining property

What is top mass and how is it measured?

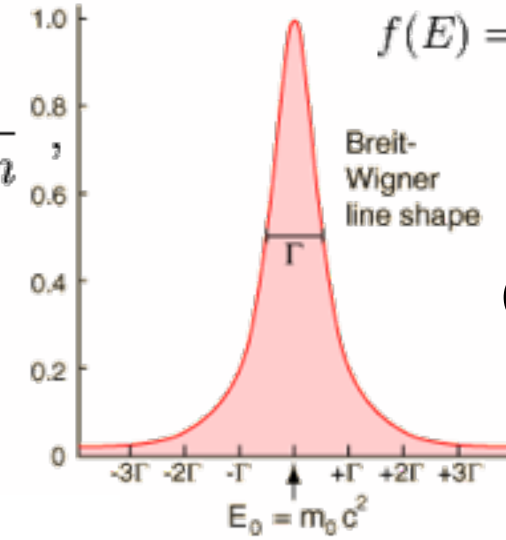
propagator to amplitude: higher order corrections

$$\frac{1}{p^2 - m^2} \cdot$$



$$= \frac{1}{p^2 - m^2 - i \cdot \Gamma(p^2) \cdot m}$$

1 part irreducible: cannot be split in two by removing a single line



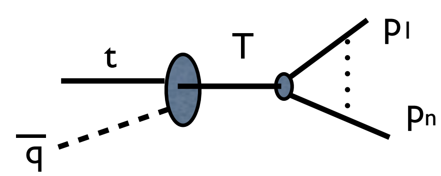
$$f(E) = \frac{k}{\left(E^2 - M^2\right)^2 + M^2\Gamma^2}.$$

⊗ Detector

Definition

Definition of m_{top} from top decays

If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark

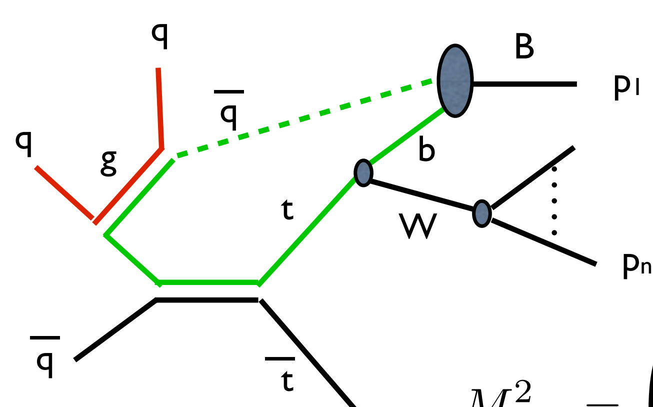


$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

$m_t = F_{lattice/potential\ models}(m_T, \alpha_{QCD})$

essential clues

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top})$~ 1 GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

- The parameter of the Breit-Wigner for a resonance : **property of a distribution.**

M Mangano at TOP2013

What is top mass and how is it measured?

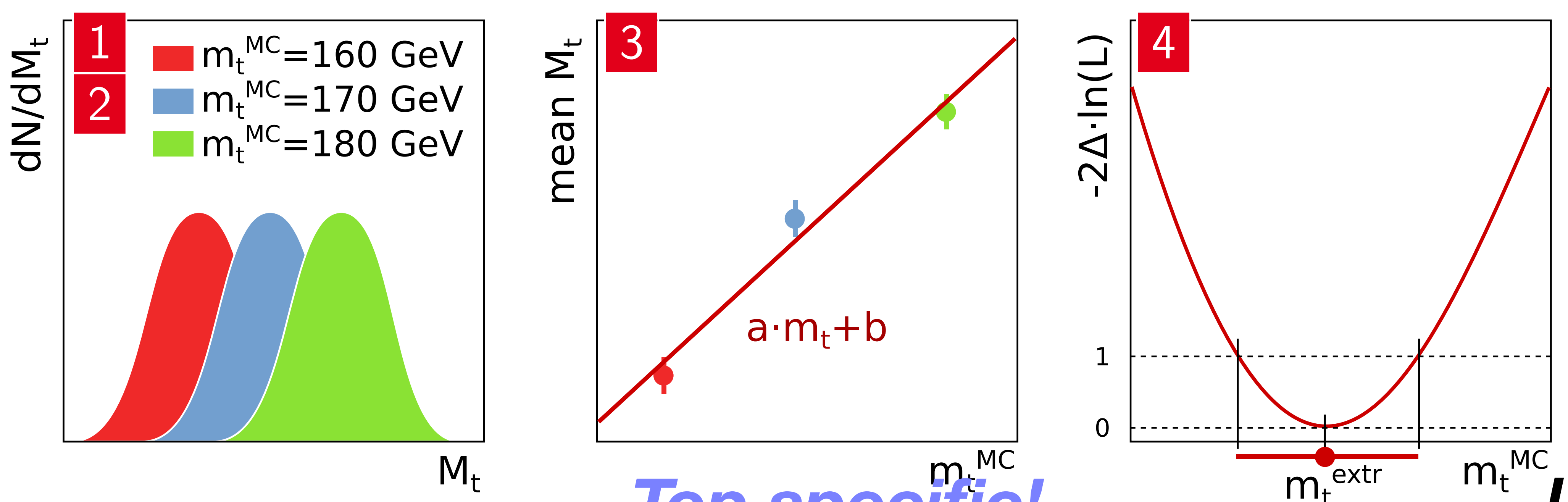
essential clues

Techniques

- **Compare predicted distribution with measured. Calculate and maximize likelihood as a function of top mass associated to observable**: distance "measured" by likelihood, measured **top mass is the simulation mass**
  - template method, ideogram method, matrix element, end-point...

1. **Select** $t\bar{t}$ events
2. Construct **observable**
3. **Parametrize** observable in m_t using MC simulation
4. **Fit** to data, extract mass

(images by B Stieger (CERN))



Top specific!

