ATLAS EXPERIMENT
http://atlas.ch

CMS
Compact Muon Solenoid

Top Quark at LHC

2013-2014 Intercollegiate PostGraduate Course in Elementary Particle Physics

London, UCL Bloomsbury Campus
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Outline

- **Why top quark? History and SM**
- **The tools of the trade**
  - **LHC:** a top factory at work
  - **The ATLAS and CMS detectors**: top observers
- Measuring **top quark production**
  - top pair
  - differential cross sections
- Top Mass
- Top pair production as a **window on new physics**
  - **The emergence of boosted tops**

Attention, navigators!!

your rosetta stone
to the topic

essential clues =

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

Waiting for the top? a history of expectations

Top quark is needed in SM

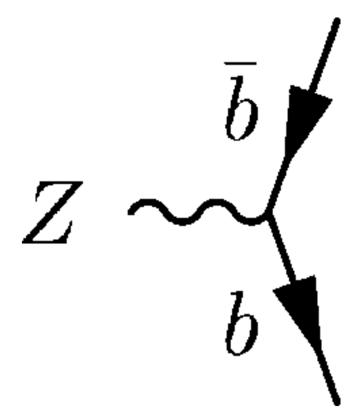
No flavour changing neutral currents: no b iso-singlet

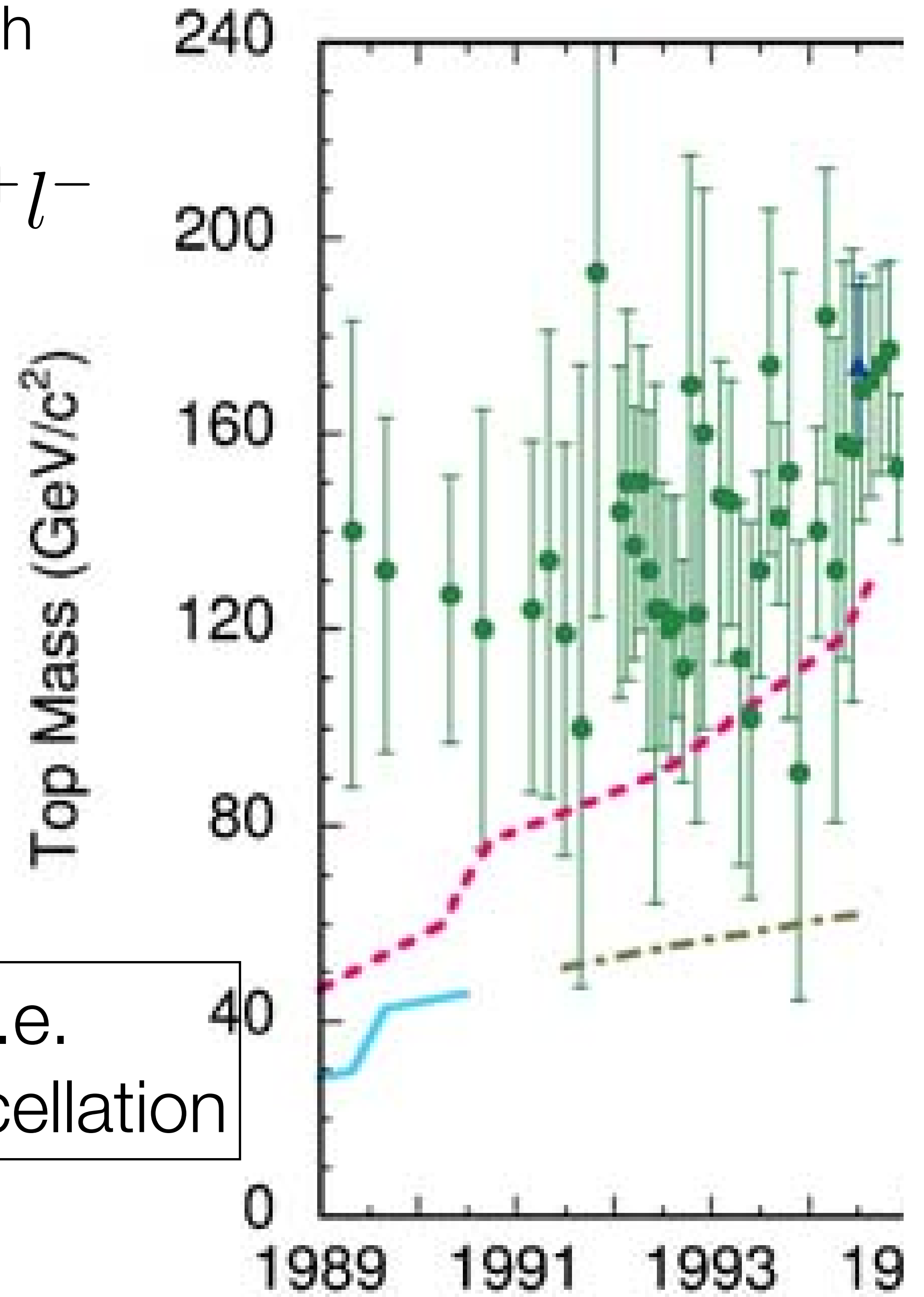
$$\begin{bmatrix} c \\ s' \end{bmatrix}_L \quad b'_L$$

b couples to s only with neutral mediator

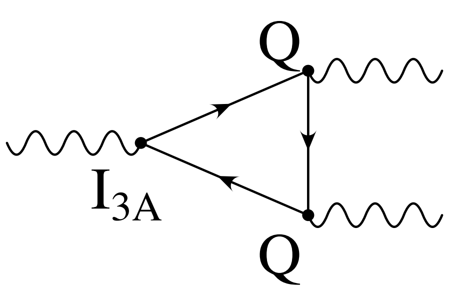
$$b \longrightarrow s + l^+ l^-$$

I_3 = -1.2 for b quark required by Z width in $b\bar{b}$ decay. Need additional quark, isospin partner of b, with I_3 = +1.2





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



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

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

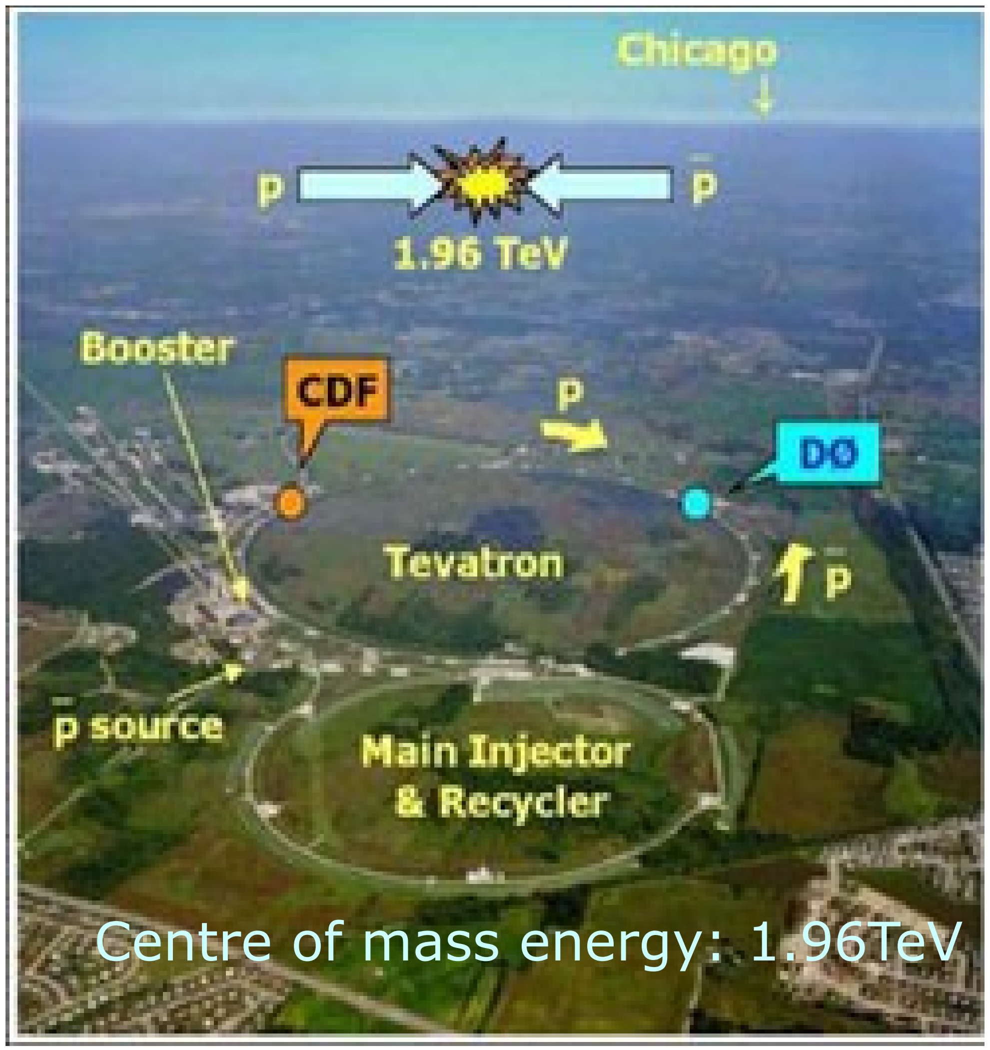
1995: top is discovered!

$\sqrt{s} = 1.8$ TeV

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

$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb.

p$\bar{\text{p}}$ collisions



19 sel. events
exp bkg:6.9
4.8 s.d.significance

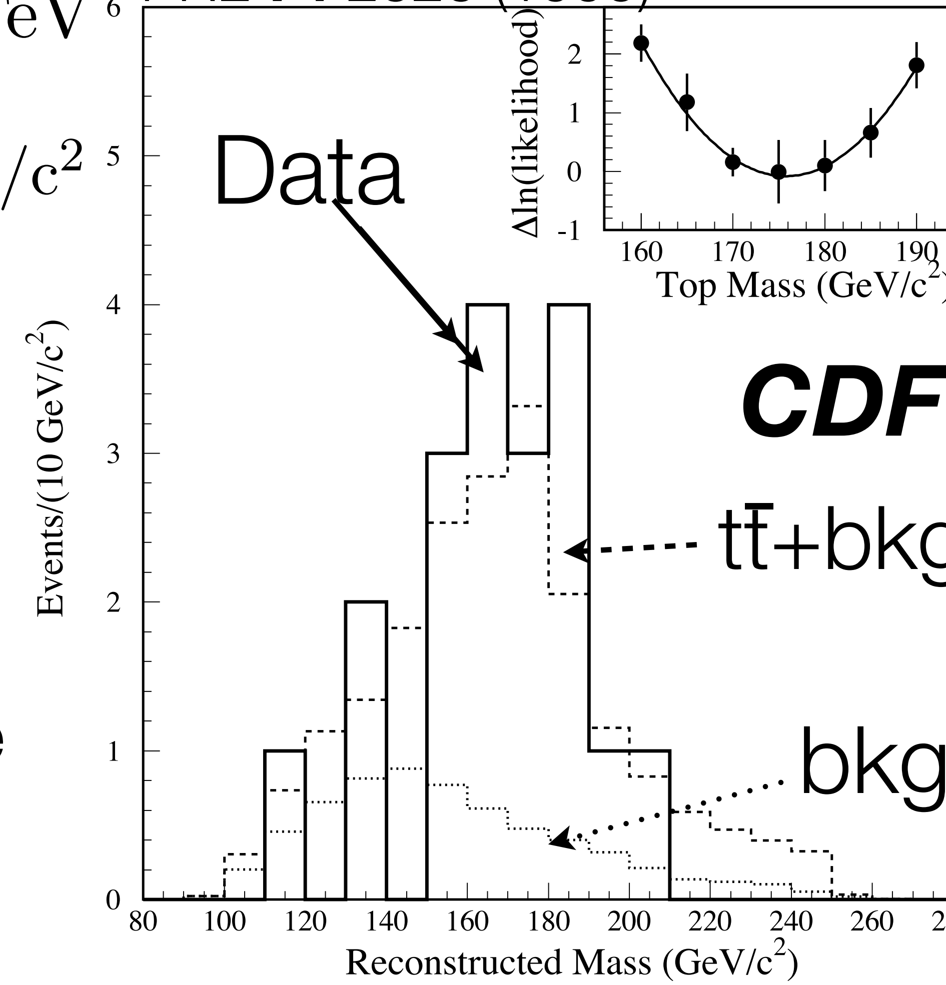
mass from ***likelihood fit*** *to shape*

17 sel. events
exp bkg: 3.8
4.6 s.d. significance

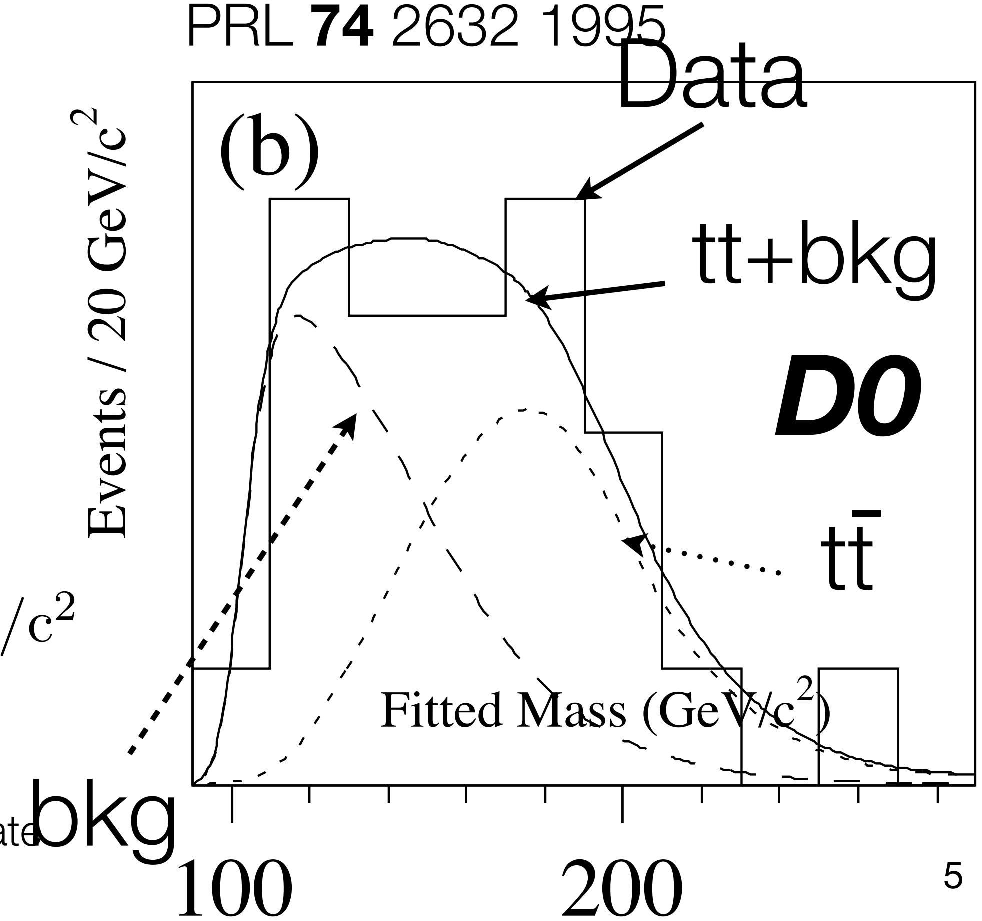
$m_{top} = 199^{+19}_{-21}\ (\text{stat.}) \pm 22\ (\text{syst.})\ \text{GeV/c}^2$

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

PRL **74** 2626 (1995)



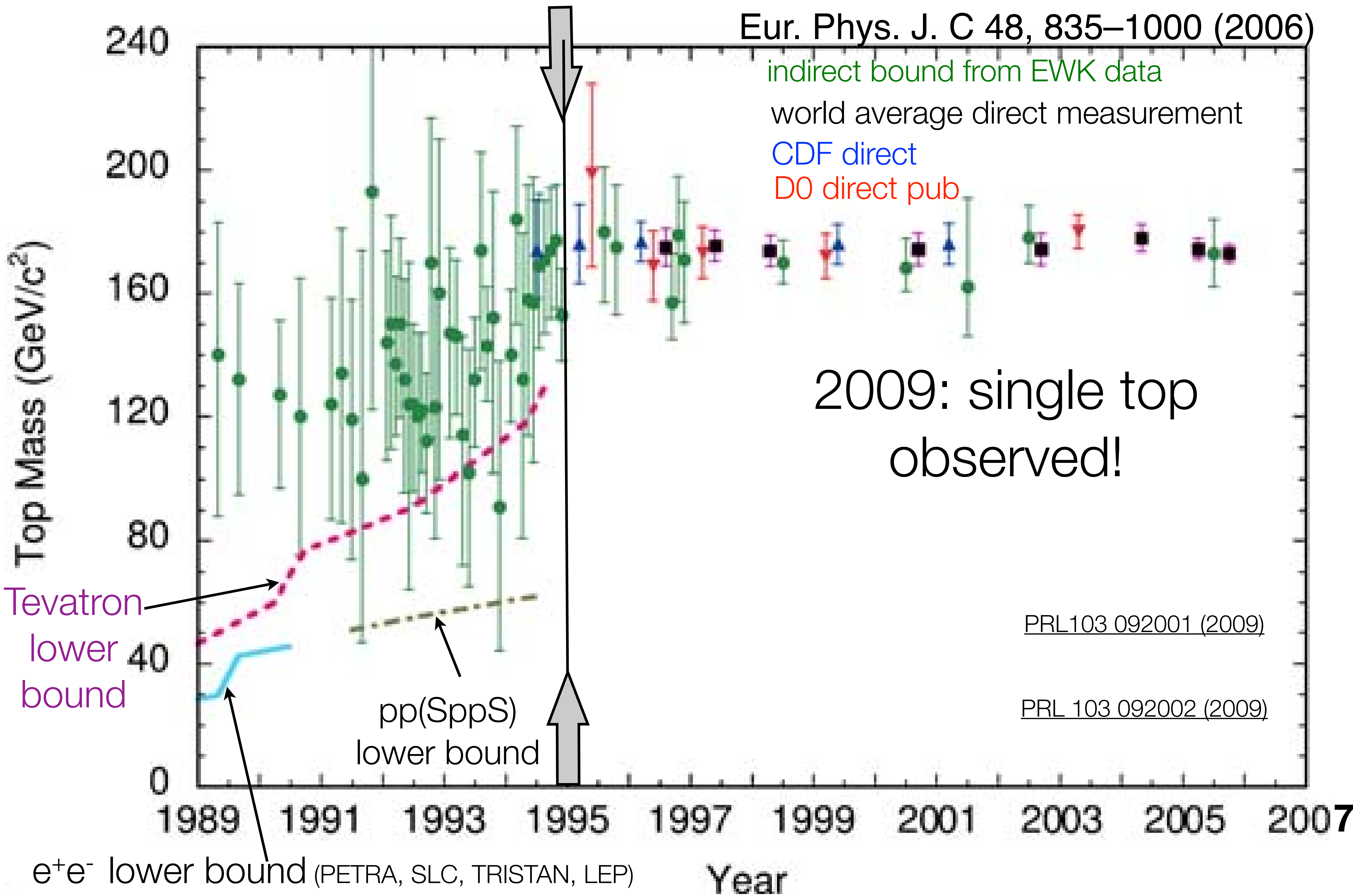
PRL **74** 2632 1995



From bottom to top: the global picture

A.Quadt

Eur. Phys. J. C 48, 835–1000 (2006)

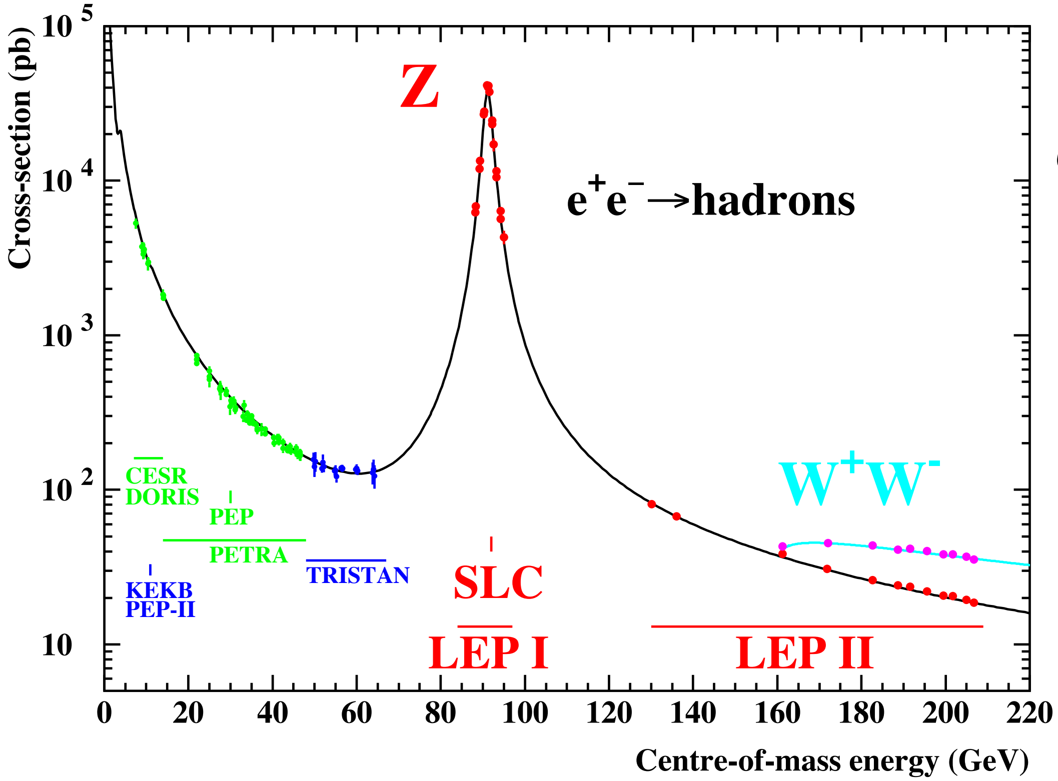


2009: single top observed!