Uncertainties

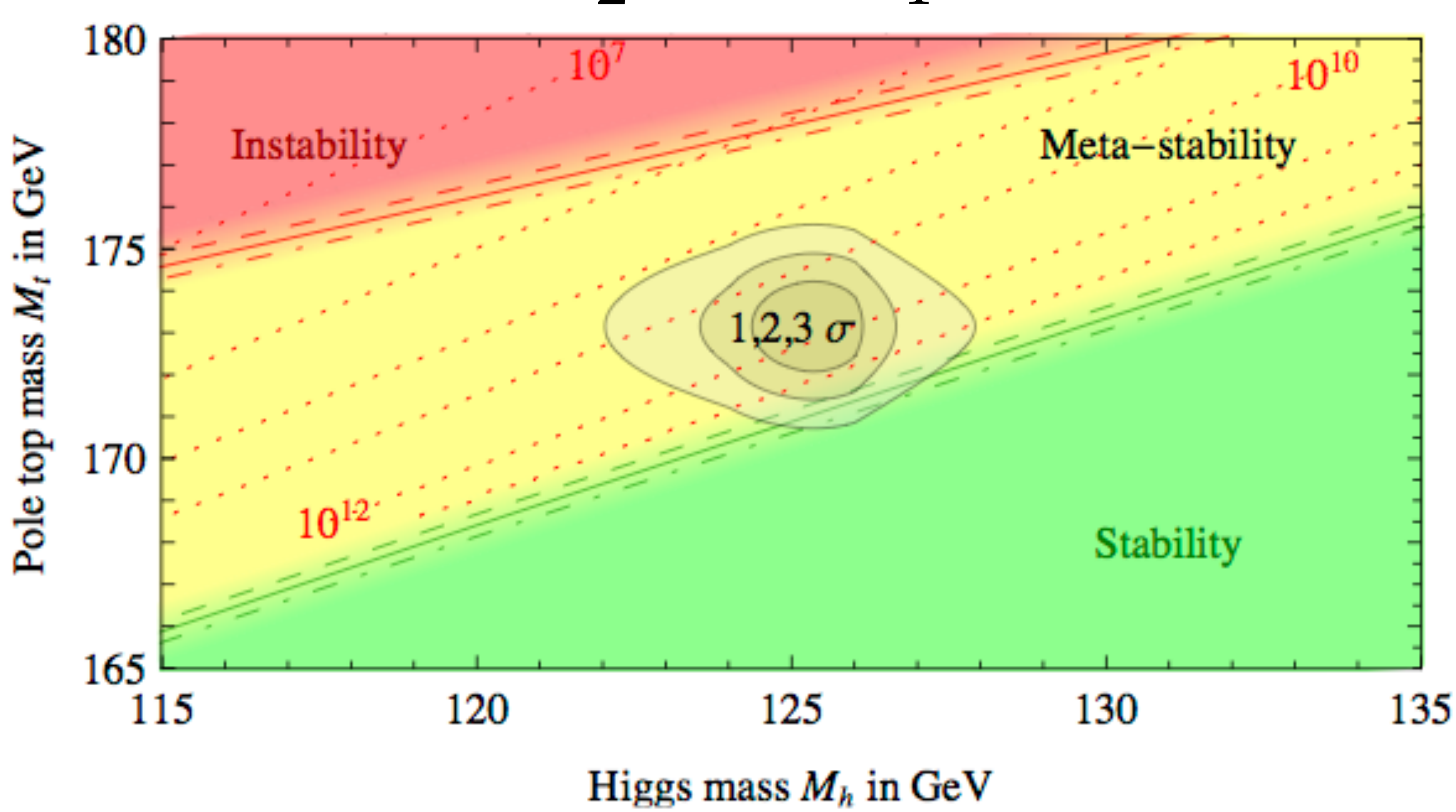
- Most precise methods **need full event reconstruction**: what jets to use and assign to quark, missing energy due to neutrinos in final state
- Precision measurement dominated by systematic uncertainties: mostly jet & theory related. **Develop techniques to constrain uncertainties from data or make analysis less sensitive or insensitive.**

Higgs potential stability

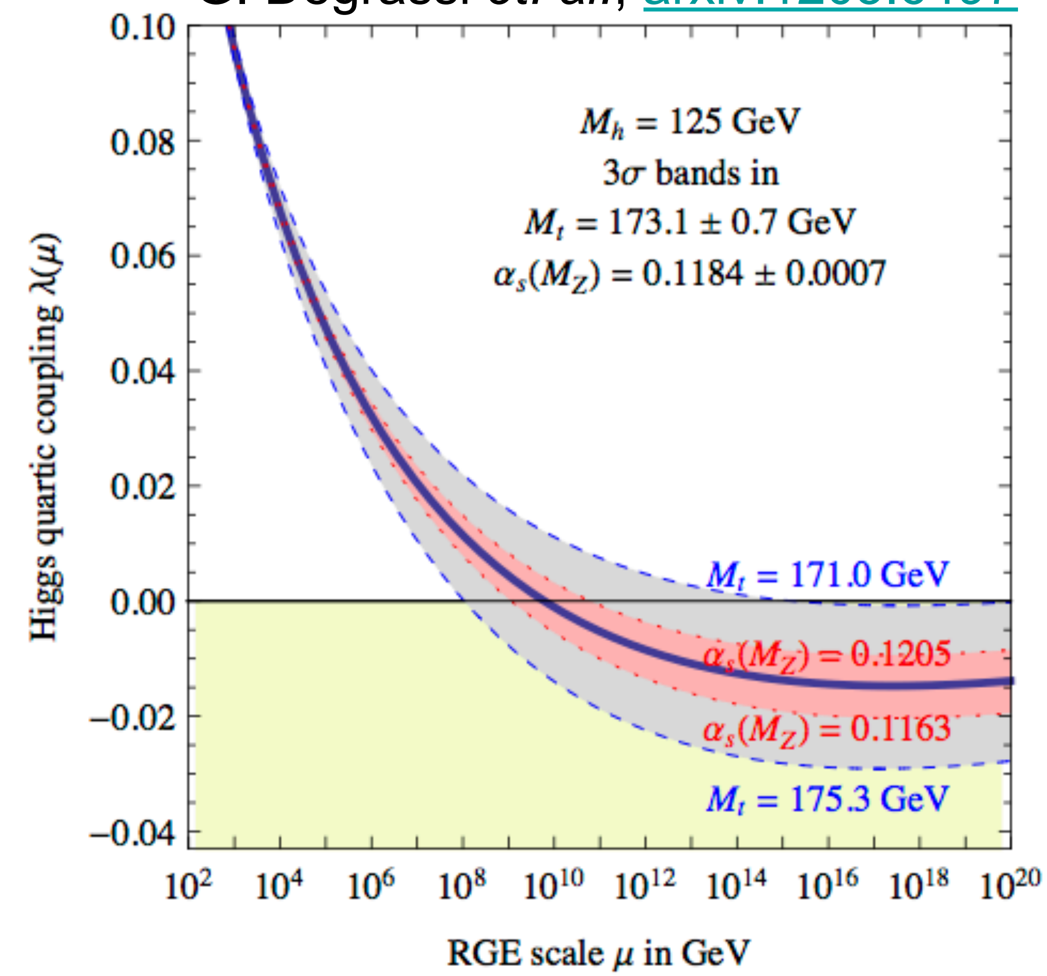
IF SM is valid up to the Planck scale

- The current experimental values of m_H and m_{top} are very intriguing from the theoretical point of view:
  - the Higgs quartic coupling could be rather small, vanish or even turn negative at a scale slightly smaller than the Planck scale.
  - if λ(μ)>0
    the electroweak vacuum is a global minimum
  - if λ(μ) <0
    the electroweak vacuum becomes metastable (does not become unstable over the age of the universe)

$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$



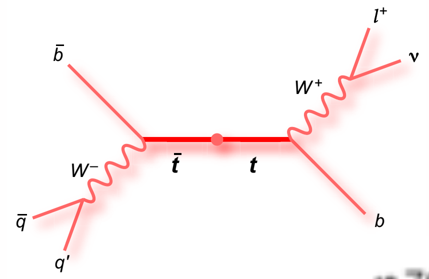
G. Degrassi *et. al.*, arxiv:1205.6497



- Even in the absence of direct evidences for new physics at the LHC, the experimental information on m_H and m_{top} gives us useful hints on the structure of the theory at very short distances
- Renewed interest for precision m_{top} measurements

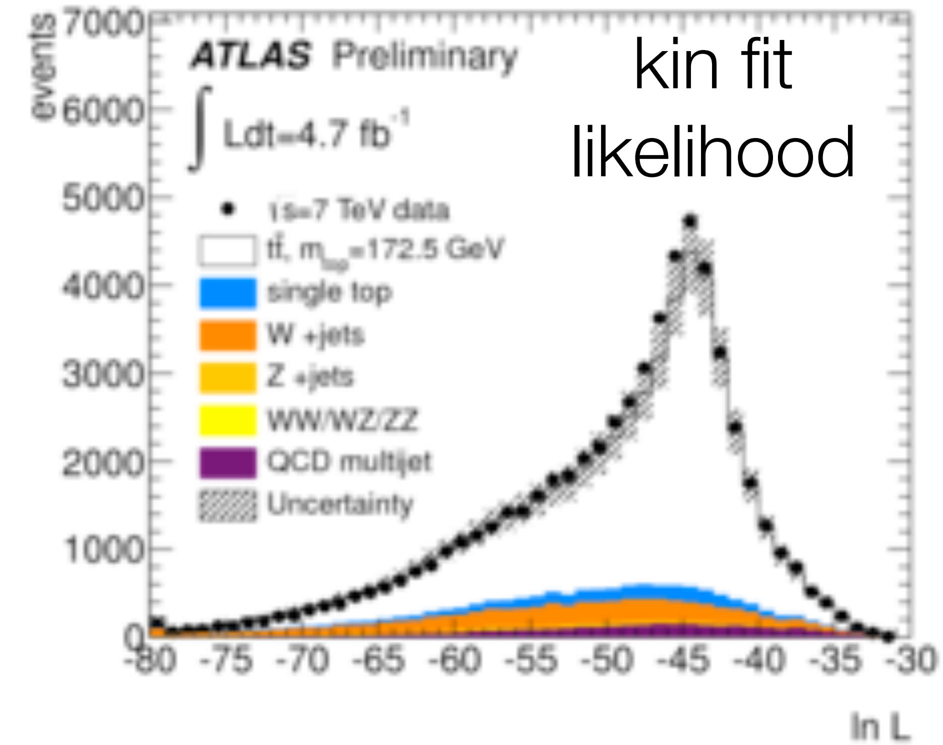
Measuring top mass $\int L dt = \mathbf{4.7\ fb^{-1}}$ *(2011)*

ATLAS-CONF-2013-046



qqℓ**νbb**

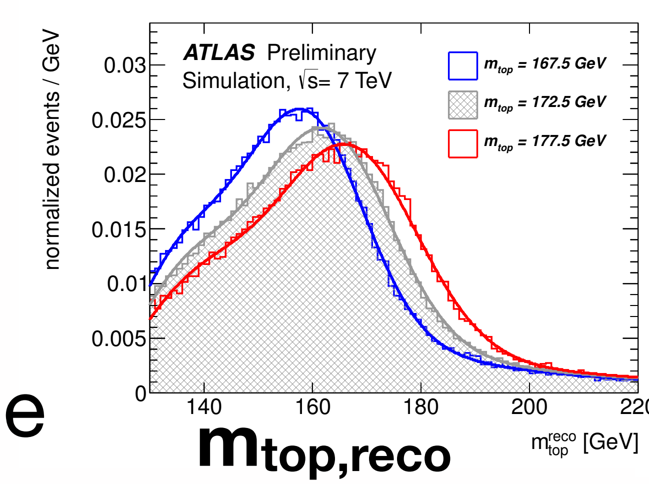
- **Standard single lepton selection**
  - *good quality objects, 1 lepton, cuts on E_T, m_T^W, ≥4 jets, at least 1 b-tagged jet*
  - *channel dep analytic shape for bkg,*
  - *W+jets and QCD from data*

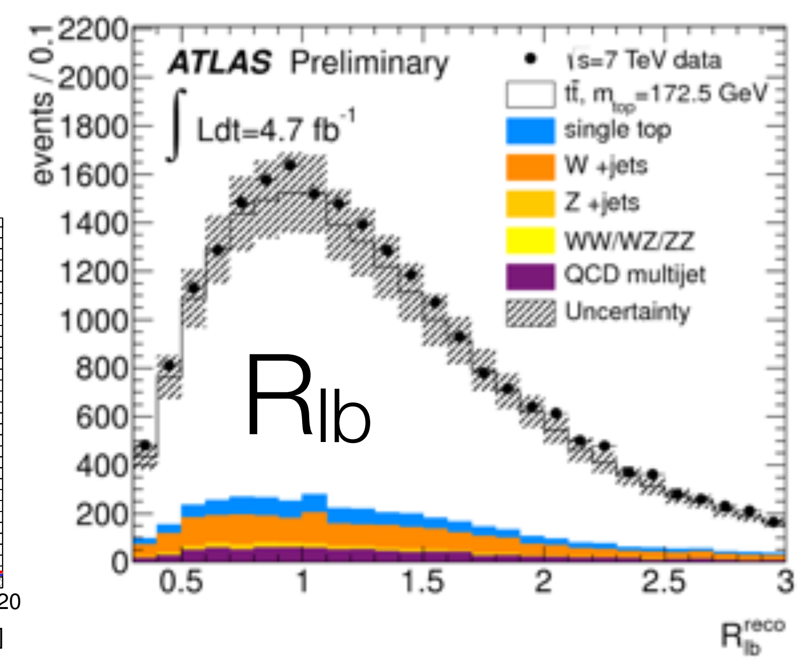


- **Reconstruct m_{top}-sensitive variables Reconstruct LO tt picture with kinematic likelihood fit** *($m_{top,HAD}$= $m_{top,LEP}$ + weight for b/ mis-tag ,m_W constraint)* → assign jets
  - **$m_{top,reco}$ from fit-assigned & constrained jets**
  - **$m_{W,reco}$ from fit-assigned but unconstrained jets**
  - **R_{lb} (1 or 2 btag) = $\alpha \sum_{b\text{-tag}} p_{T,b\text{-tag}} / (p_{T,Wjet1} + p_{T,Wjet2})$**

α=2 for 1-btag and α=1 for 2 b-tag

- **Build simulated template(s)** of variables as a function of
  - m_{top}
  - global jet en. scale factor (JSF)
  - relative b-to-light jet energy scale factor (truth matched):b-JSF