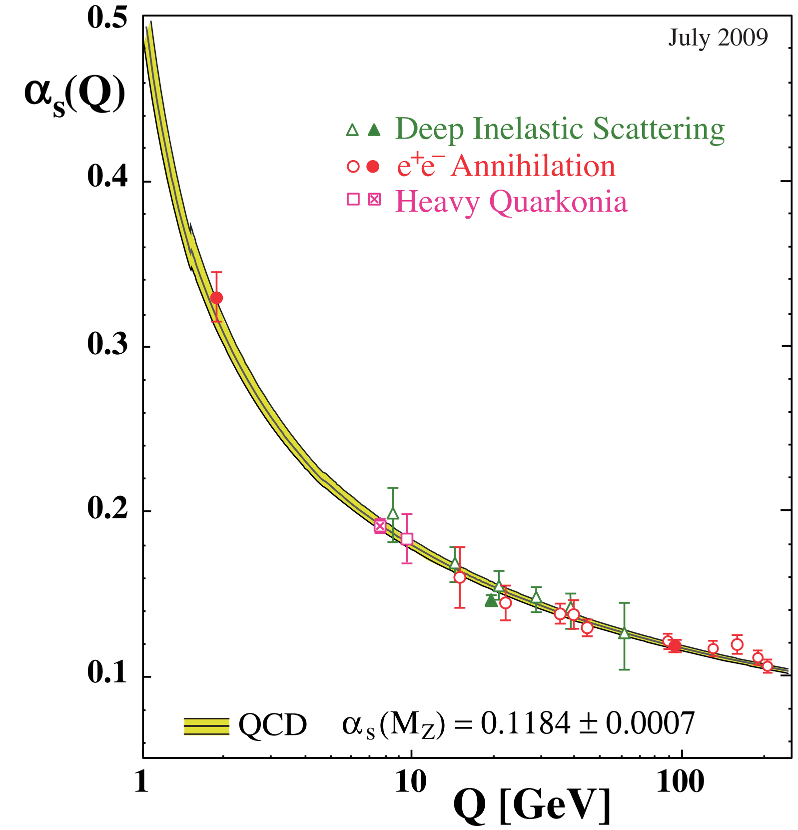
PRL103 092001 (2009)

PRL 103 092002 (2009)

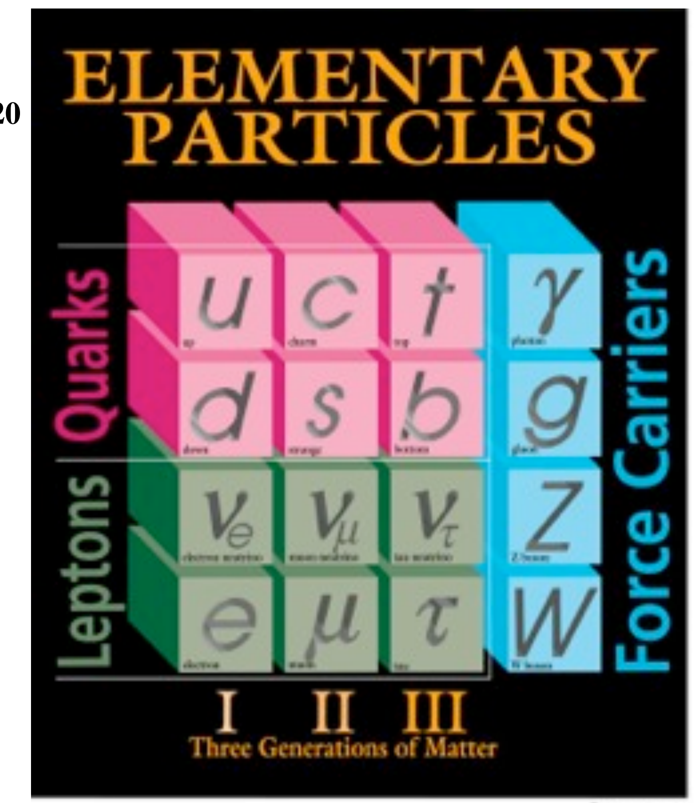
Standard (model) **successes**

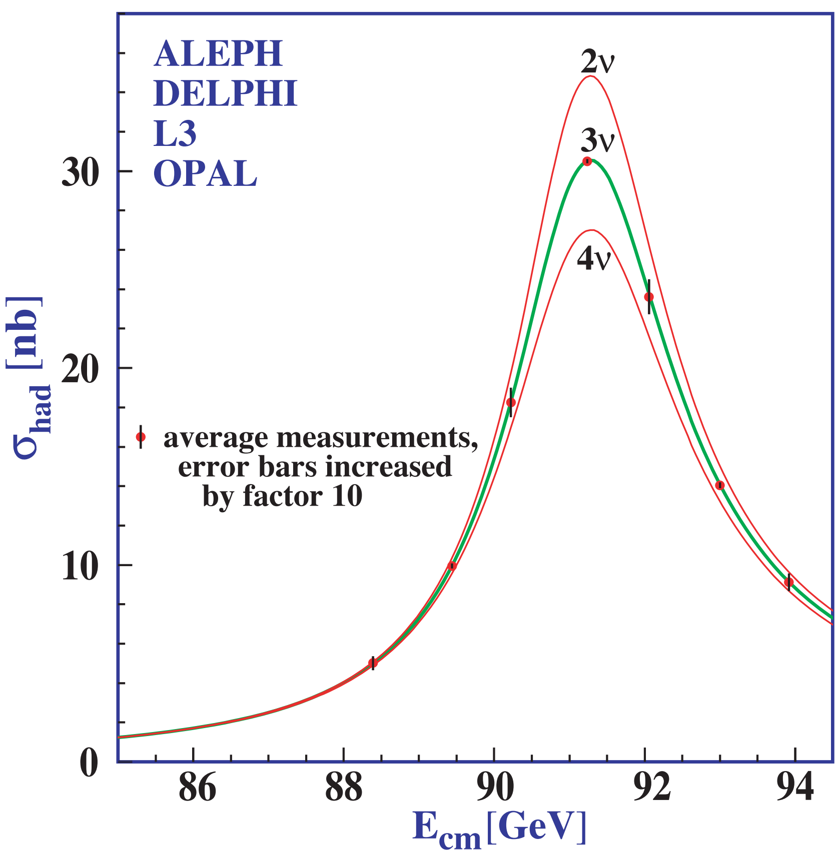


W, Z, bosons unify Electro-weak force

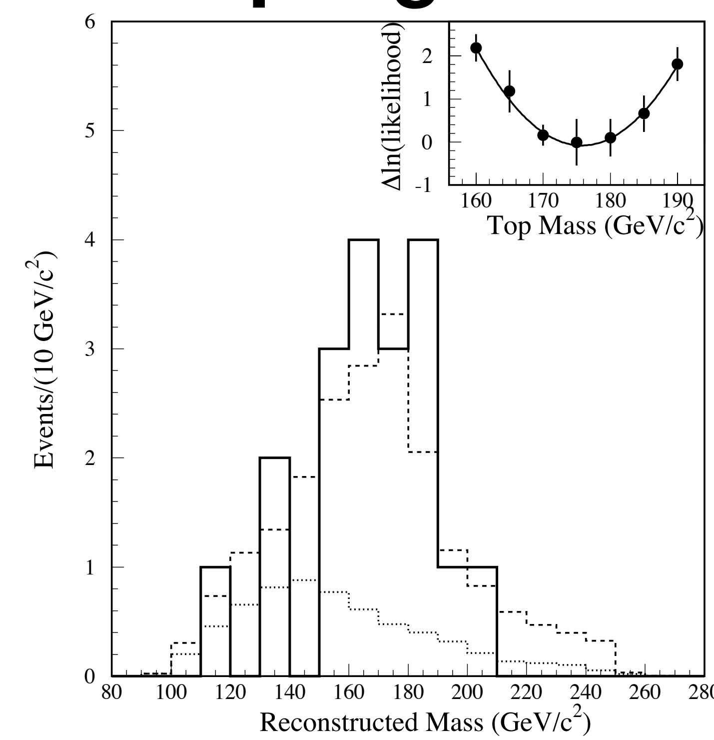


Strong coupling runs





a quick (biased) selection..

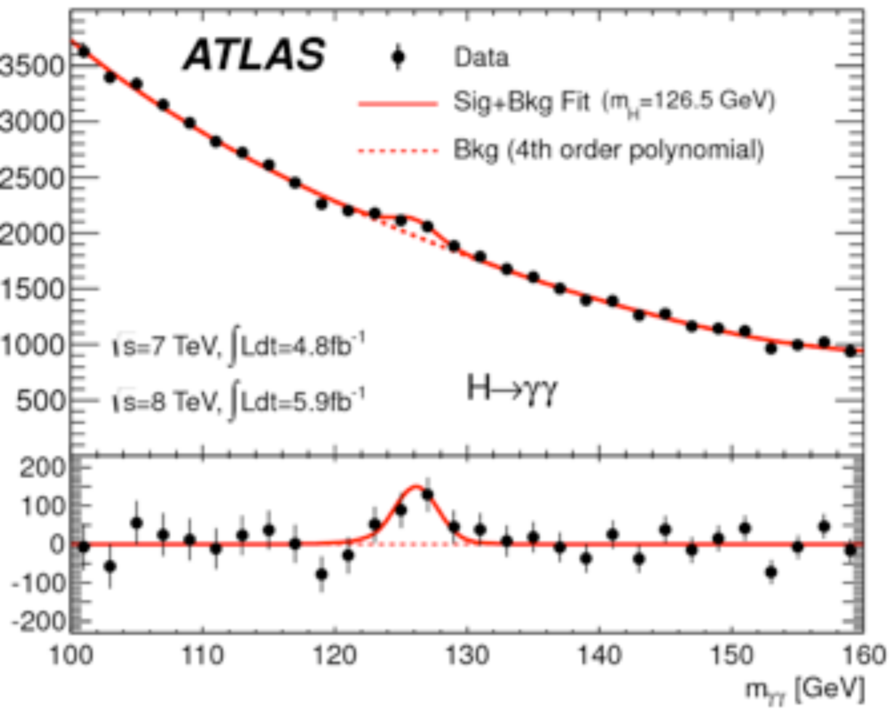


only 3 standard neutrinos

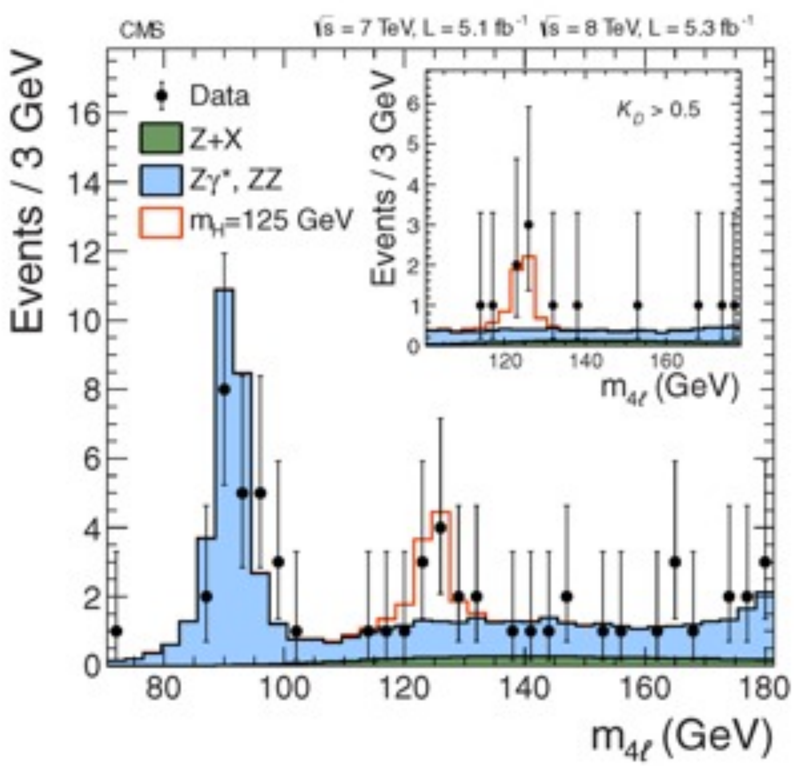
Top quark is found

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

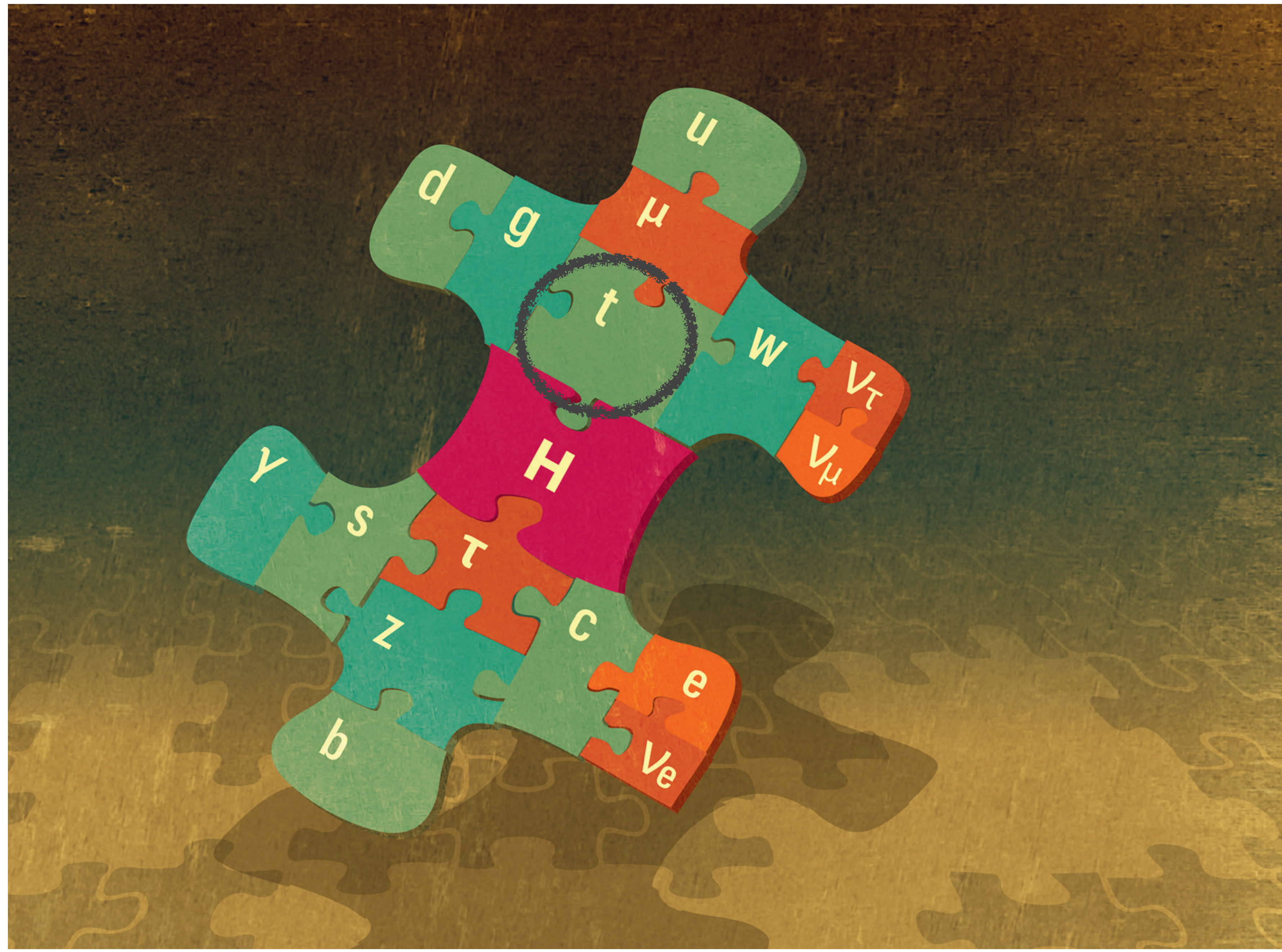
[Phys. Lett. B 716 (2012) 1-29]



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



[Nobel for Phys 2013 - InfoForPublic]



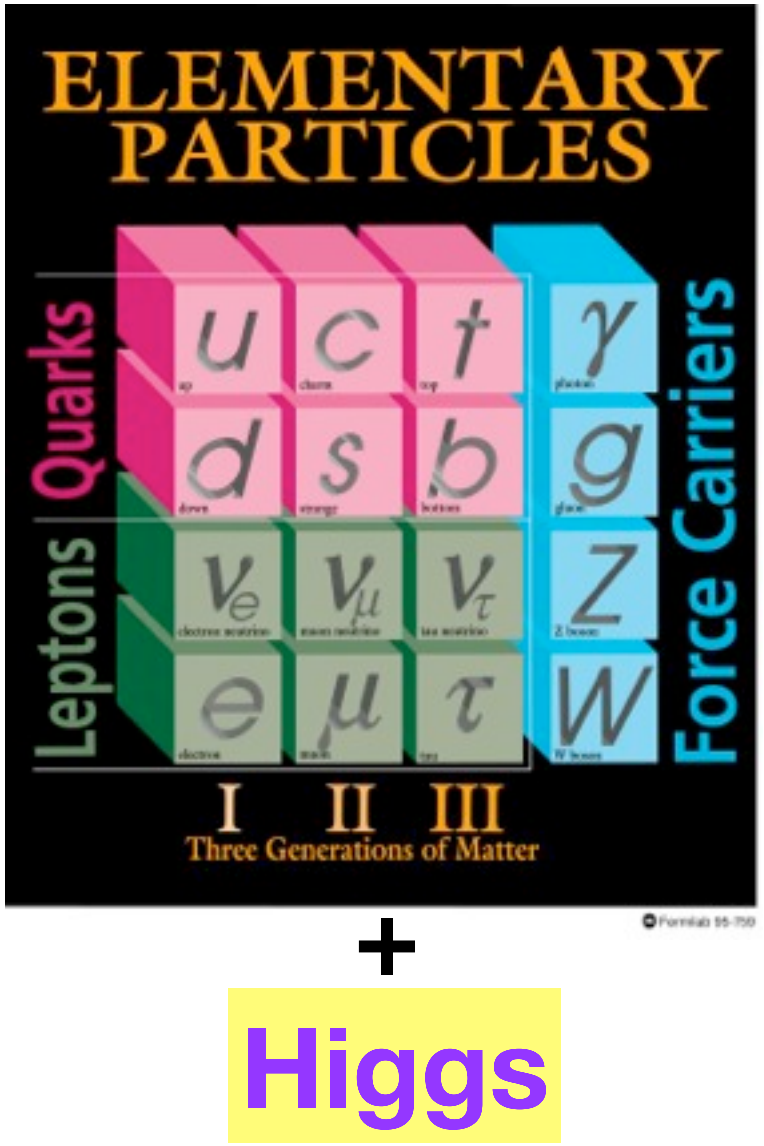
Even if the Higgs particle has completed the Standard Model puzzle, the Standard Model is not the final piece in the greater cosmic puzzle.

The puzzle is not complete though...

Standard (model) **questions**

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

- **What is the origin of mass?**



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

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

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

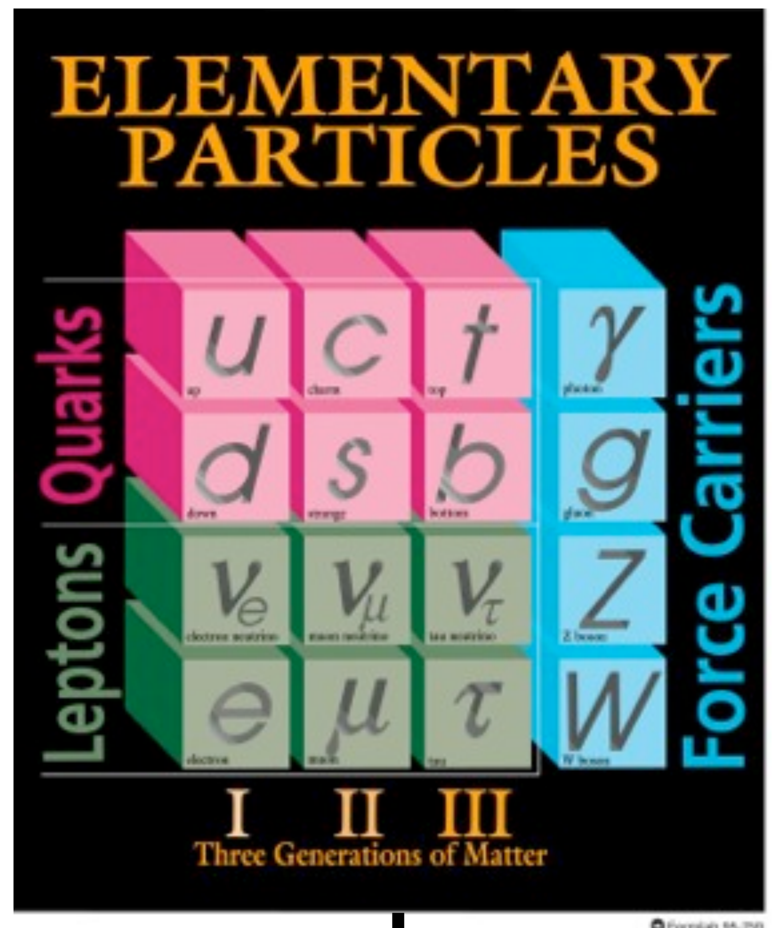
Standard (model) **questions**

- **What is the origin of mass?**

Higgs, SuperSymmetry, New Strong forces..

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

Quantum gravity
Extra dimensions...



+ Higgs

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

4th generation...?

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

String theory..

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

Dark matter, Dark energy...

Standard (model) **questions**

- ***What is the origin of mass?***

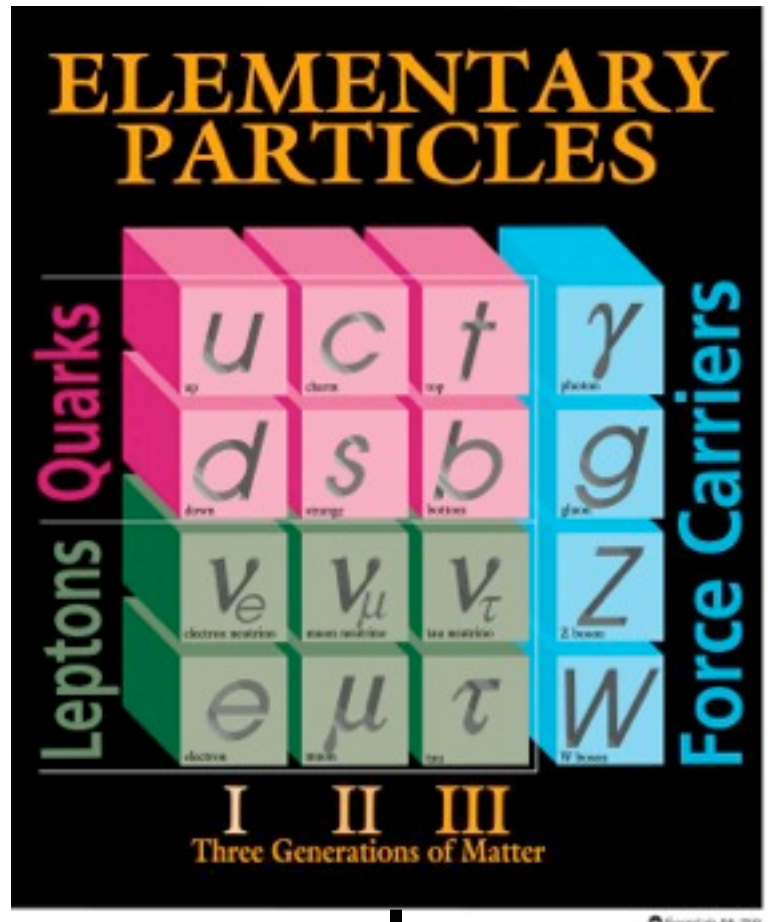
Higgs, SuperSymmetry, New Strong forces..

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

Quantum gravity
Extra dimensions...

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

4th generation...?



+ **Higgs**

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

String theory..

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

Dark matter, Dark energy...

Why Top (quark) TODAY?

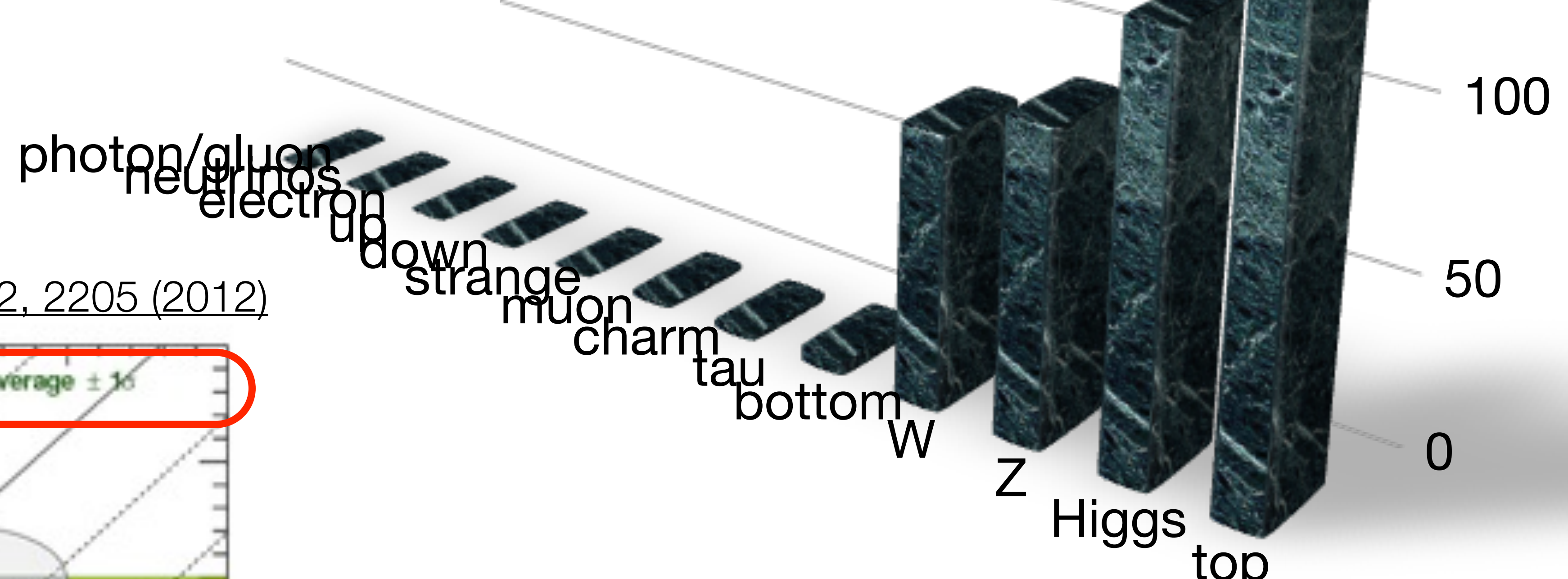
Most massive constituent of matter

Large Yukawa coupling in SM: $Y_t > 0.9$

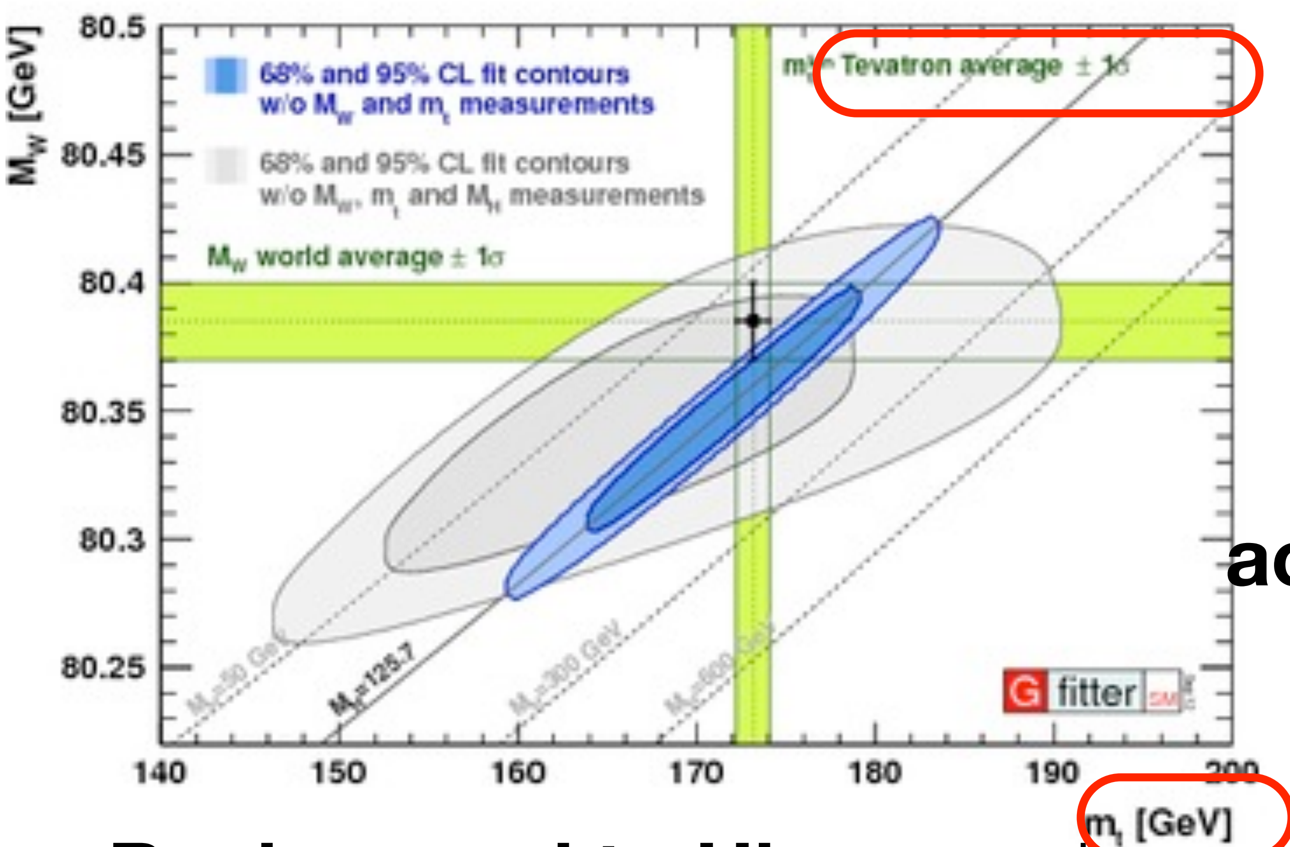
$M_{top} \sim$ electroweak symmetry breaking scale

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

Decay and strong production rate are **tests of standard model**

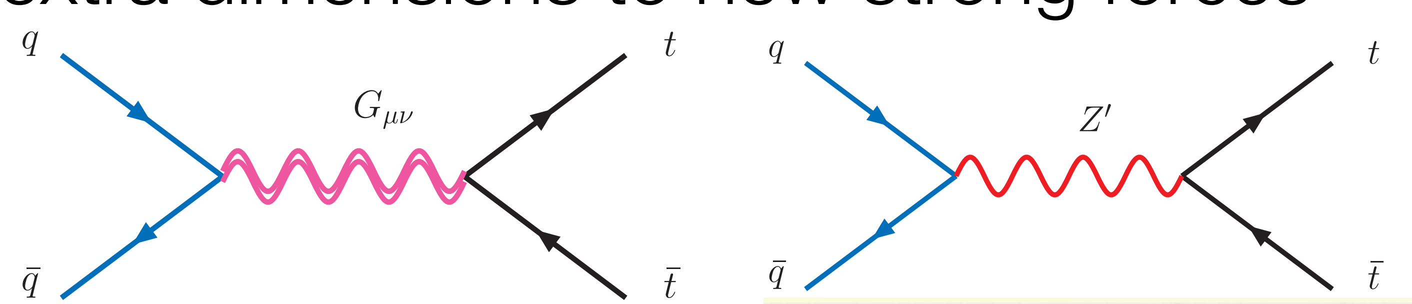


GFitter, Eur. Phys. J. C 72, 2205 (2012)



Background to Higgs and possible **new physics** (SUSY,..)

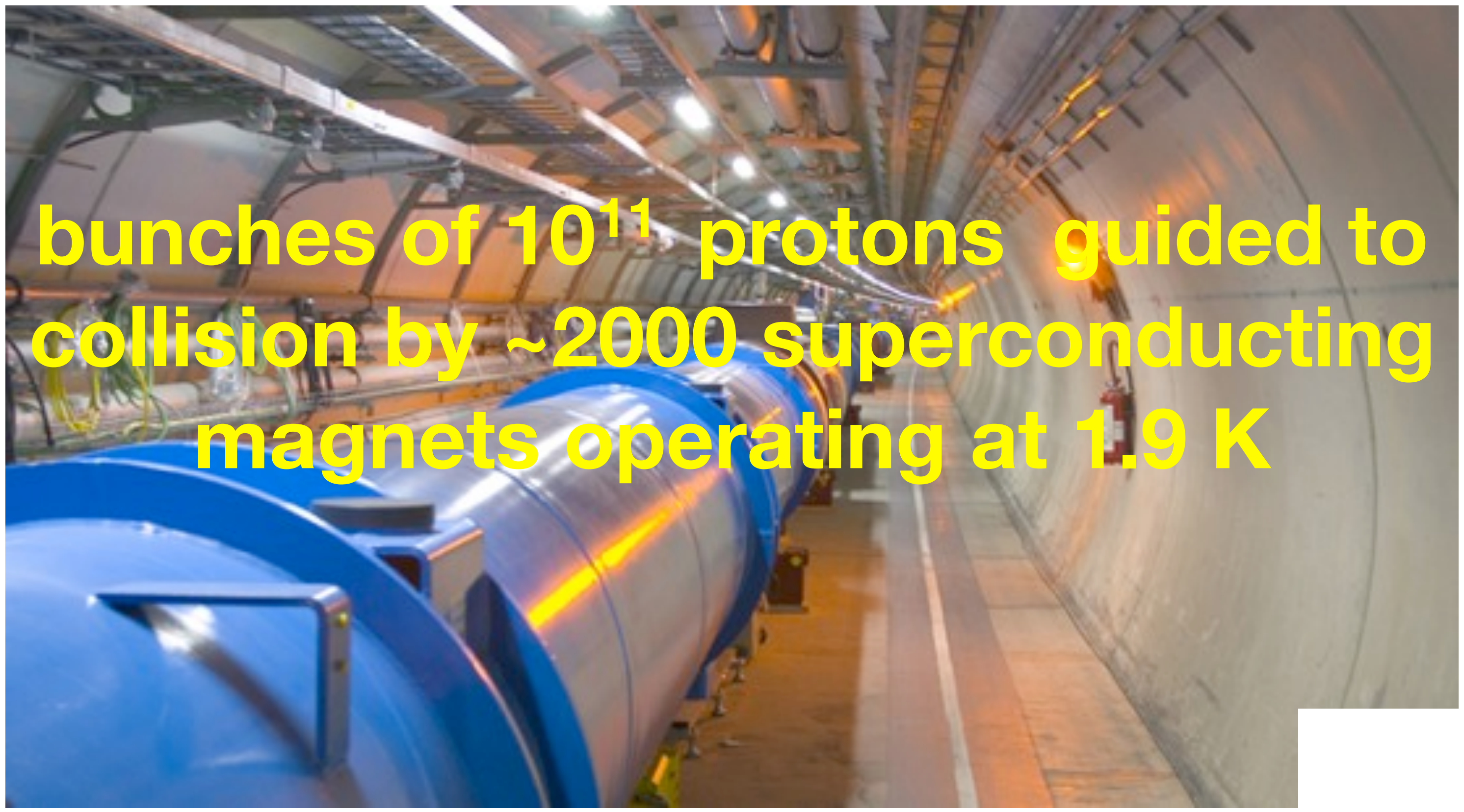
Many scenarios with **direct/indirect coupling to new physics need to accommodate the high top mass :** from extra dimensions to new strong forces

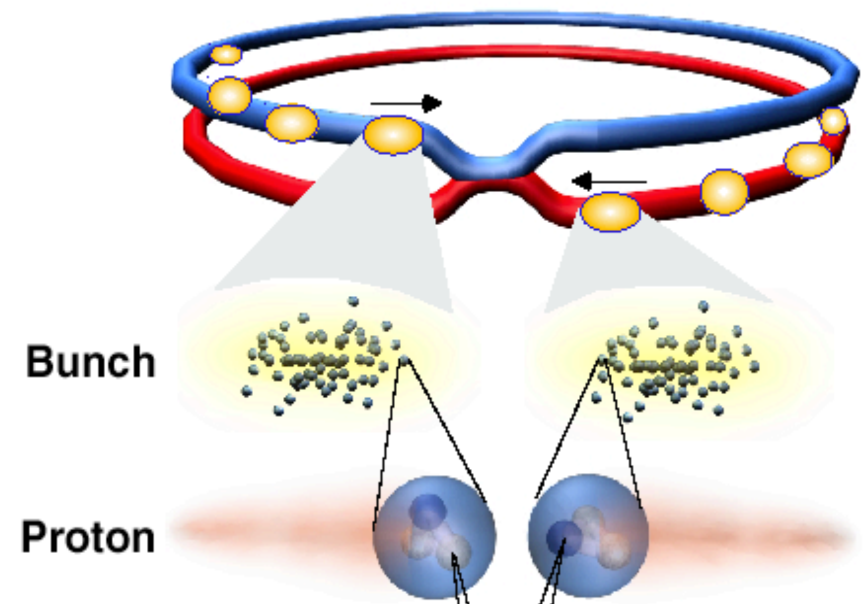


LHC : a *Top* producer

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm}) = 7 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