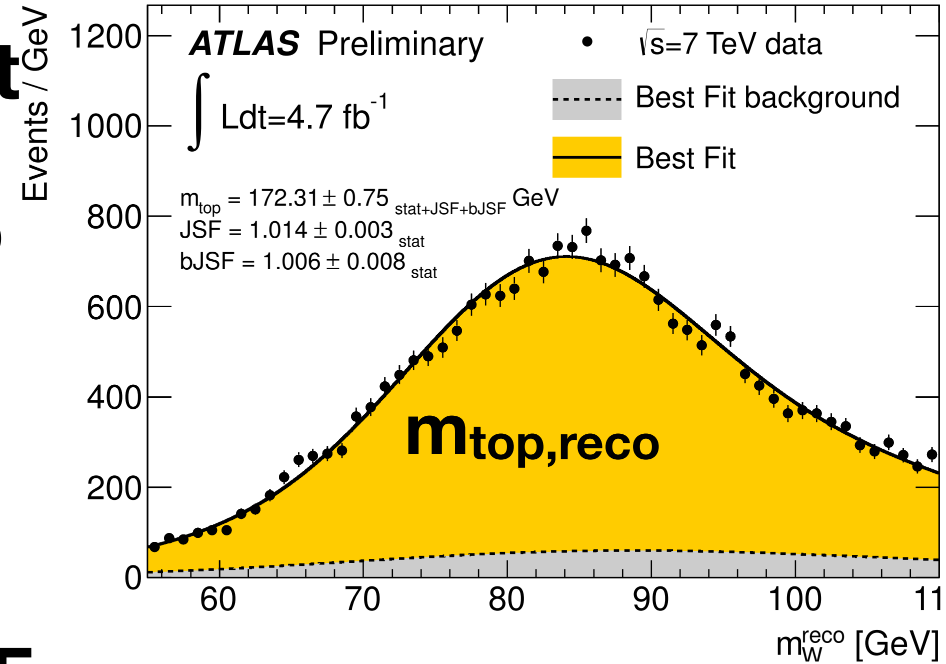


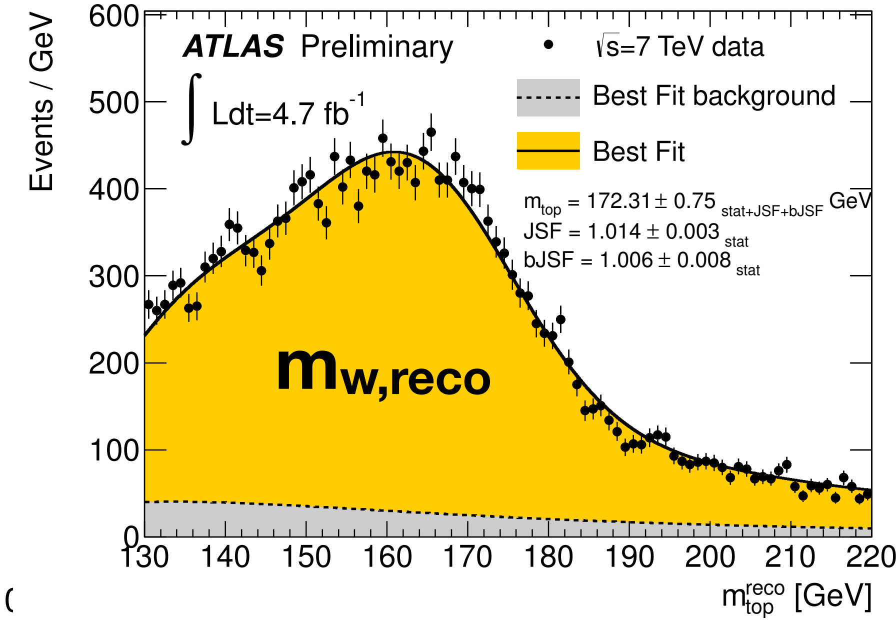
Jet energy scale is crucial: different reduction

Measuring top mass

$\int L dt$ = **4.7 fb^{-1}** *(2011)* ATLAS-CONF-2013-046

- **Unbinned likelihood fit** *of data in windows of $m_{W,rec}$, $m_{top,reco}$ and R_{lb}* **to 3 analytic template(s)** *derived by fit to MC→* **m_{top},JSF,bJSF**

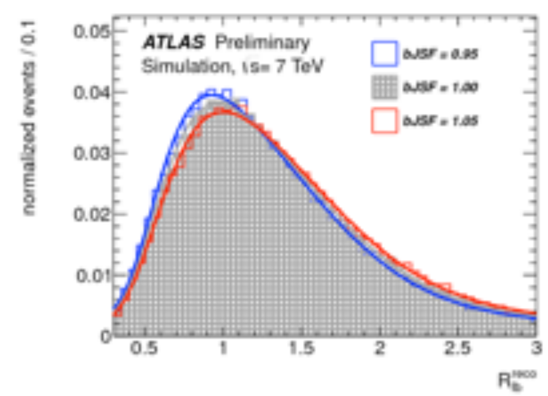


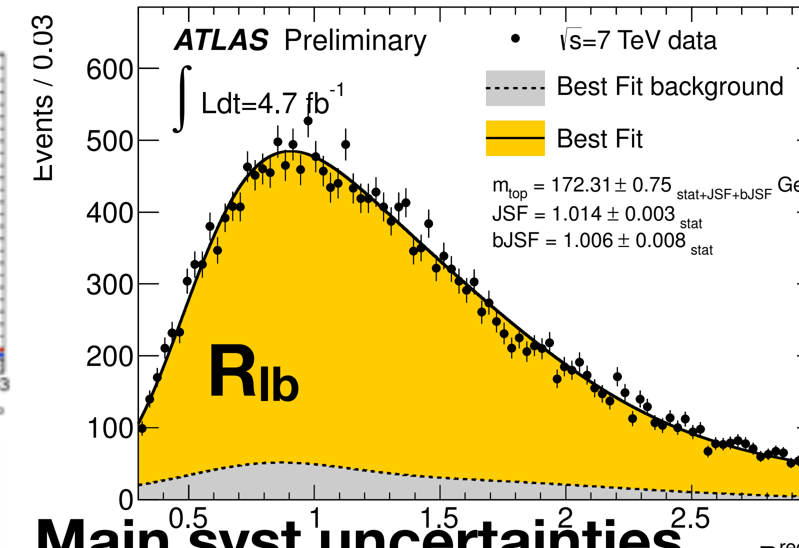


Template dependence

- **$m_{top,reco}$: m_{top}, JSF,b-JSF**
- **$m_{w,reco}$: JSF**
- **R_{lb}: m_{top}, b-JSF**

variables correlations at 15% level





reduce JES *by in-situ fix to W mass + transfer uncertainty to JSF, bJSF*

$$m_t = 172.31 \pm 0.75(\text{stat + JSF + bJSF}) \pm 1.35(\text{syst})\text{GeV}$$

$$\text{JSF} = 1.014 \pm 0.003(\text{stat}) \pm 0.021(\text{syst})$$

$$\text{bJSF} = 1.006 \pm 0.008(\text{stat}) \pm 0.020(\text{syst})$$

$\delta m_{top} / m_{top}$ ~0.90%

Main syst uncertainties

Description	Value [GeV]
Statistics	0.23
JSF (stat)	0.27
bJSF (stat)	0.67
Hadronisation	0.27
Colour reconnection	0.32
ISR/FSR	0.45
Jet energy scale	0.79
b-tagging	0.81
Total systematic	**1.35**