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

LHC : a *Top* producer

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

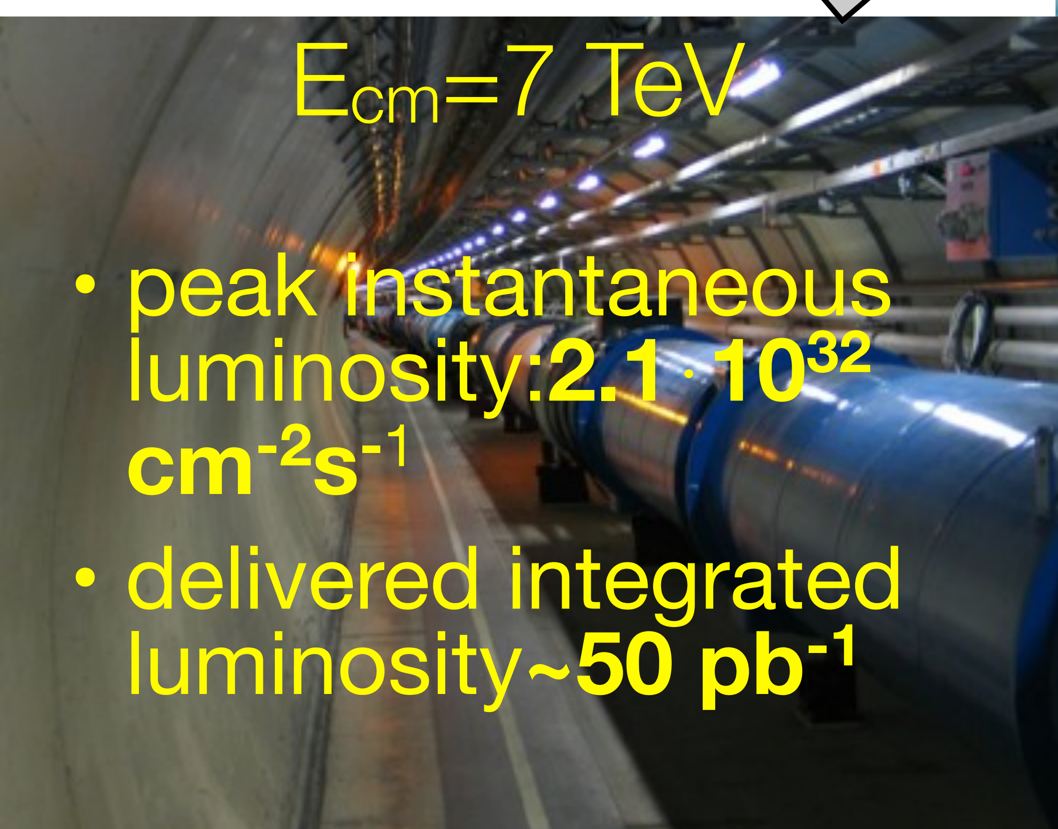
$$\mathcal{L} \propto \frac{N_1 N_2}{\sigma^2}$$

Key parameters:

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

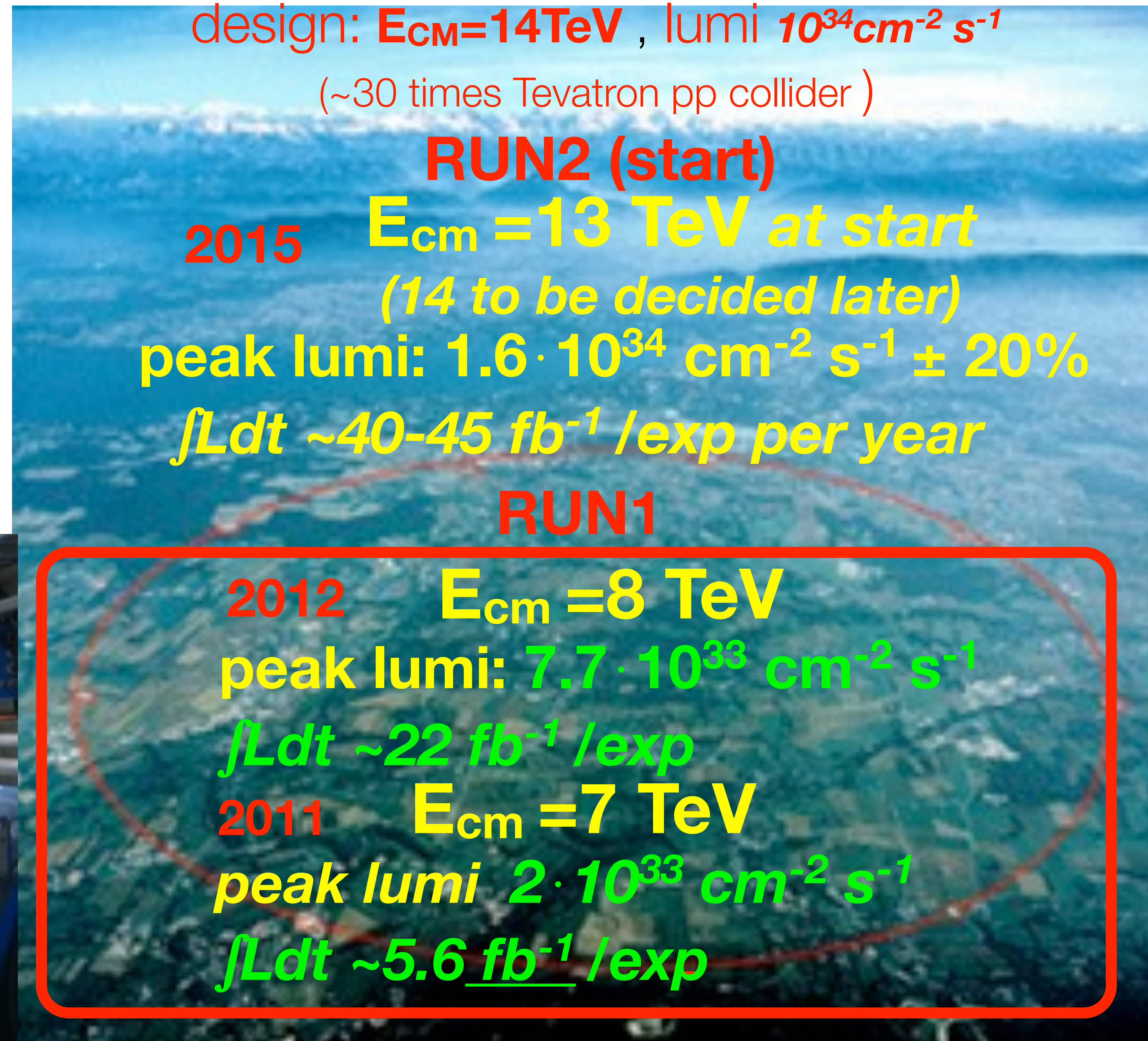
Ad maiora..

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**

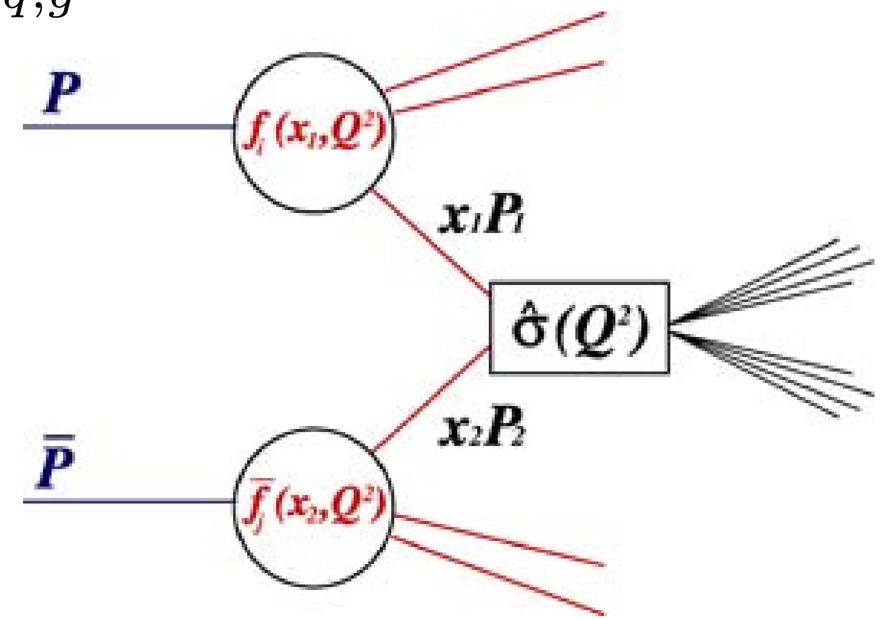
peak lumi 2·10^{33} cm^{-2} s^{-1}

∫Ldt ~5.6 fb^{-1} /exp

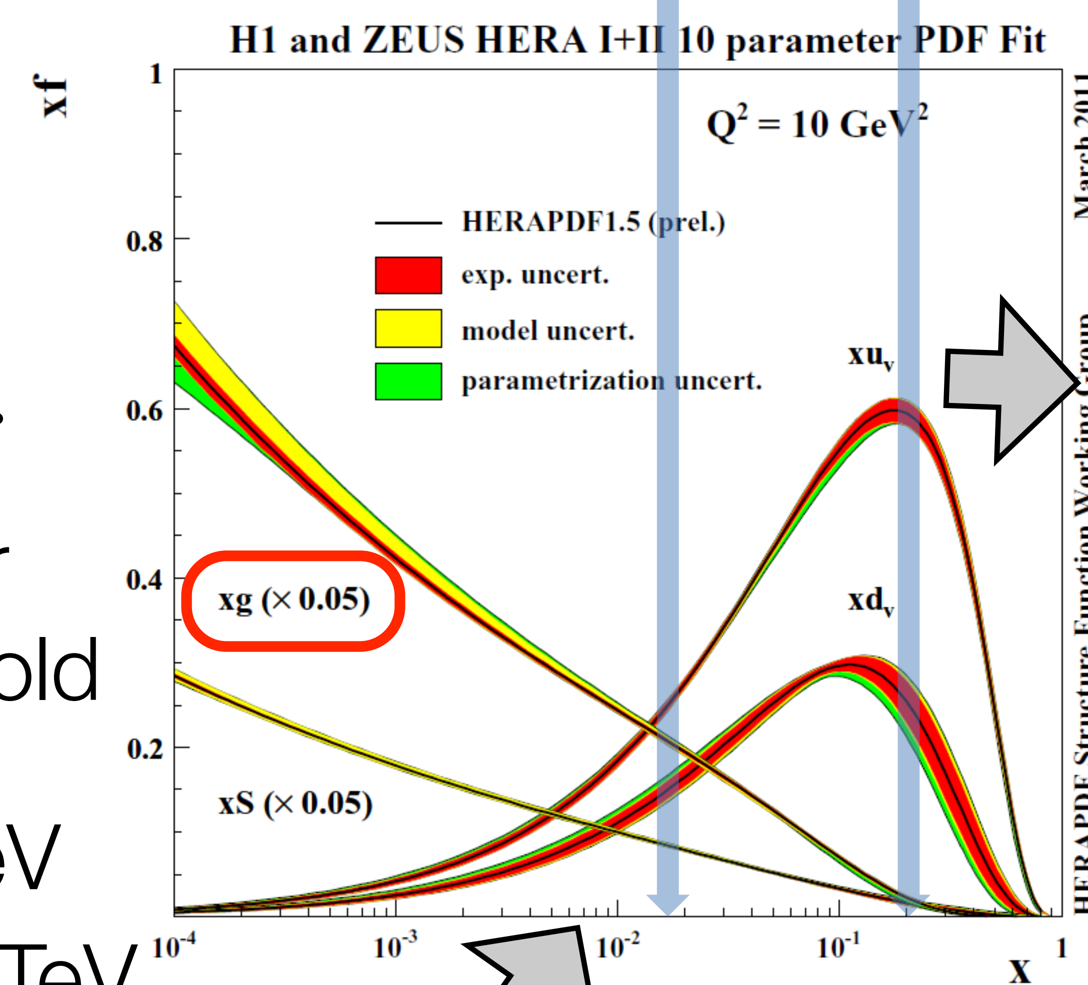
$N_{events}(\Delta t)$= ***∫Ldt*** * cross section

Top quark @ LHC: production(I)

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



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



To produce $t\bar{t}$

~massless partons

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

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

⇒ $x \approx \frac{2m_{\rm t}}{\sqrt{s}} =$ 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 (II)

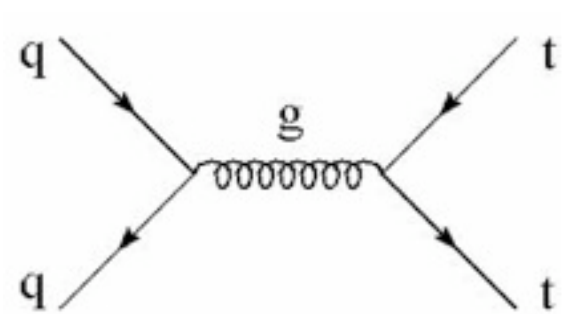
probe low x in pdfs → (abundant) gluon fusion dominated

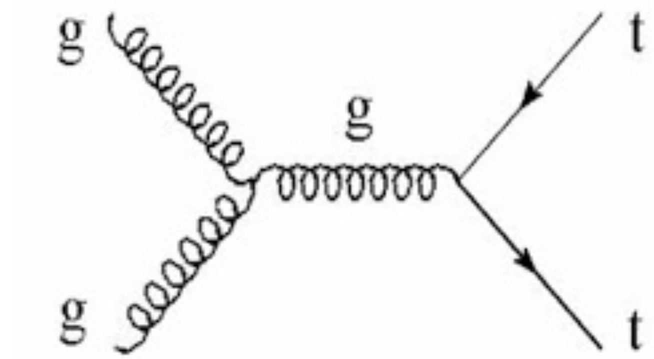
	Tevat	LHC(7)	LHC(14)
gg	~10%	**~85%**	~90%
qq	~90%	**~15%**	~10%

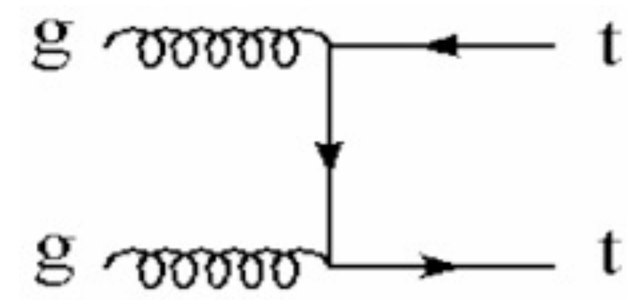
qq annihilation

gluon fusion

top pairs: strong







Czakon,Mitov,Fiedler 2013

NNLO+NNLL accuracy

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

$$\sigma_{7TeV} = 172\ ^{+4.4}_{-5.8}\ ^{+4.7}_{-4.8}\ \text{pb}$$

$$\sigma_{8TeV} = 245.8\ ^{+6.2}_{-8.4}\ ^{+6.2}_{-6.4}\ \text{pb}$$

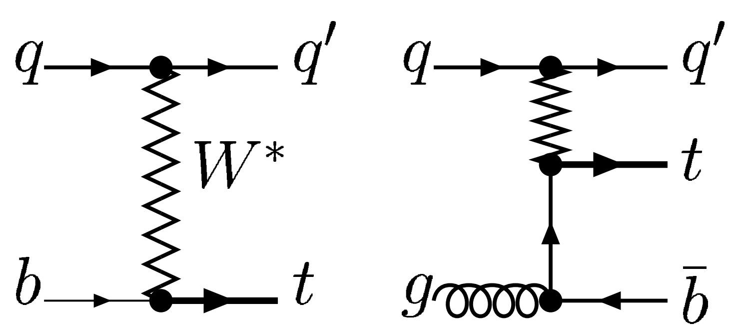
scales *PDF*

PDF=MSTW2008nnlo68cl
for m_{top}= 173.3

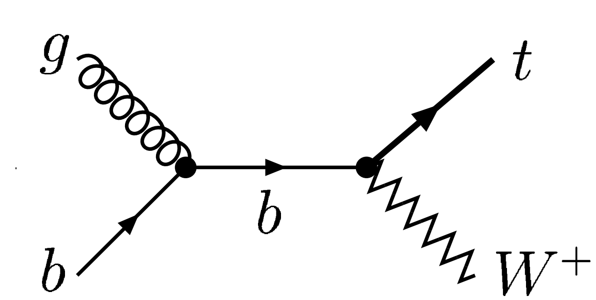
single top: electroweak

m_{top}= 172.5

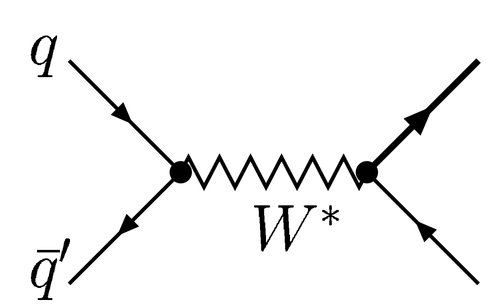
t chan



Wt chan



s chan



Kidonakis 2010,2011

approx NNLO

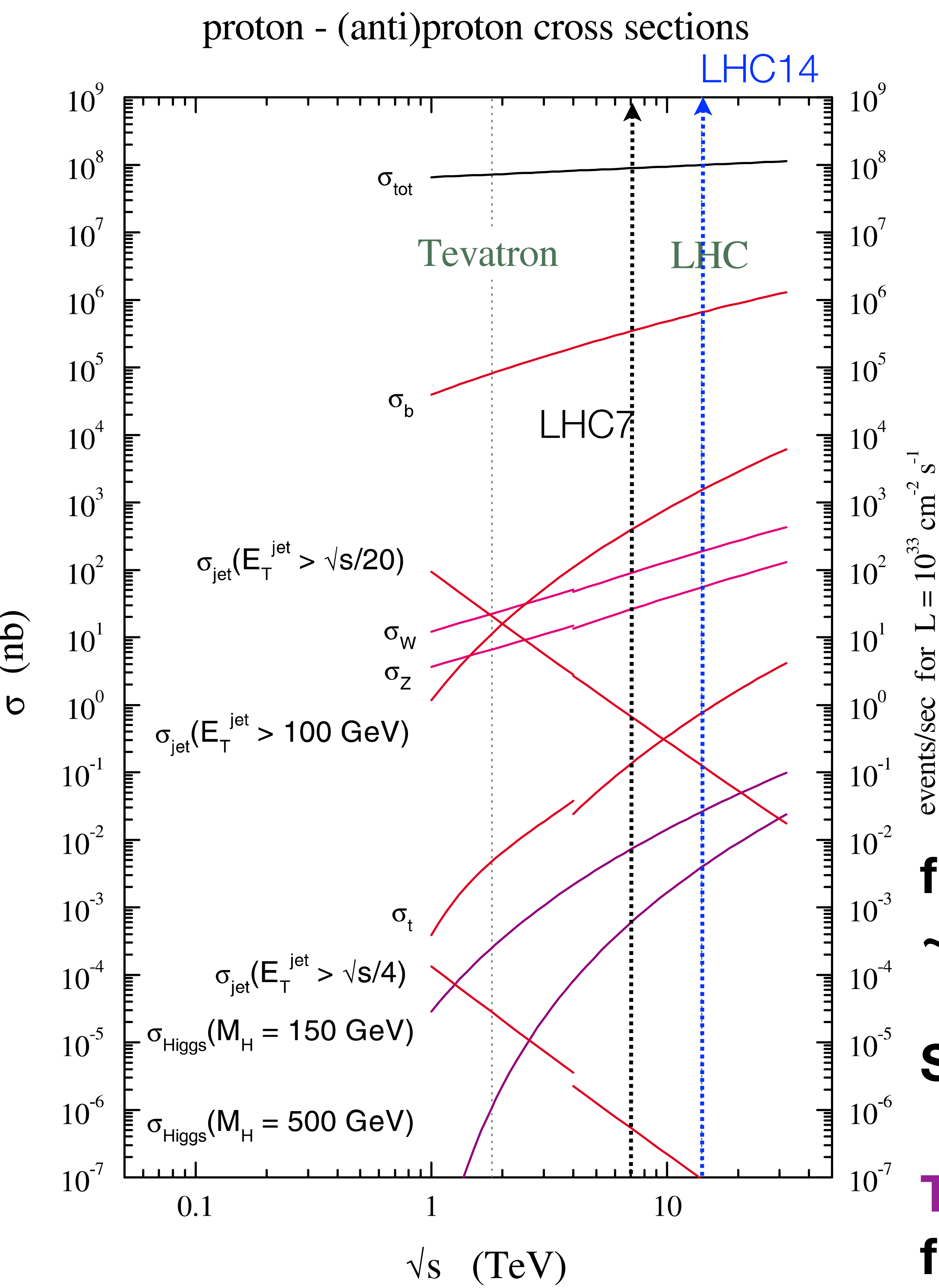
$\delta\sigma_t/\sigma_t$ ~2 to 7%

t chan: $\sigma_{7TeV} = 64.6 \pm 2.4$ pb, $\sigma_{8TeV} = 87.8 \pm 3.4$ pb

Wt chan: $\sigma_{7TeV} = 15.7 \pm 1.1$ pb, $\sigma_{8TeV} = 22.4 \pm 1.5$ pb

s chan: $\sigma_{7TeV} = 4.6 \pm 0.2$ pb, $\sigma_{8TeV} = 5.6 \pm 0.2$ pb

Top @ LHC: in the context



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

$\sqrt{s}$(TeV)	σ_{tt}(pb)	σ_t(pb)
1.96 (pp)	~7	
7 (pp)	~172	~65
8(pp)	~230	~88
14 (pp)	~900	

tt/t Rate at L= 10^{33}cm^{-2} s^{-1}

0.16 (0.06)Hz

0.23 (0.08)Hz

0.9Hz

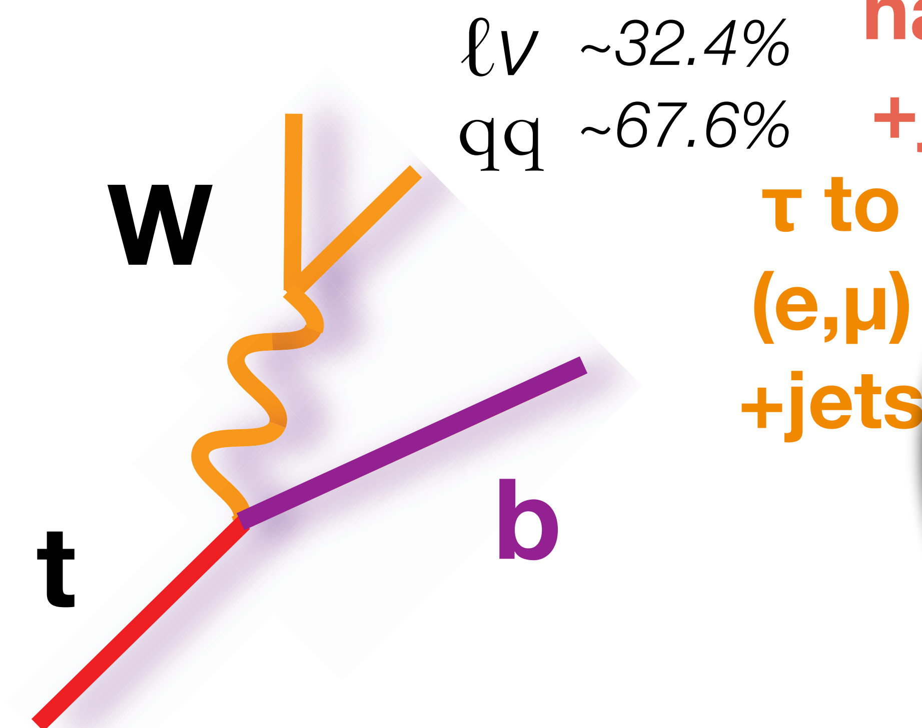
for $\int Ldt$ = 5 fb^{-1} (18fb^{-1})@7 (8) TeV, expect ~$8\cdot10^5$ (~4.5 10^6)tt events

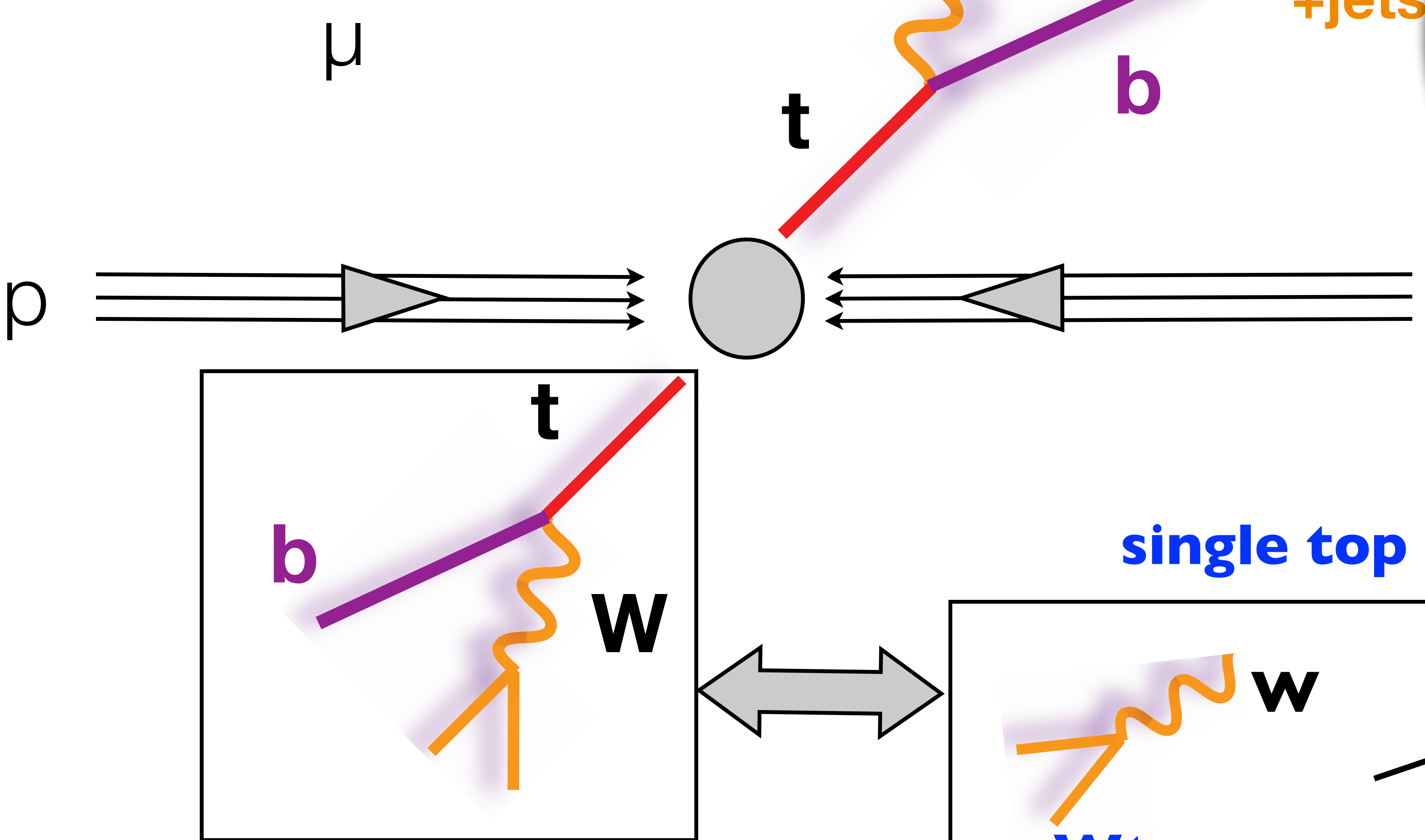
Single top events are ~50%

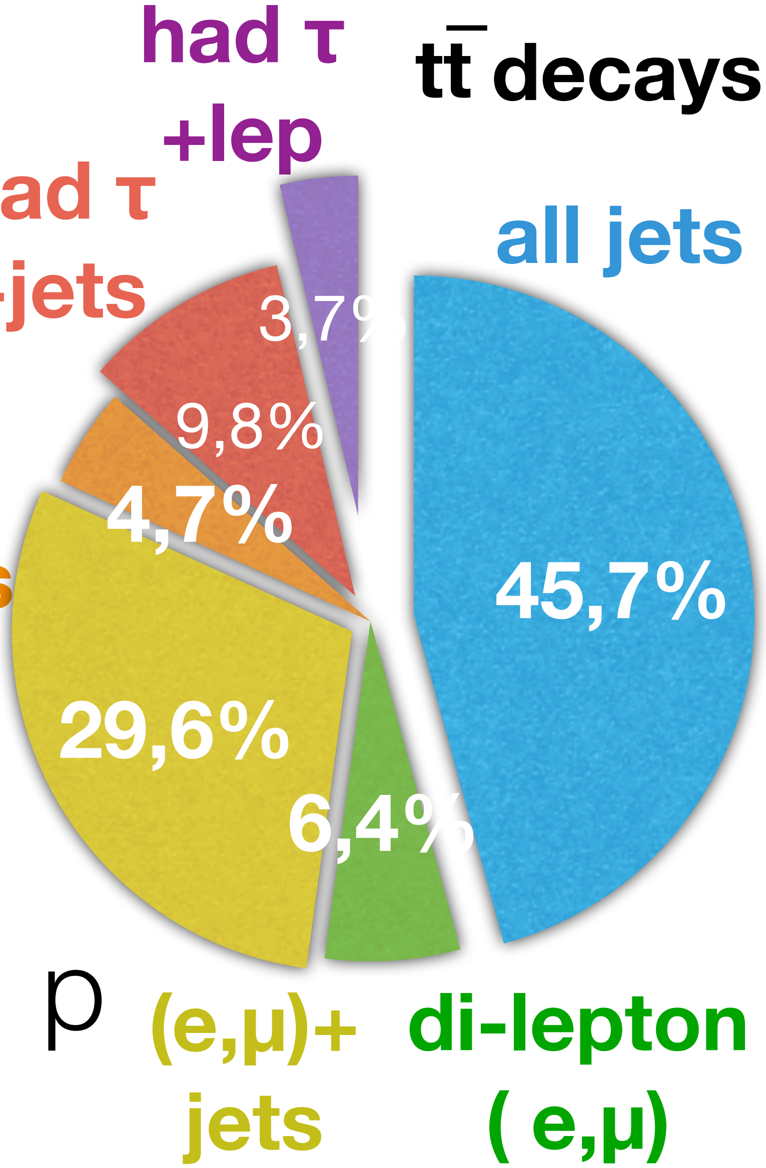
Tevatron (lower energy collider): $\int Ldt$ =9.4 fb^{-1} on tape, expect ~ $6.6\cdot10^4$ events

Top signatures

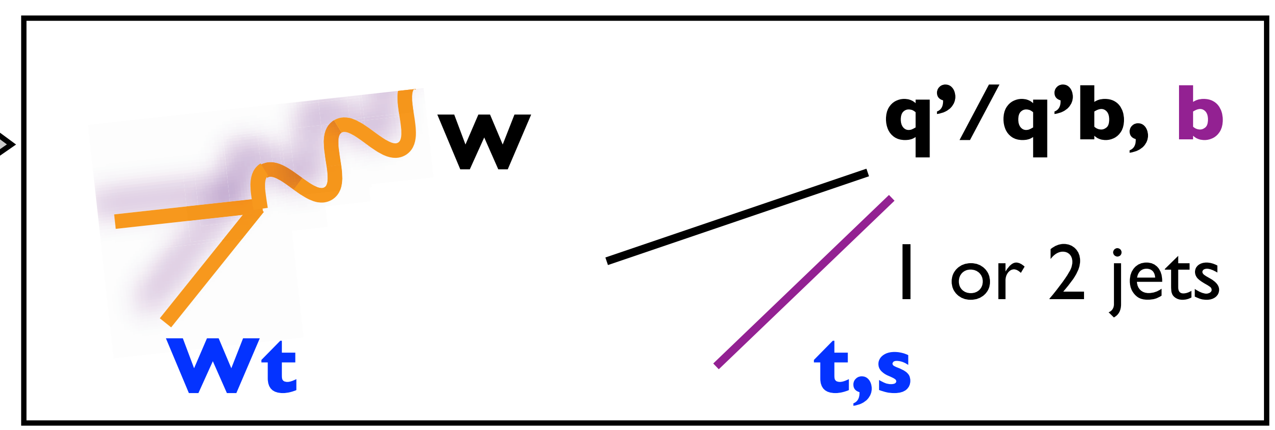
- **High P_T jets**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**







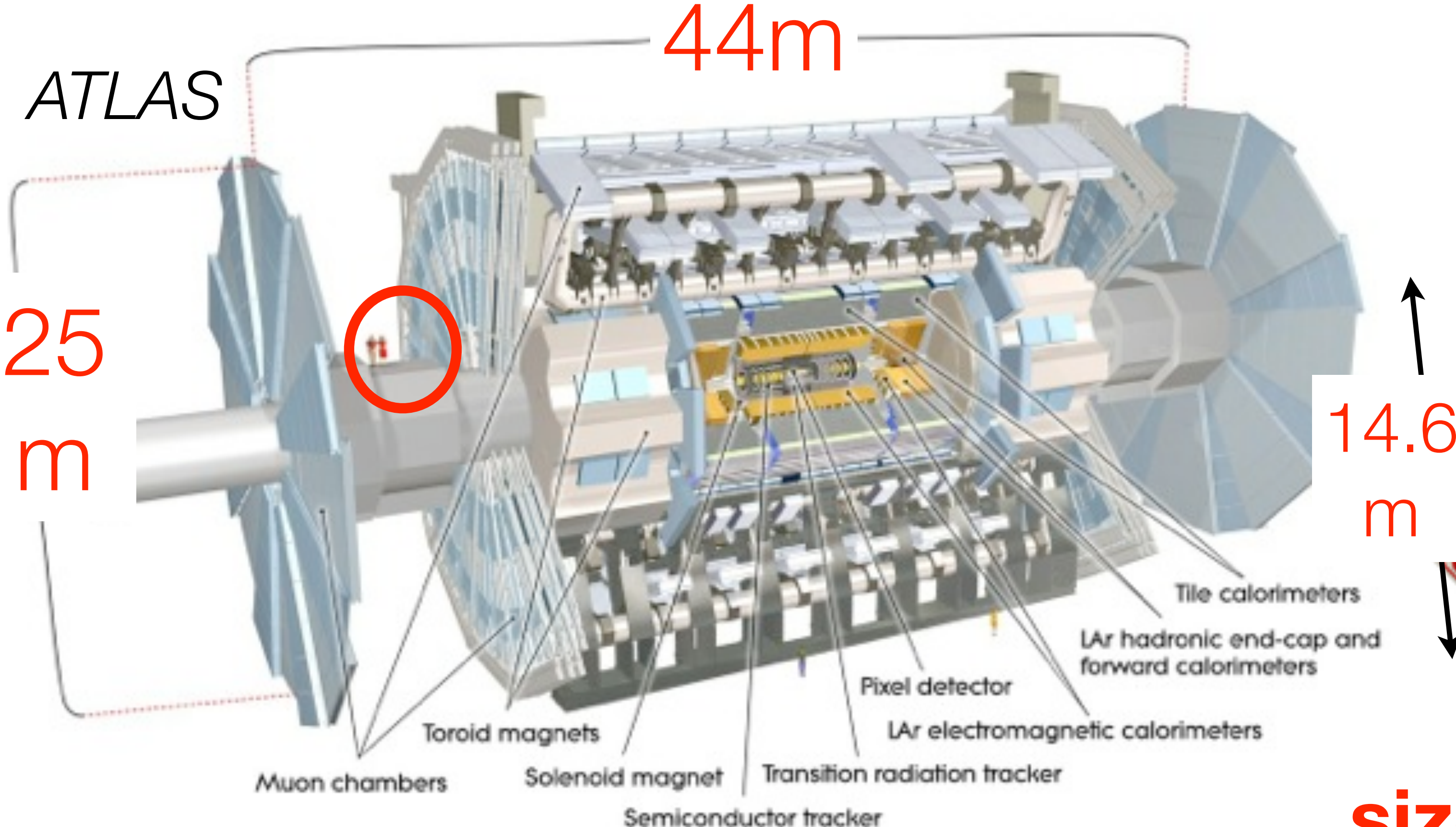
single top

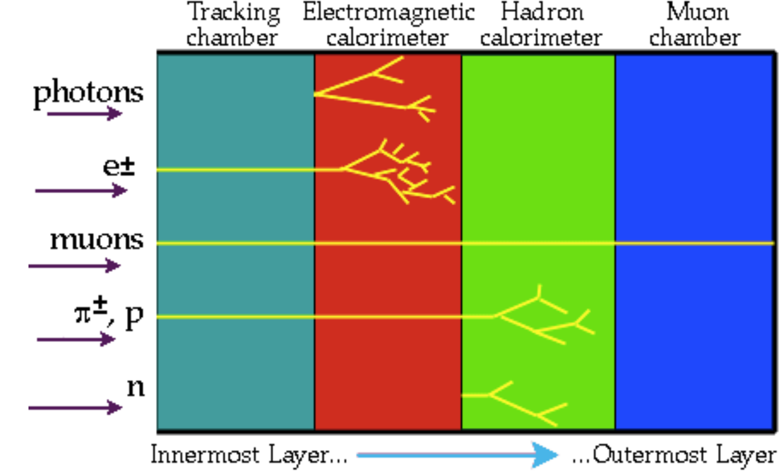


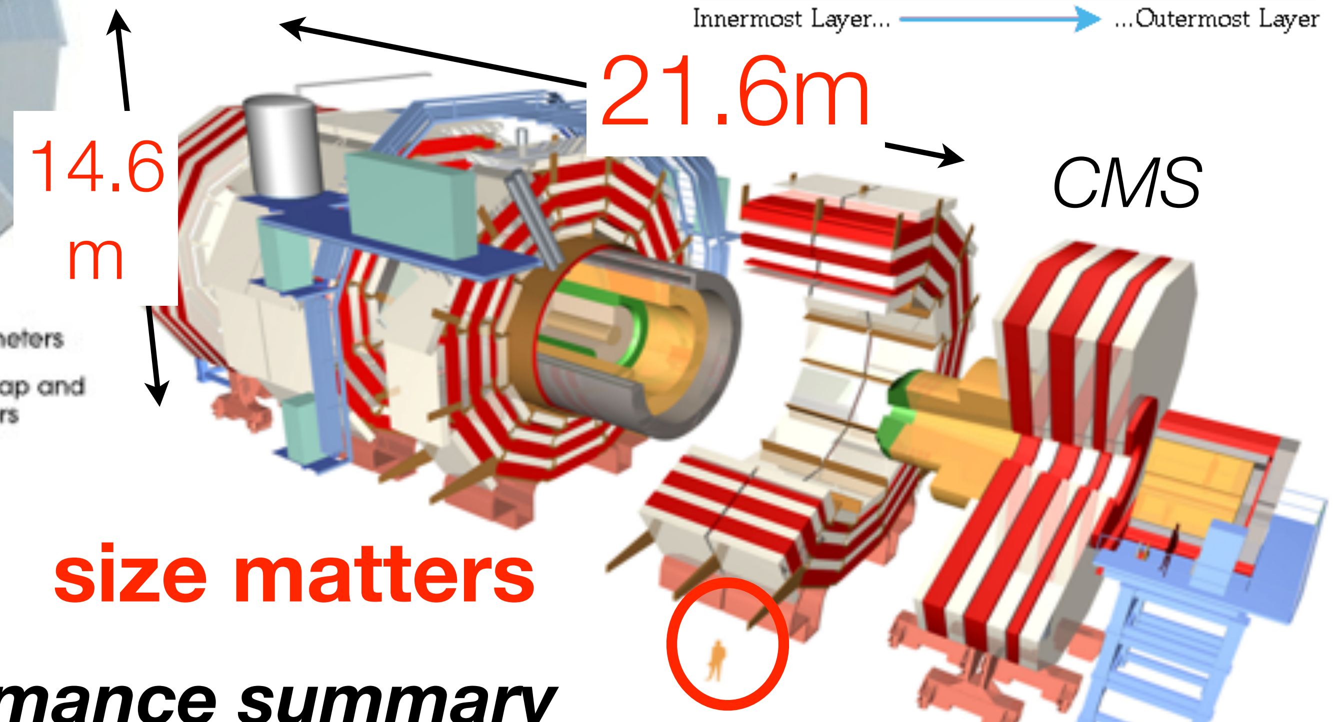
bkgs_tt̄: W/Z(+jets), single top, QCD, Di-bosons