- ***Systematic dominated! b-JES reduced by 40% w.r.t to previous measurement***
  - ***b-JES*** (starting from reduced baseline), *reduction ISR/FSR modelling (jet activity), jets are dominant, modelling is still important*

m_{top} @ ATLAS with 3D template: uncertainties

(thanks to G. Cortiana's CERN seminar, 2nd July 2013)

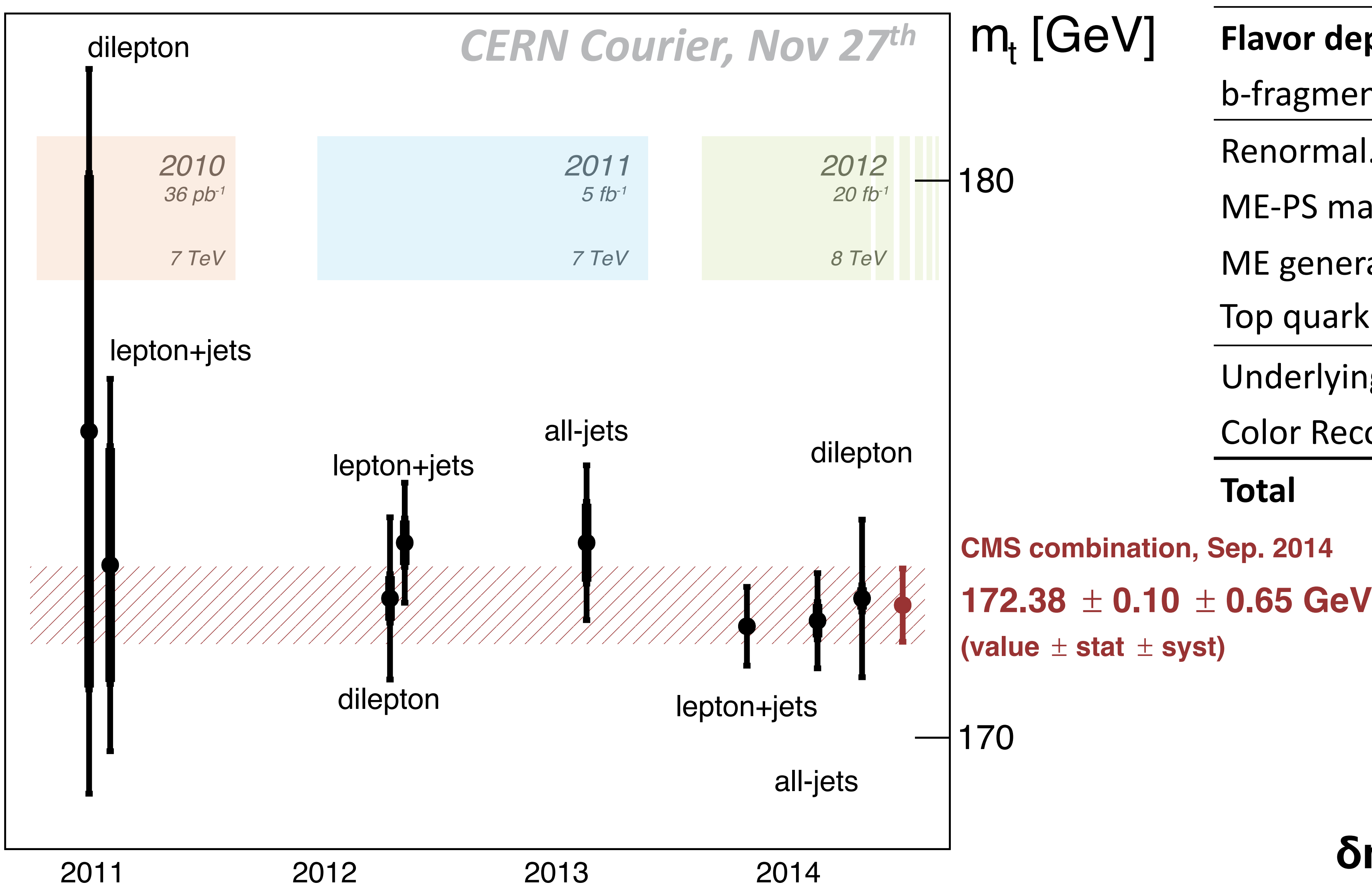
set b-JES to 1

- Larger stat in 3D because of higher dim, but reduced b-JES
- Dominant modelling is reduced by JSF/ b-JSF
- Residual JES from p_T dependence of JES
- b-tag:p_T dependence of scale factors affecting R_{lb}
- Overall: better total syst , bJES absorbed by bJSF, scaling with lumi, uncorrelated in combinations

ATLAS-CONF-2013-046

	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	reduced
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	reduced
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	reduced
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	reduced
Total uncertainty	2.05	0.021	1.55	0.021	0.022	

Most precise result from single experiment



Major combined uncertainties	Δm_t (GeV)
Uncorrelated JES component	0.14
Jet energy resolution	0.17
Pileup	**0.20**
Flavor dependent hadronization	**0.36**
b-fragmentation / B hadron decays	0.14
Renormal. / factorization scales	0.17
ME-PS matching threshold	0.16
ME generator	0.13
Top quark p_T	0.12
Underlying Event	0.16
Color Reconnection	0.18
Total	**0.65**