bkgs_single_t: tt̄ + same bkgs_tt̄

ATLAS & CMS: *Top* observers







size matters

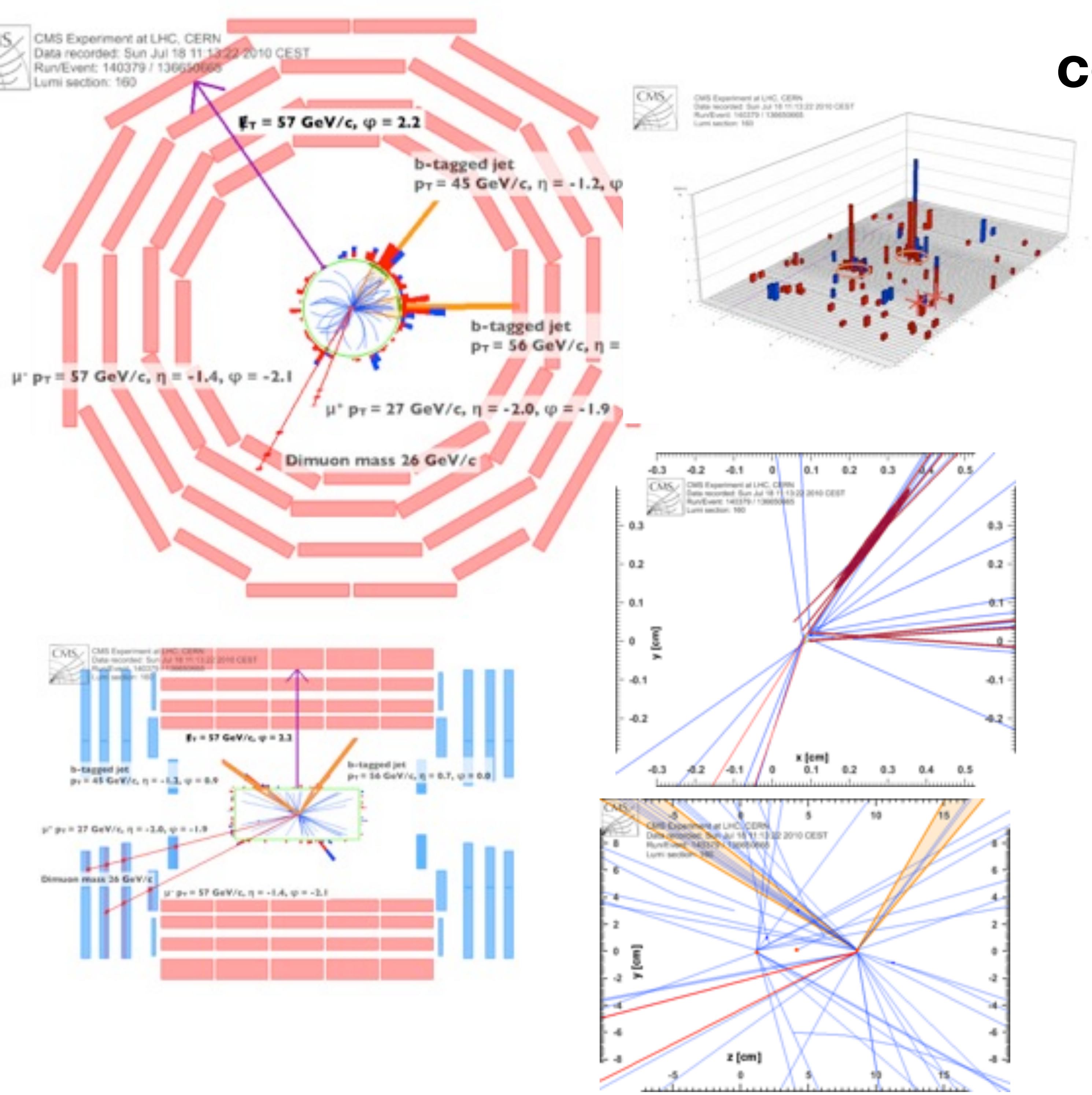
3 (ATLAS) or 2(CMS) trigger levels for event selection

Performance summary

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr/W+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E}$ + 0.03 GeV (central)	Cu+scintillator (5.8λ + catcher)/Fe+quartz fibres $\sigma/E \approx 100\%/\sqrt{E}$ + 0.05 GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx$ 1% @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

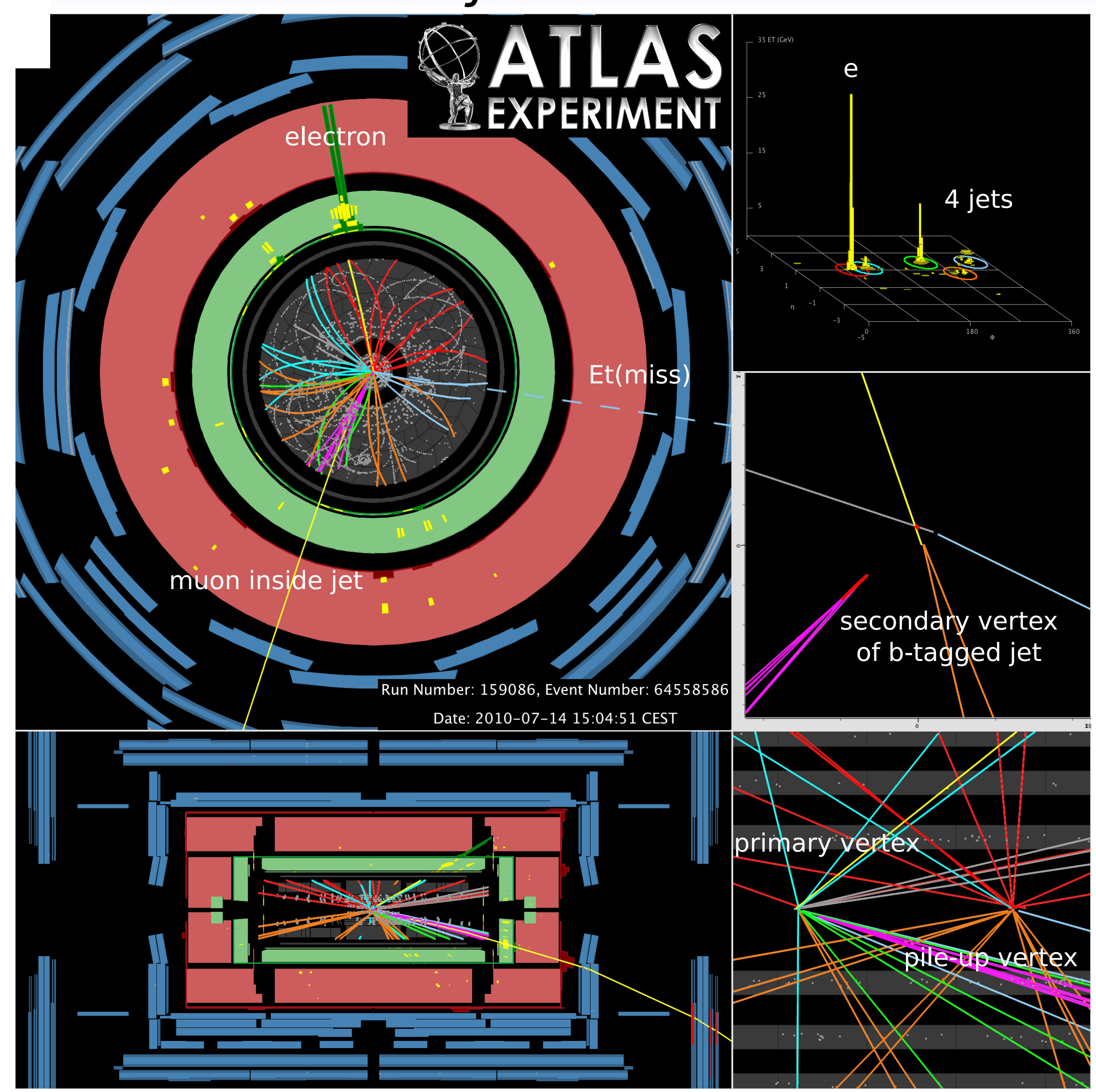
ATLAS and CMS: *Top* observers.....

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



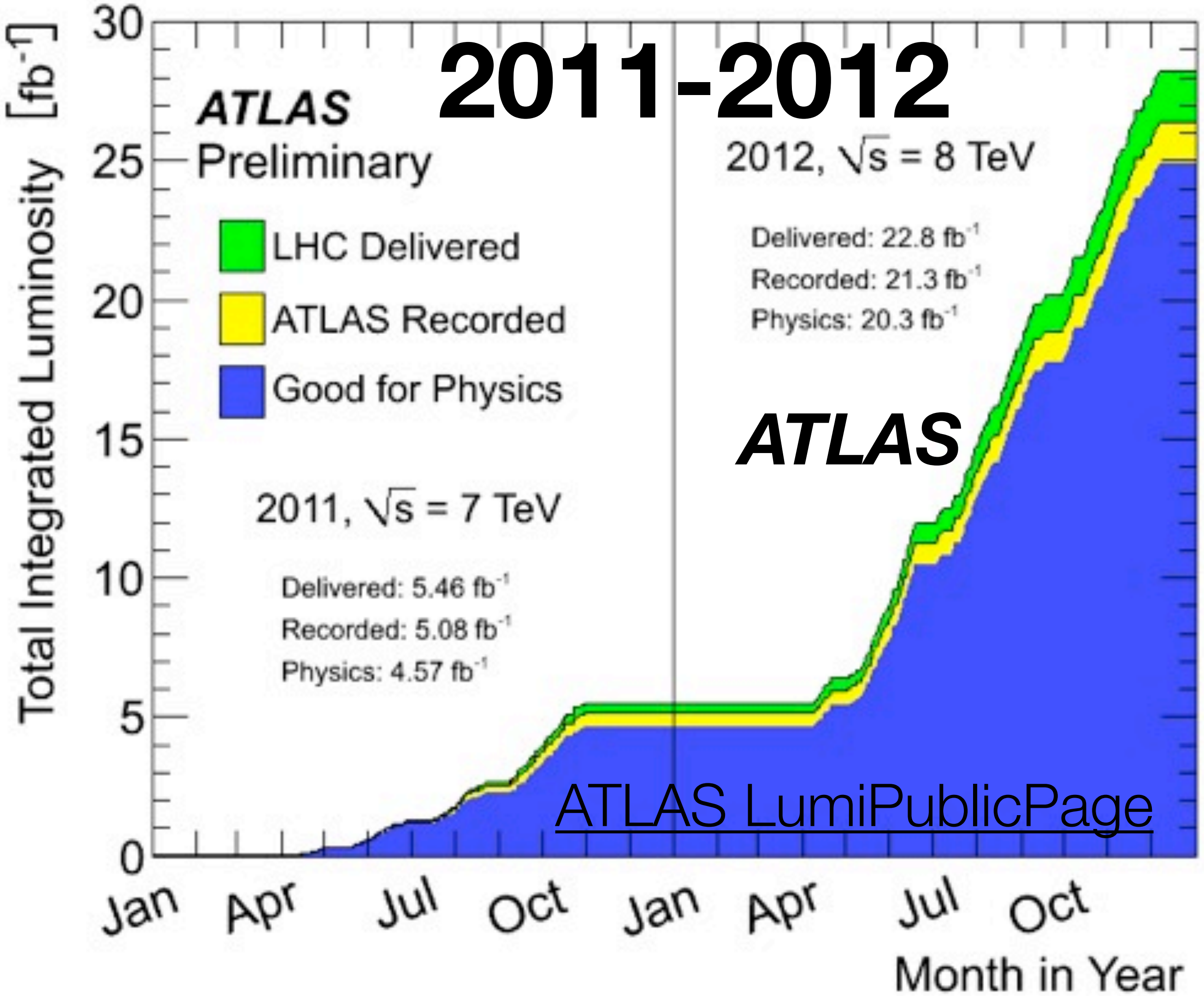
di-lepton (μμ+jets) candidate

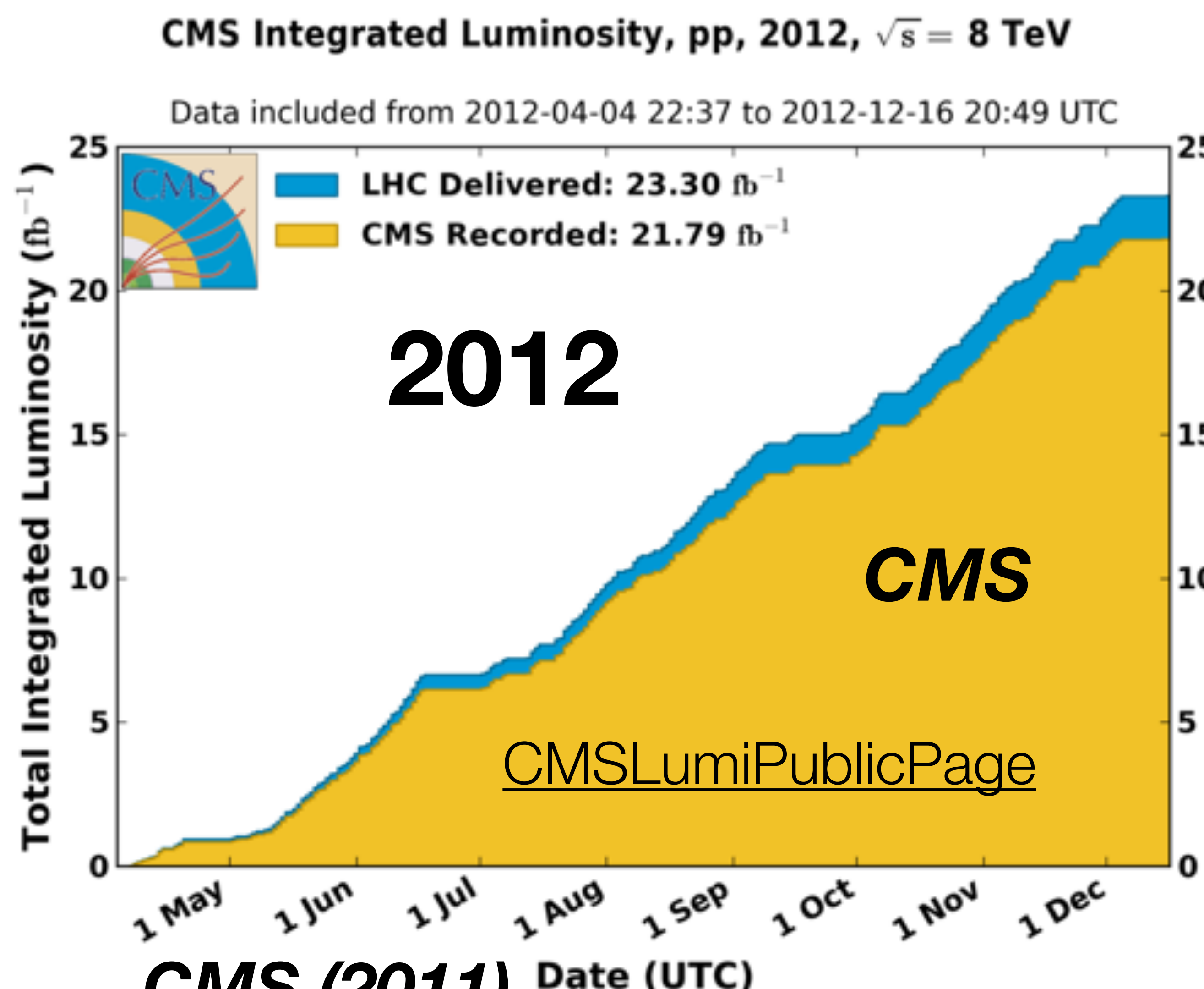
e+jets candidate



...with excellent data taking performance

Analyses use : 4.7 fb^{-1} (2011) to 20.3 fb^{-1} (2012)





Lumi uncertainty ~1.8% to 3.1%(prel)

CMS (2011)

Total Recorded (Delivered) Lumi:

5.41(5.51) fb^{-1}

Lumi uncertainty~4.6%

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 (2010)

Total Recorded (Delivered) Lumi:

40.76 (44.22) pb^{-1}

Lumi uncertainty~4%

...In a harsh environment

Number of Interactions per Crossing

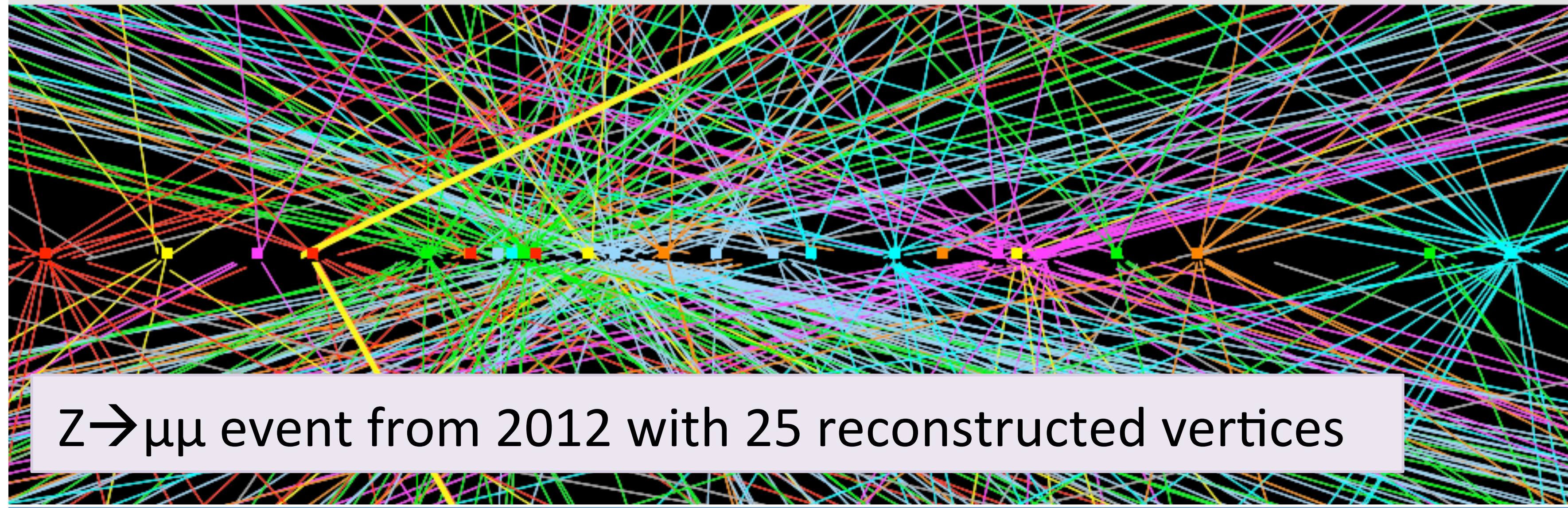
*Shown is **the luminosity-weighted distribution of the mean number of interactions per crossing for the 2011 and 2012 data.***

*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.*

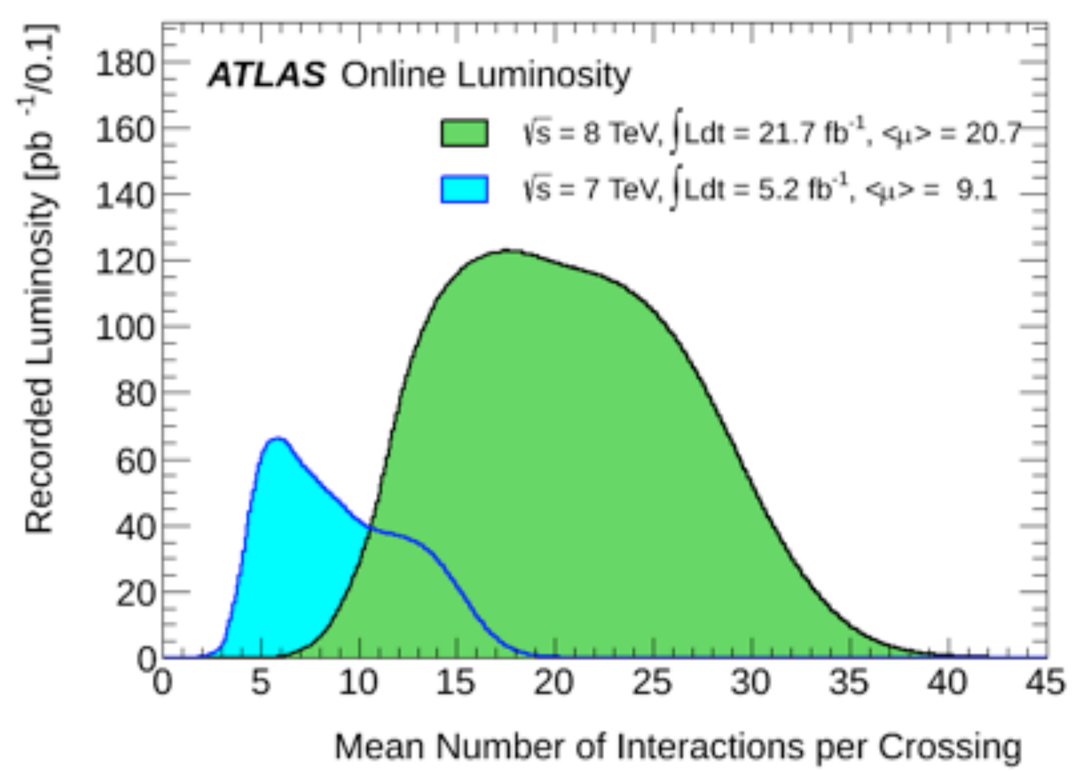
ATLAS LumiPublicPage

M. Aleksa
TOP2012

- 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…

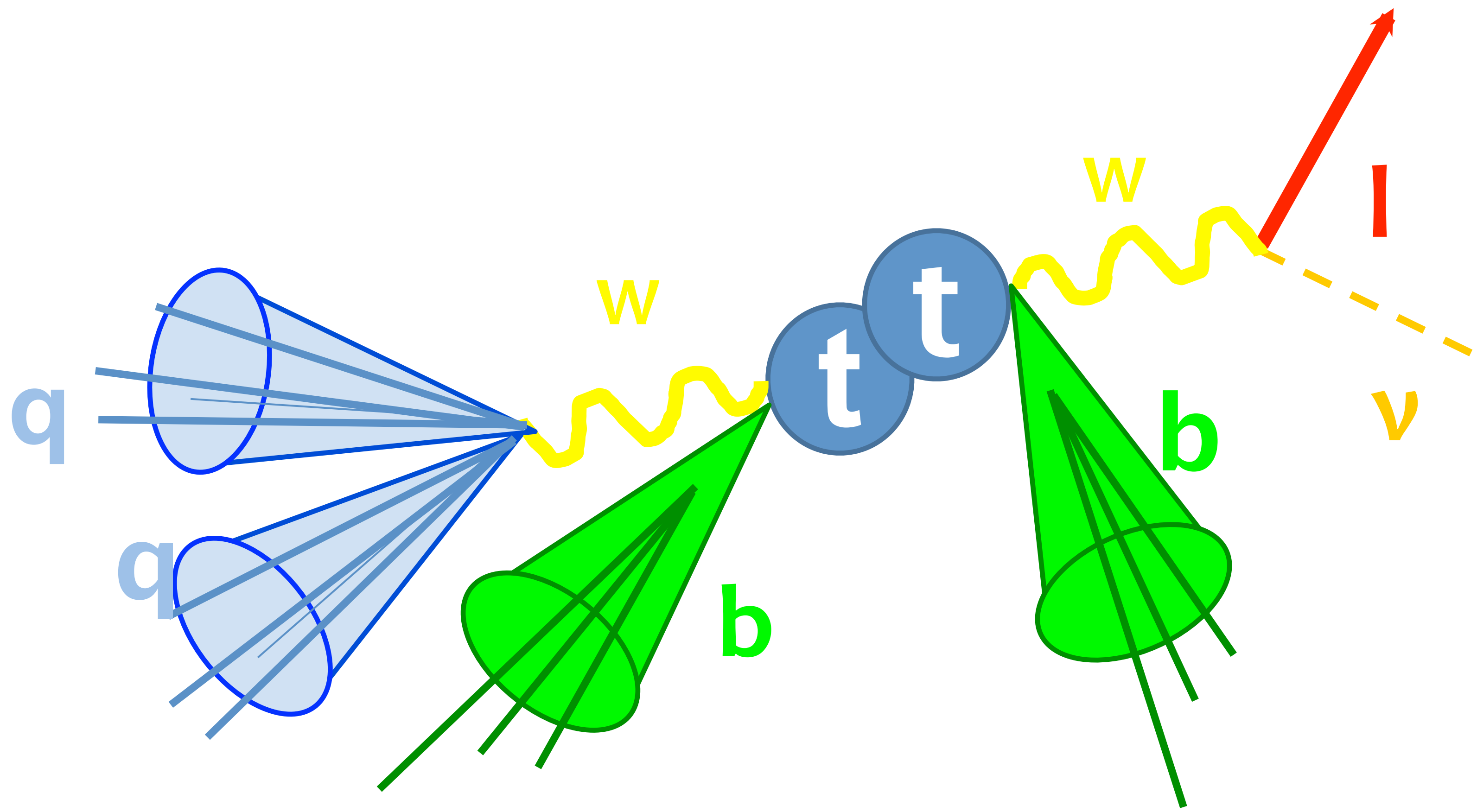


Z→μμ event from 2012 with 25 reconstructed vertices



Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)



Selection/Ingredients for top quark pairs/single-top

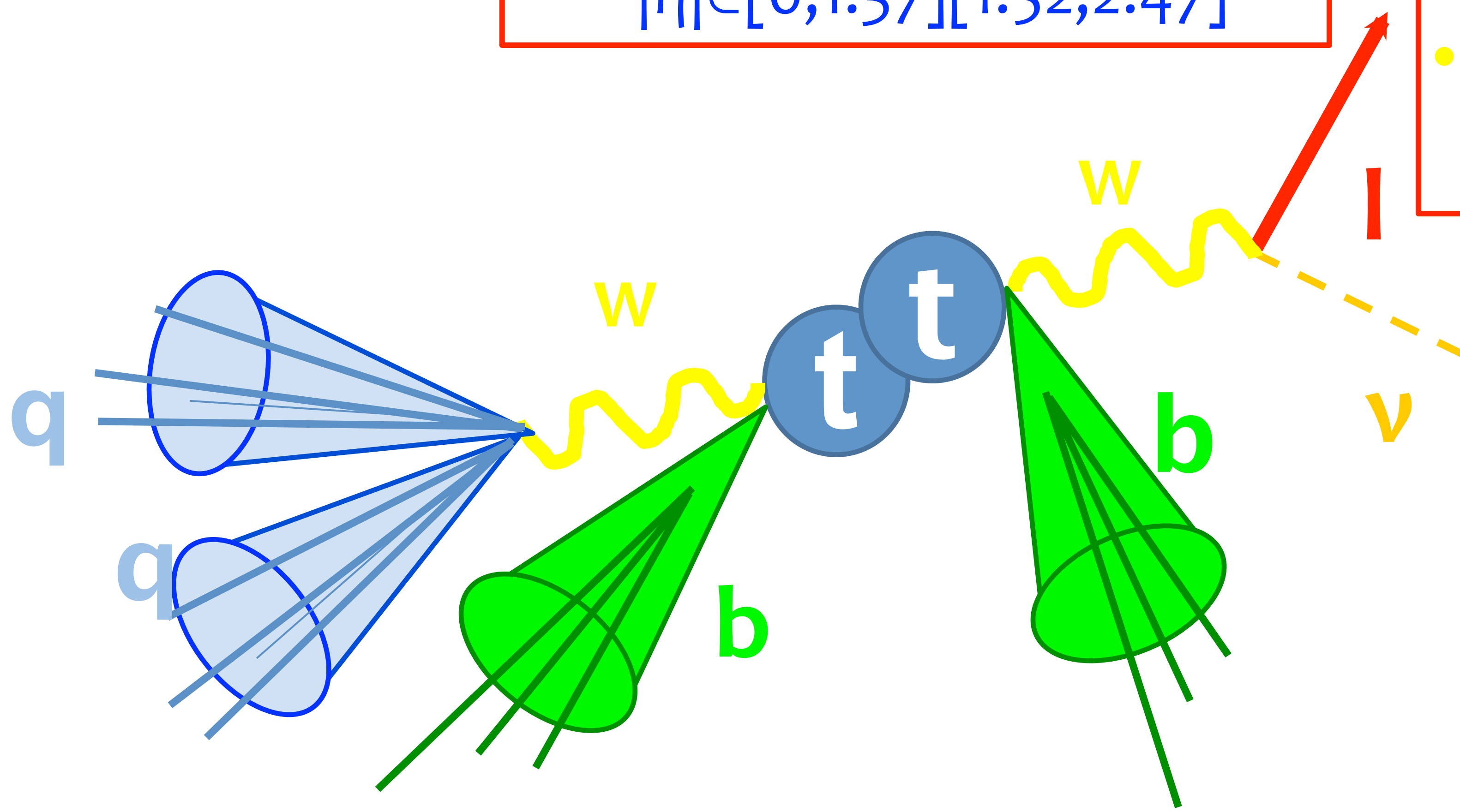
ATLAS (CMS is similar)

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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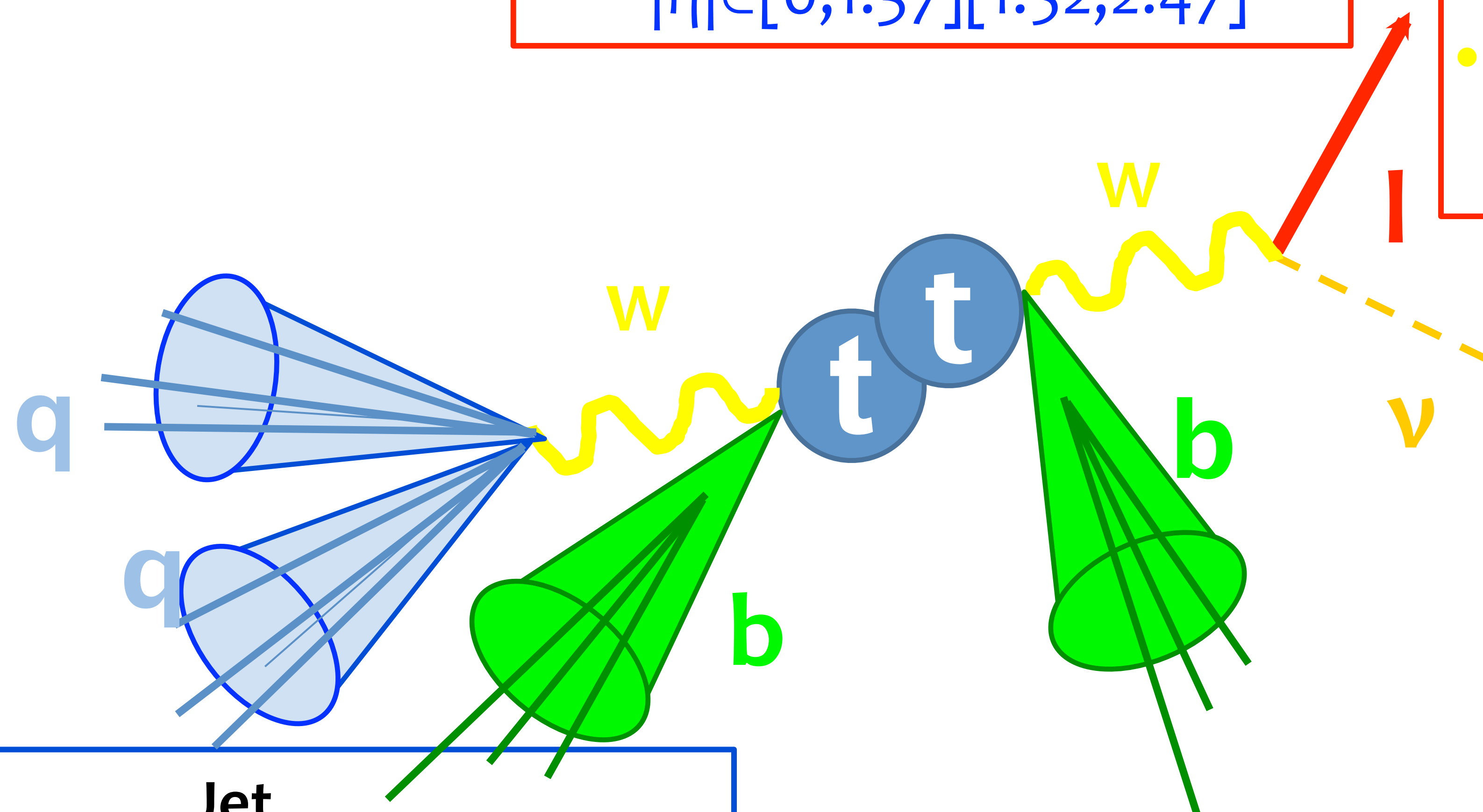

Jet

- 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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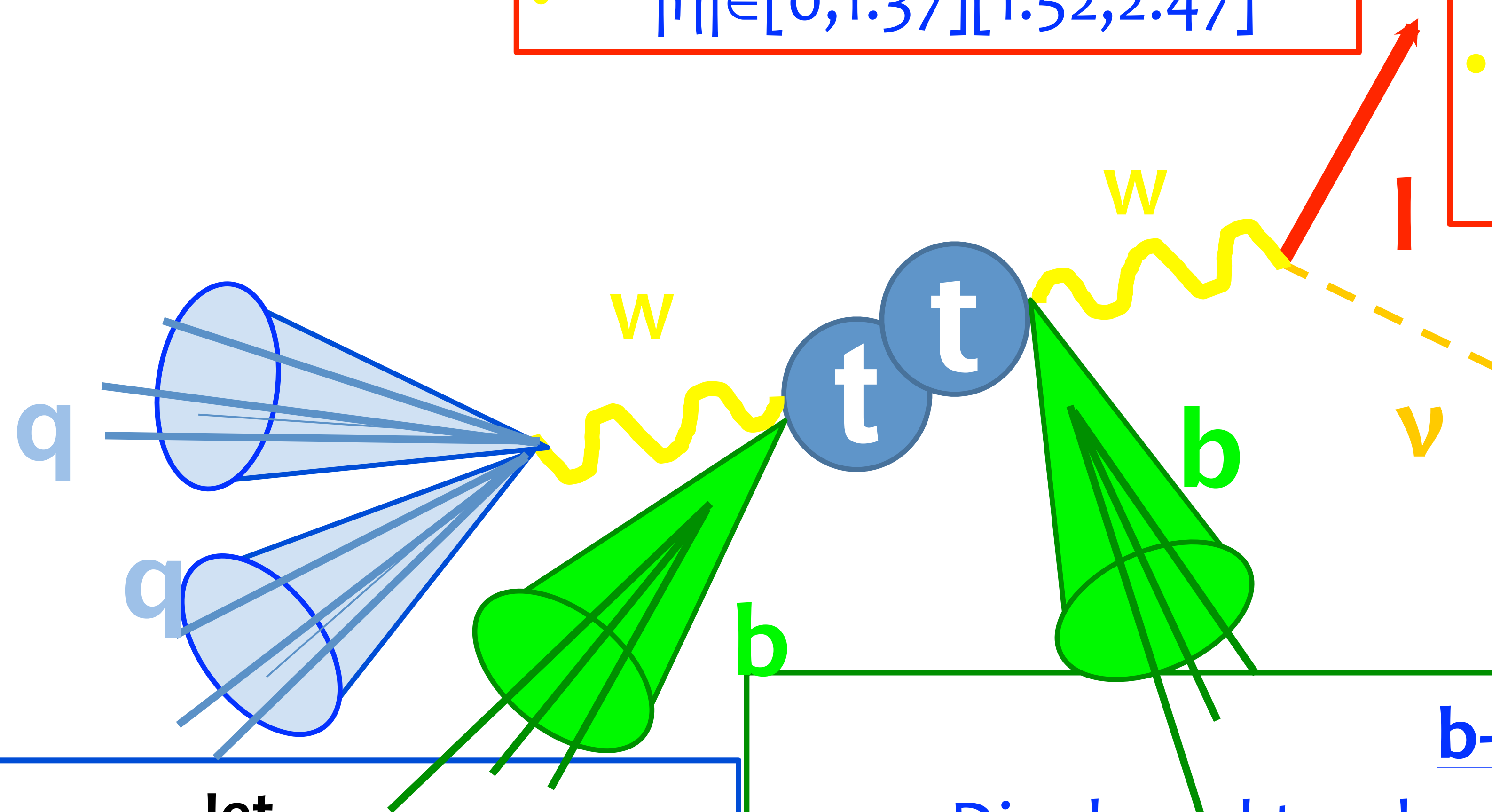

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b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with prim. vertex
- IP3D+SV1 +/or JetFitter: advanced lkl/NN taggers

Selection/Ingredients for top quark pairs/single-top

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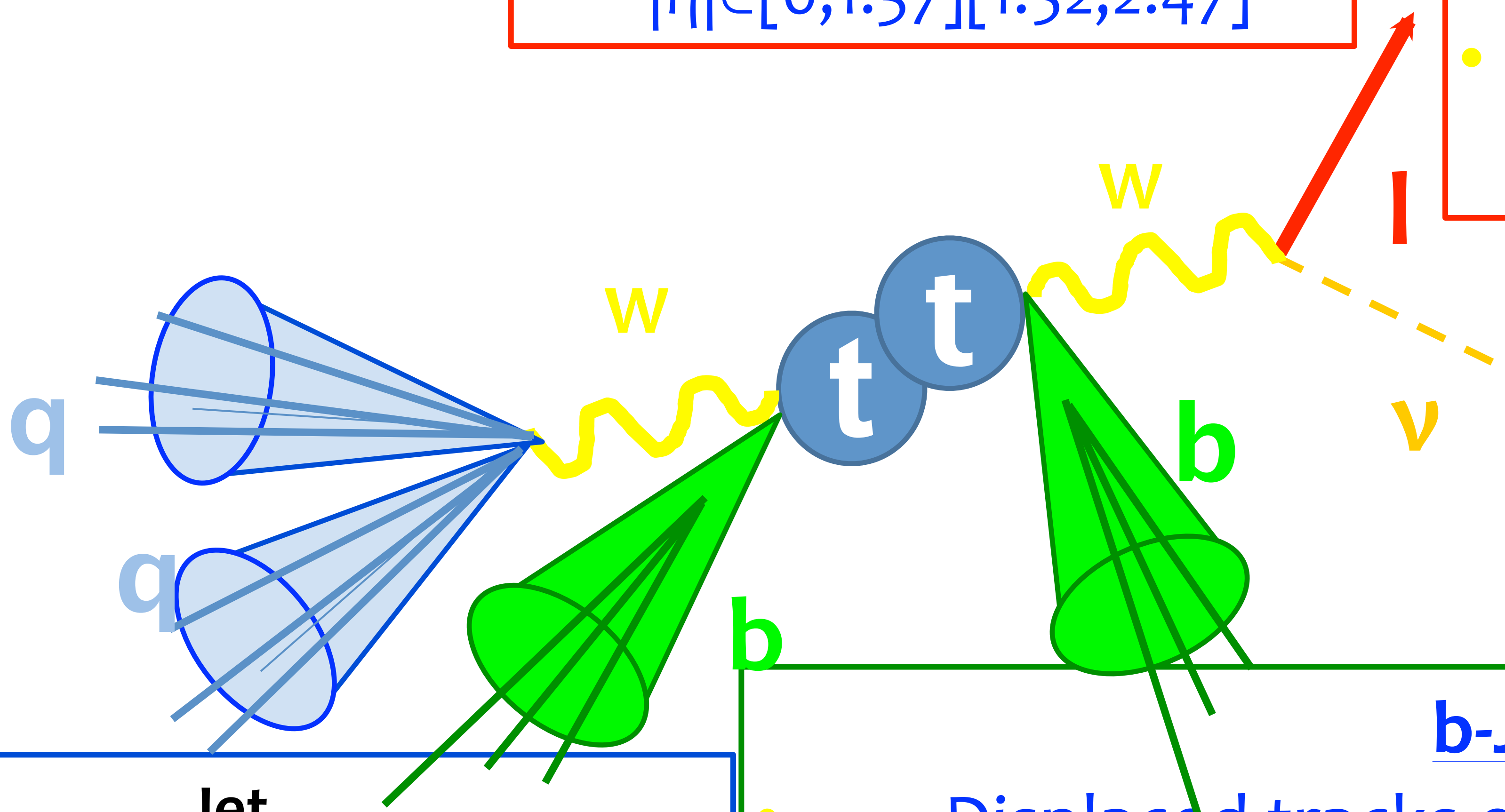

E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

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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
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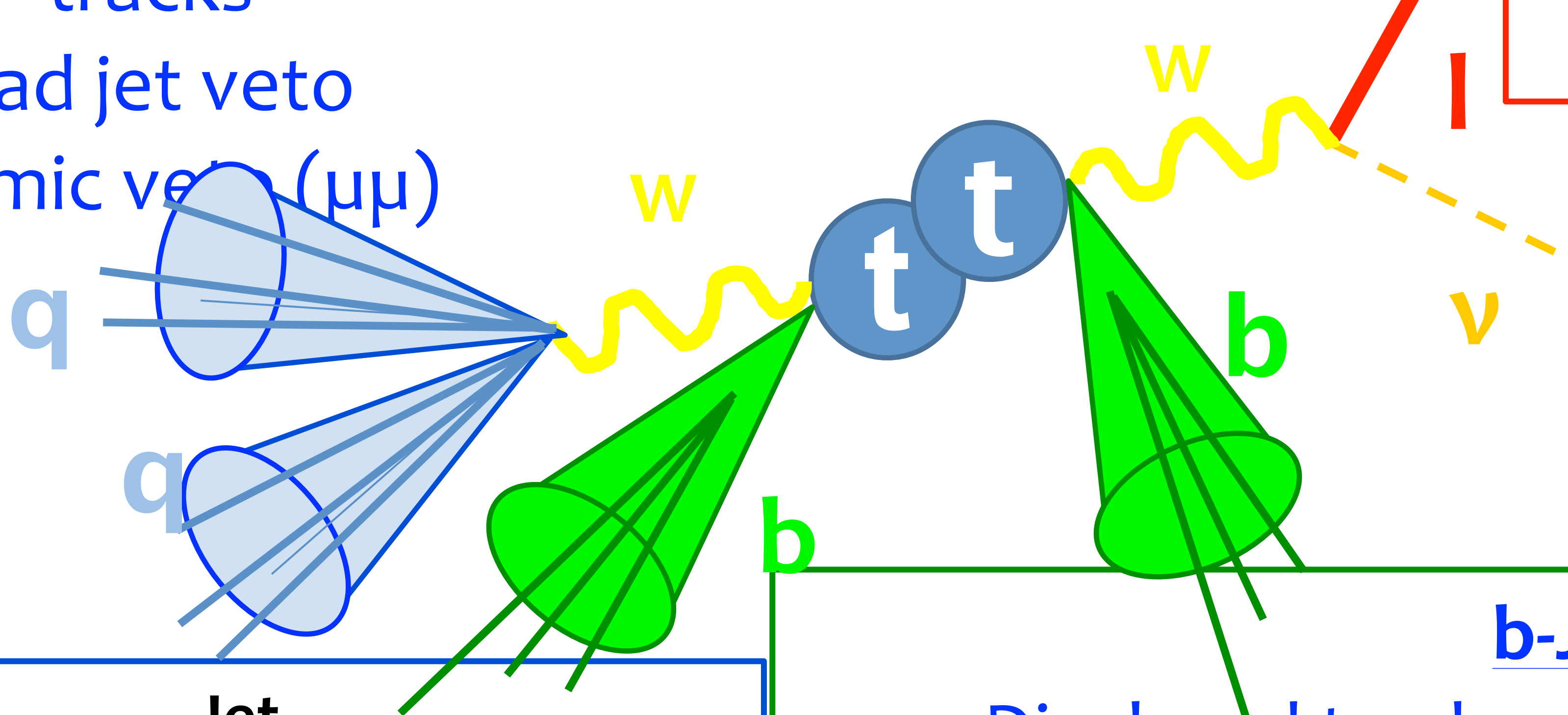

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Backgrounds: what are they ? How are they estimated?