$\delta m_{top} / m_{top}$ ~0.38%

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

53/53

Benjamin Stieger (CERN) Dec. 2nd 2014

First M_{top} World average

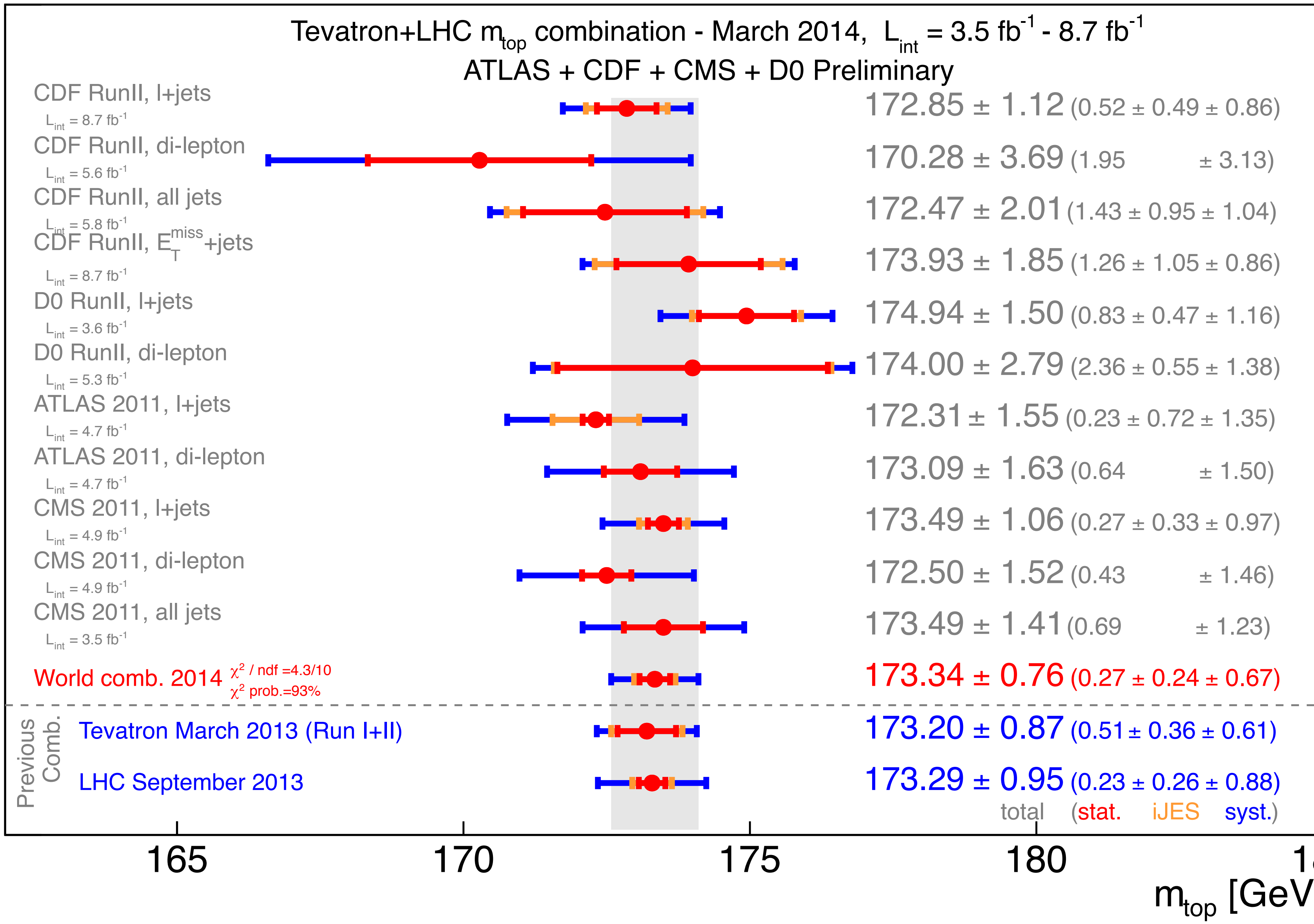
- **First combination** of m_{top} from **1.96 TeV $p\bar{p}$ & 7 TeV pp** collisions

arxiv:1403.4427[hep-ex]

- Tevatron: up to 8.7/fb
- LHC: up to 4.9/fb
- Use most precise measurement in each channel by each experiment

- **δm_{top} reduced** by
  - 28% w.r.t. most precise single input
  - 13% w.r.t to previous most precise combination

- **Systematics dominated**
  - tt modelling
  - energy scale of light and b-jets



$$m_{top} = 173.34 \pm 0.27(stat) \pm 0.71(syst)\ GeV$$

$$\delta m_{top} / m_{top} \sim 0.44\%$$

First M_{top} World average : uncertainties & correlations

arxiv:1403.4427[hep-ex]

GeV

Uncertainty	World Combination
m_{top}	173.34
Stat	0.27
iJES	0.24
stdJES	0.20
flavourJES	0.12
bJES	0.25
MC	0.38
Rad	0.21
CR	0.31
PDF	0.09
DetMod	0.10
b-tag	0.11
LepPt	0.02
BGMC	0.10
BGData	0.07
Meth	0.05
MHI	0.04
Total Syst	0.71
Total	0.76

- Major effort to classify **uncertainties** & define **correlations**

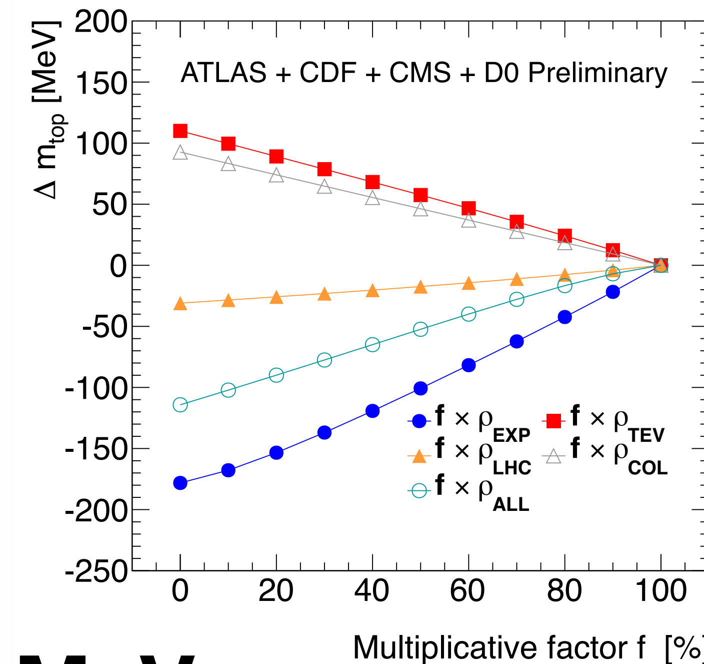
11 input columns combined with

within same experiment — *within same collider* — *between colliders*

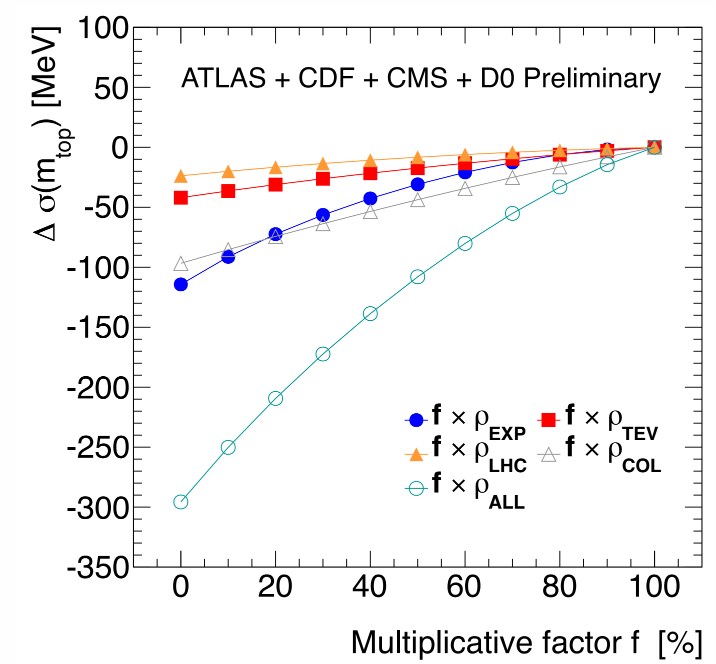
	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC†	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

- Vary correlation scenarios **(m_{top}, δm_{top}) stable** within uncertainties

MeV



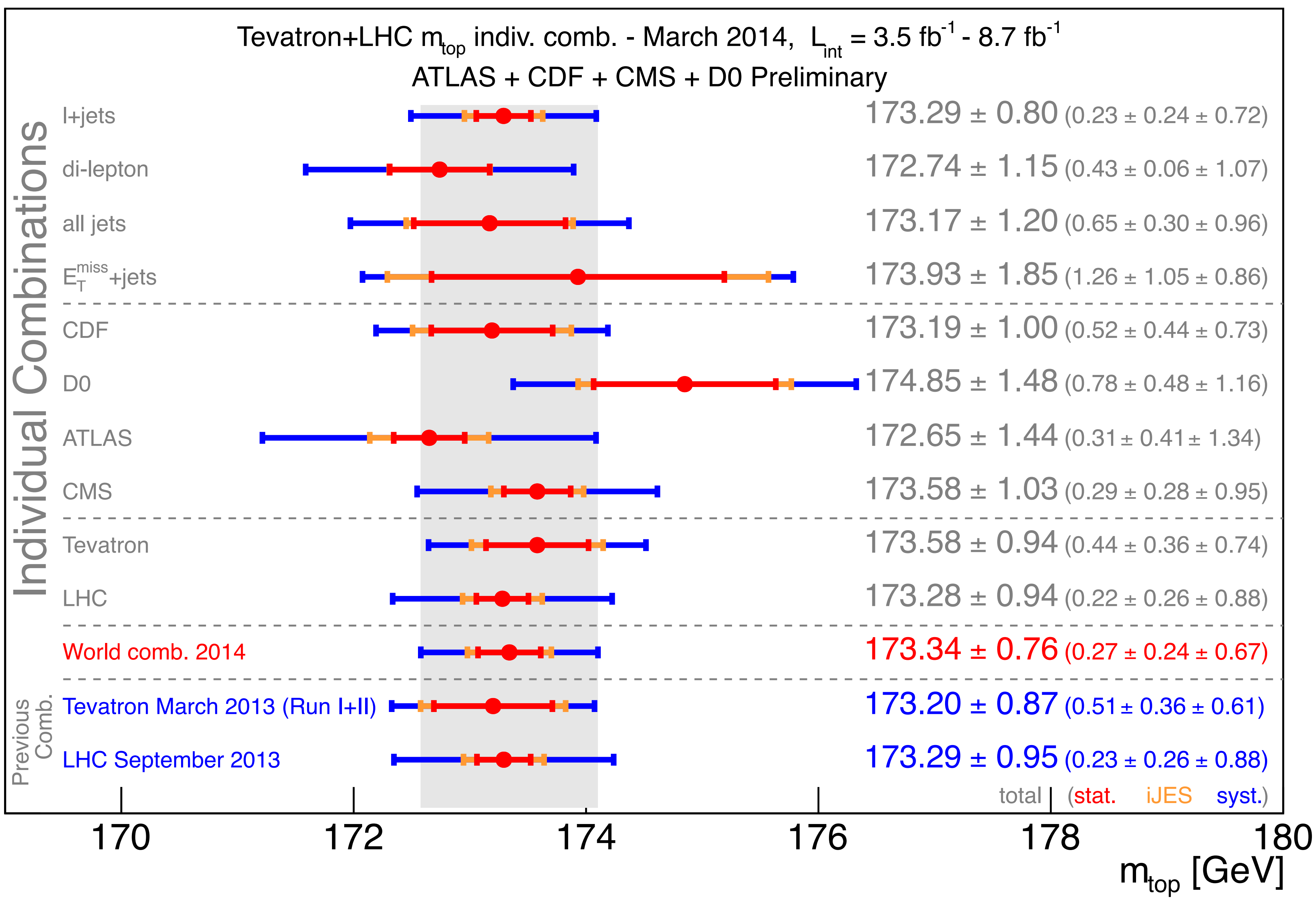
MeV



First M_{top} World average : consistency

- Combine by allowing different top masses for different data sets
  - *for inst. 4 parameter fit (m^{l+jets} $m^{di\text{-}l}$ $m^{alljets}$ m^{ETmiss}) instead of 1 m_{top}*
- Keep correlations, check consistency

arxiv:1403.4427[hep-ex]



per final state

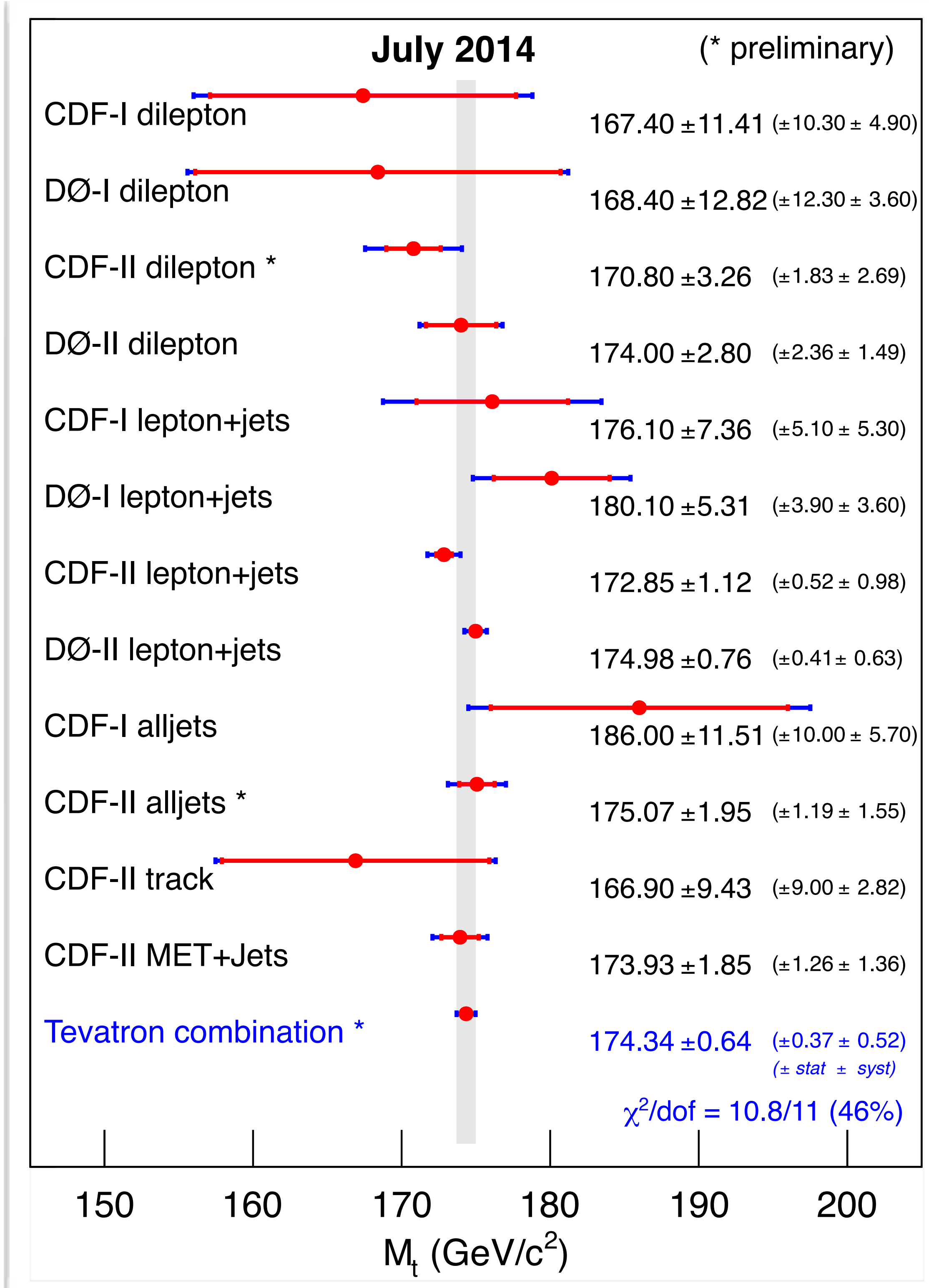
per experiment

per collider

All reported measurements: very well consistent

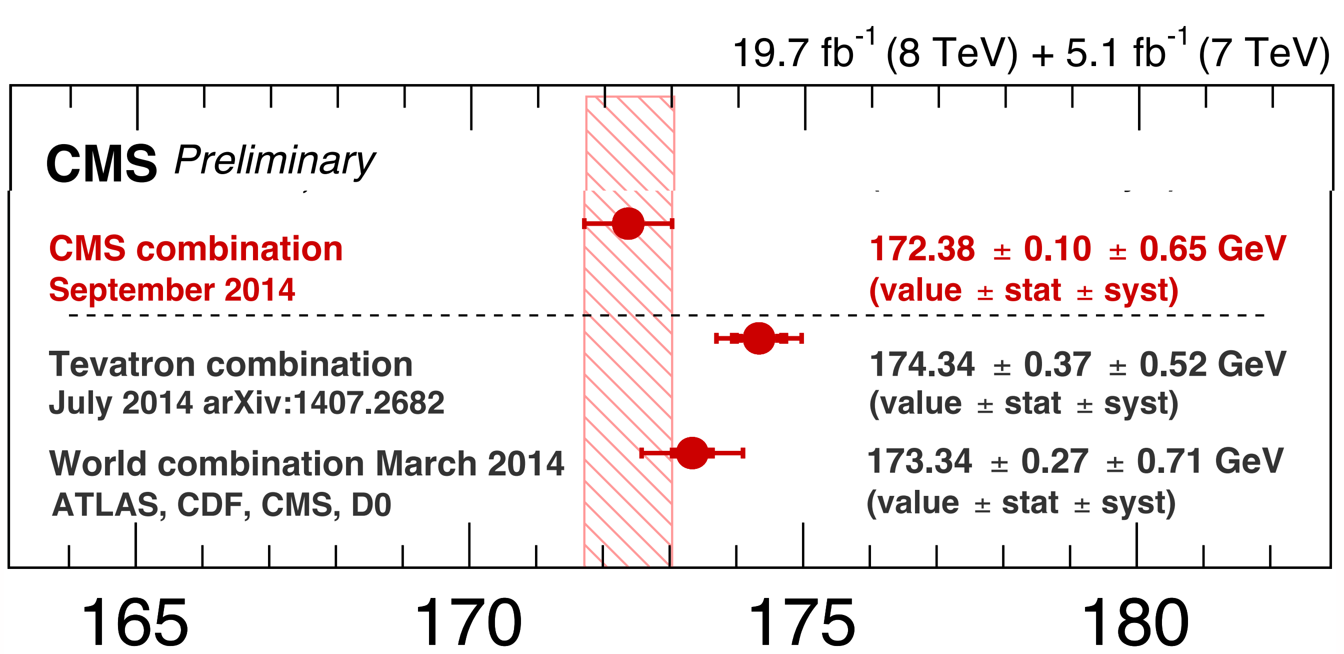
New Tevatron M_{top} combination

http://arxiv.org/abs/1407.2682



Global most precise M_{top} picture (Dec 2014)

CMS combination (Sept 2014),
World (March 2014),
Tevatron (July 2014),
LHC (Sept 2013)



$\delta m_{top} / m_{top}$ ~0.38%

$\delta m_{top} / m_{top}$ ~0.36%

$\delta m_{top} / m_{top}$ ~0.44%

m_{top}^{LHC} (2013)= 173.29± 0.95 GeV (0.23 (stat) ± 0.26(JES) ±0.88 (sys)) $\delta m_{top} / m_{top}$ ~0.54%

LHC is not including latest from CMS + new in 2014

Conclusions

- **Top analysis is in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is under way.**
- *By exploiting the LHC top quark factory* (~6M tt, ~3M single top events produced by LHC in 2011+2012) **ATLAS & CMS are testing top strong and electroweak inclusive production at unprecedented precision**
  - $\delta\sigma_{tt}/\sigma_{tt}$ ~O(3.5 to 5%) compared to ~4% prediction uncertainty (NNLO+NNLL)
  - $\delta\sigma_t/\sigma_t$:t-chan and Wt are observed, s-channel has limits only
- **Differential cross sections measurements test SM tt production and complement new physics searches in completely new phase space** with 10% to 50% relative unc. Expect higher reach in Multi TeV region with reduced syst uncertainties, due to parametrization/understanding of more phase space corners & improvement in MC generators (NNLO).
- The **top mass** is measured at 0.44% (Tevatron + LHC) level. Expect sub-GeV precision if progress is made on syst uncertainties exploiting differential info.

- ON items we did not directly touch upon
  - **Direct determination of top** quark **coupling to** the newly found **Higgs** boson is still limited by number of events. Run2 expects observation with high luminosity.
  - **New physics** connected to top quark by resonances/asymmetries and top rare decays to HIggs boson **is being searched in previously unexplored TeV/sub pb regions** of mass and cross sections: reach to be extended greatly in multi-TeV region with pile-up mitigation techniques & improved syst uncertainties

References and useful tools

- TOP2014:7th International workshop on Top Physics
- TOP2013: 6th International workshop on Top physics
- Top2012: 5th International workshop on Top physics
- Top Public results from ATLAS
- Top Public results from CMS
- Top Public results from CDF
- Top Public results from D0

Additional (useful) references

- A. Quadt, *Top quark physics at hadron colliders*, Eur. Phys. J. C 48, 835–1000 (2006) DOI 10.1140/epjc/s2006-02631-6
- A J,. Khun, *Theory of Top Quark Production and Decay*, http://arxiv.org/abs/hep-ph/9707321v1
- S Willembrock,*THE STANDARD MODEL AND THE TOP QUARK*, http://arxiv.org/abs/hep-ph/0211067v3
- Chris Quigg, *Top-ophilia*,FERMILAB-FN-0818-T

and references therein