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 large S/B→ ***test bkg modelling (shape and normalization) in bkg enchanced regions***

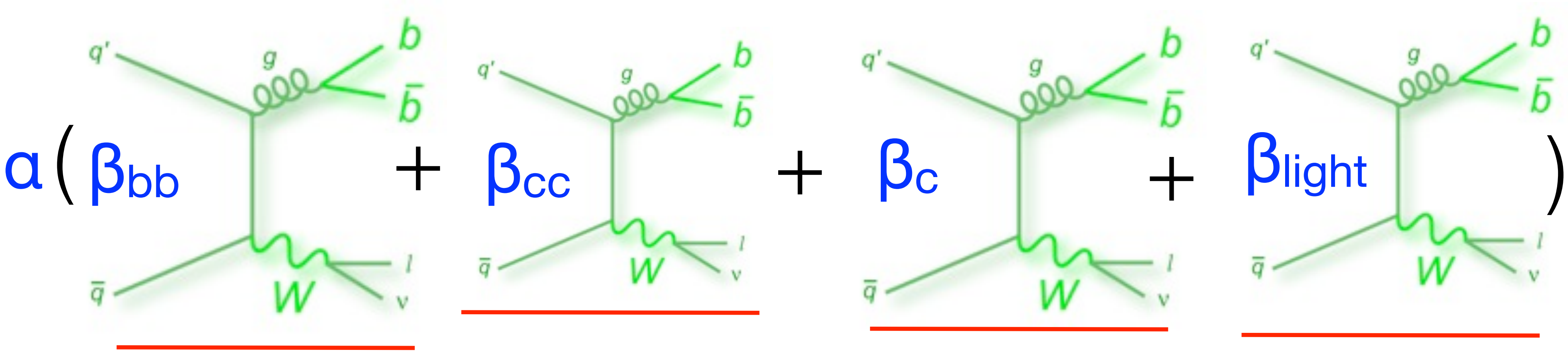
syst effect in precision measurements & searches

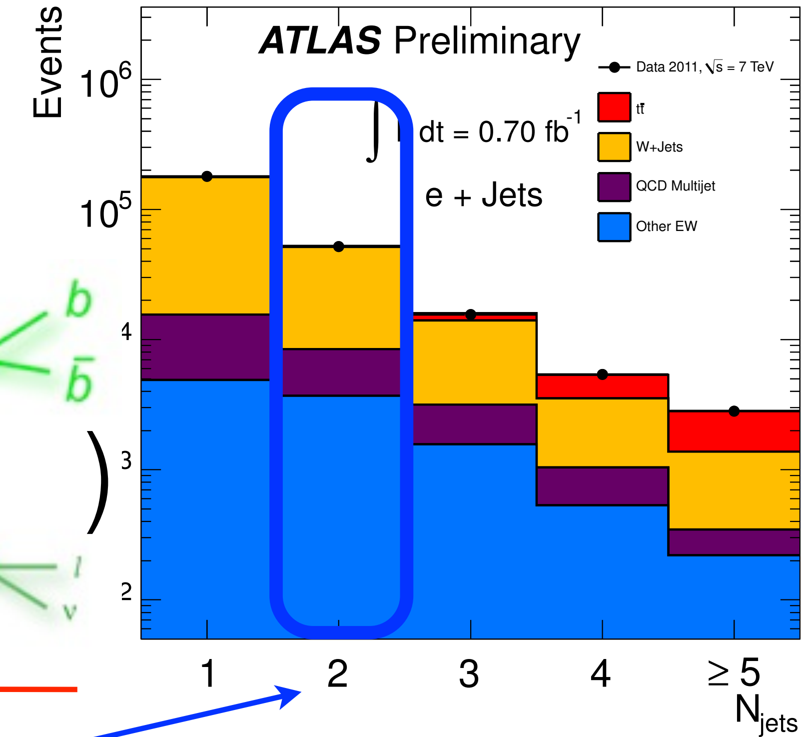
Backgrounds - single lepton+jets - **full scale example**

- ***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*

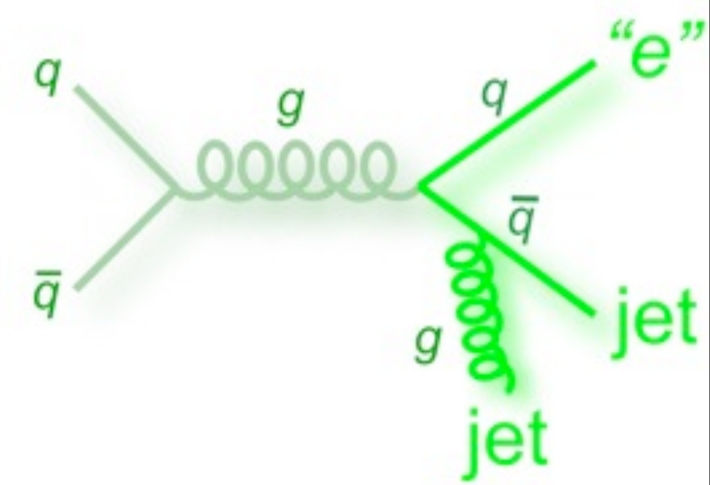
$$N_{W^+} + N_{W^-} = \frac{(N_{W^+}^{MC} + N_{W^-}^{MC})}{(N_{W^+}^{MC} - N_{W^-}^{MC})}(D^+ - D^-) = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^+ - D^-),$$

  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 (single lepton+jets)

- **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)**

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}},$$
$$N^{\text{std}} = rN^{\text{loose}}_{\text{real}} + fN^{\text{loose}}_{\text{fake}}$$

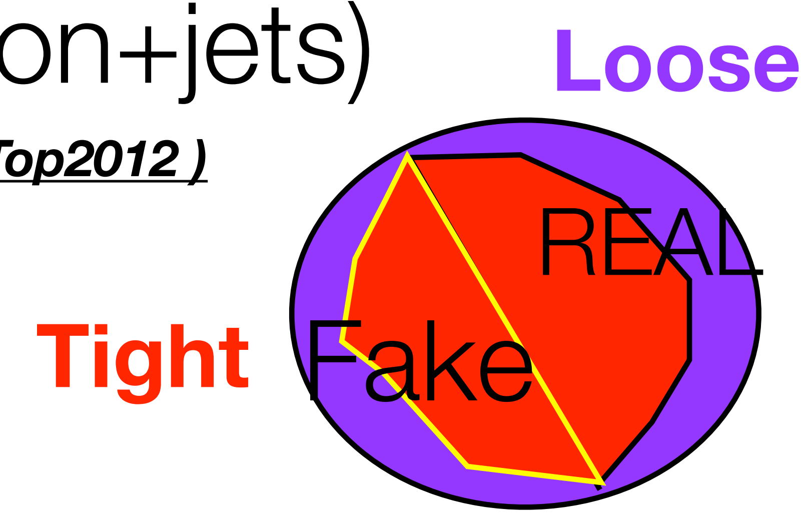
r is the marginal efficiency of standard cuts.
f is the same, for background sources

Both can be measured in pure or background event subtracted samples

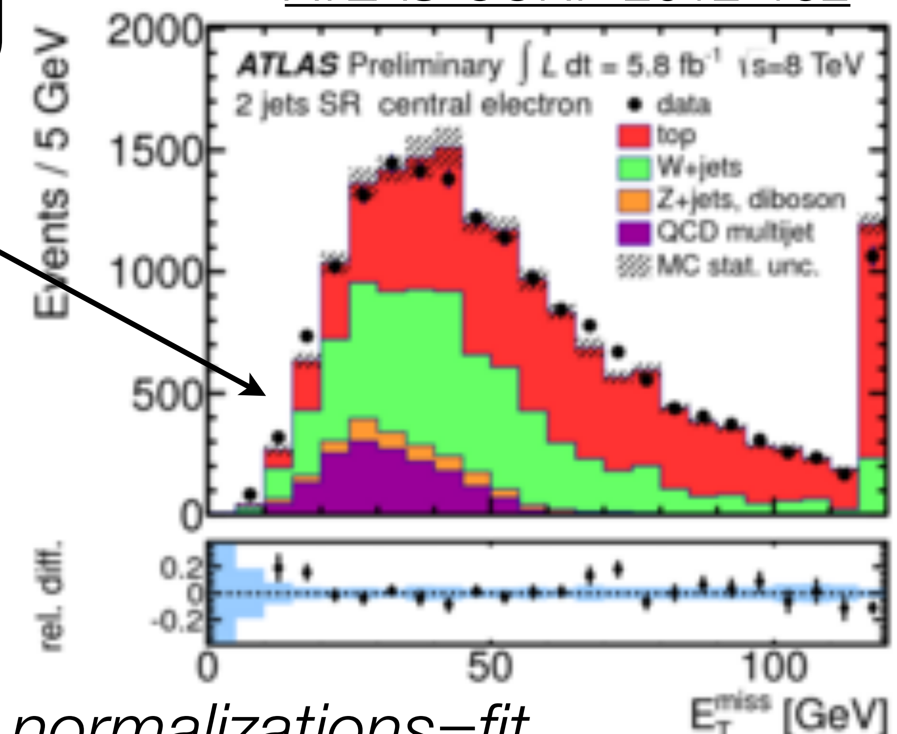
- *Jet template*

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

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

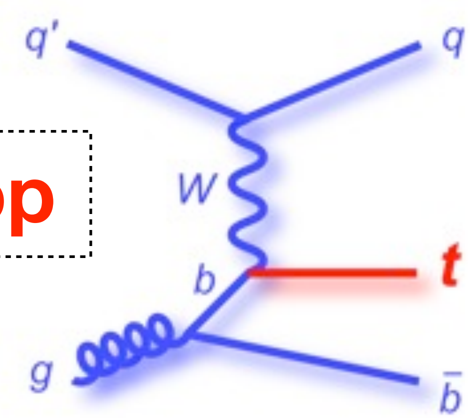


ATLAS-CONF-2012-132



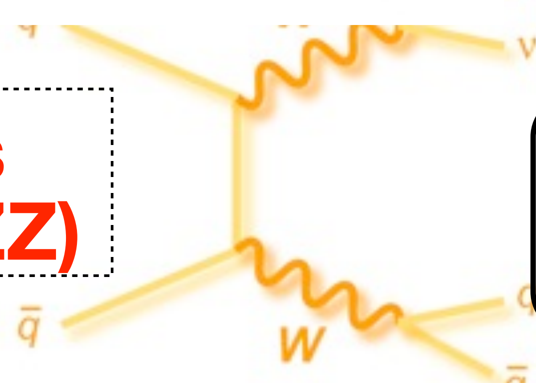
normalizations=fit parameters, estimates are starting points for fit

- **Single top**



Simulated shape+ rate set to approx NNLO

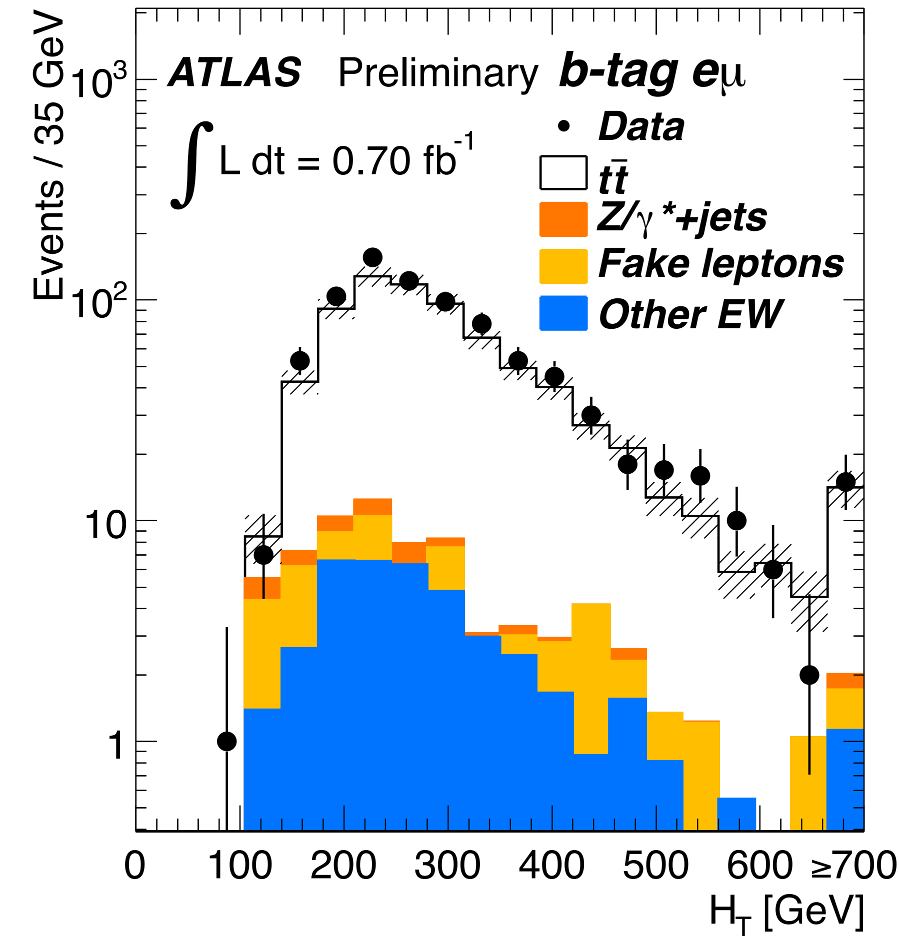
- **Di-bosons (WW,WZ,ZZ)**



Simulated shape+ rate set to SM

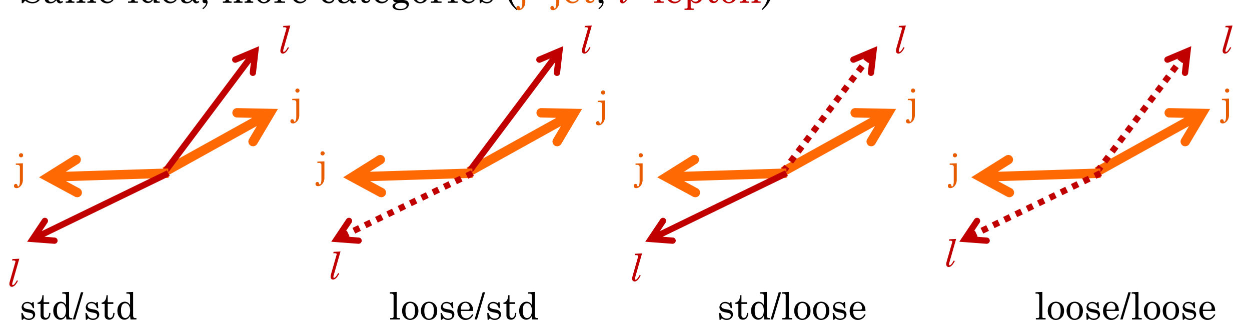
Backgrounds (di-lepton)

ATLAS-CONF-2011-100



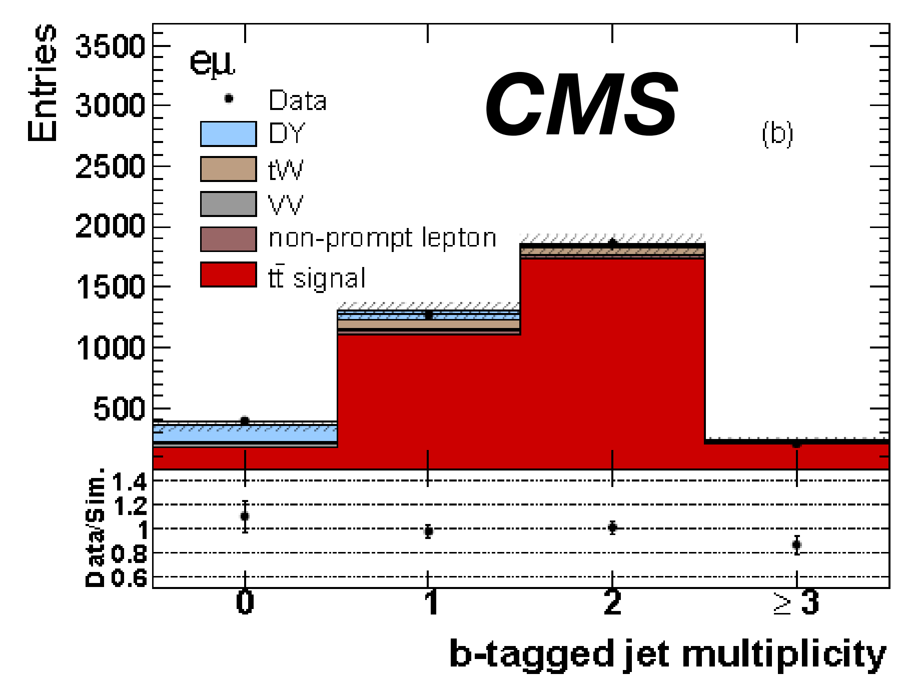
- ***Fake leptons*** : *generalized single lepton*
  - Get **probability** for **loose** “fake” and real leptons ***to be in signal region*** ← **control samples** enriched with real (in Z window) or “fake” (low E_T^{miss}) leptons
  - **Combine** with **N(di-lep)** for **all loose/tight** pairs→**fake tight** (i.e. signal) **lep**

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



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

(J Boudreau, Top2012)



- ***Z/γ* bkg (ee, μμ)*** : **scale** non-Z/γ*-bkg-subtracted **data in Z-mass window control region with ratio** of N(Z/γ*) in signal region to control region **from simul.**

What we study about the top quark

inspired by figure
by D Chakraborty

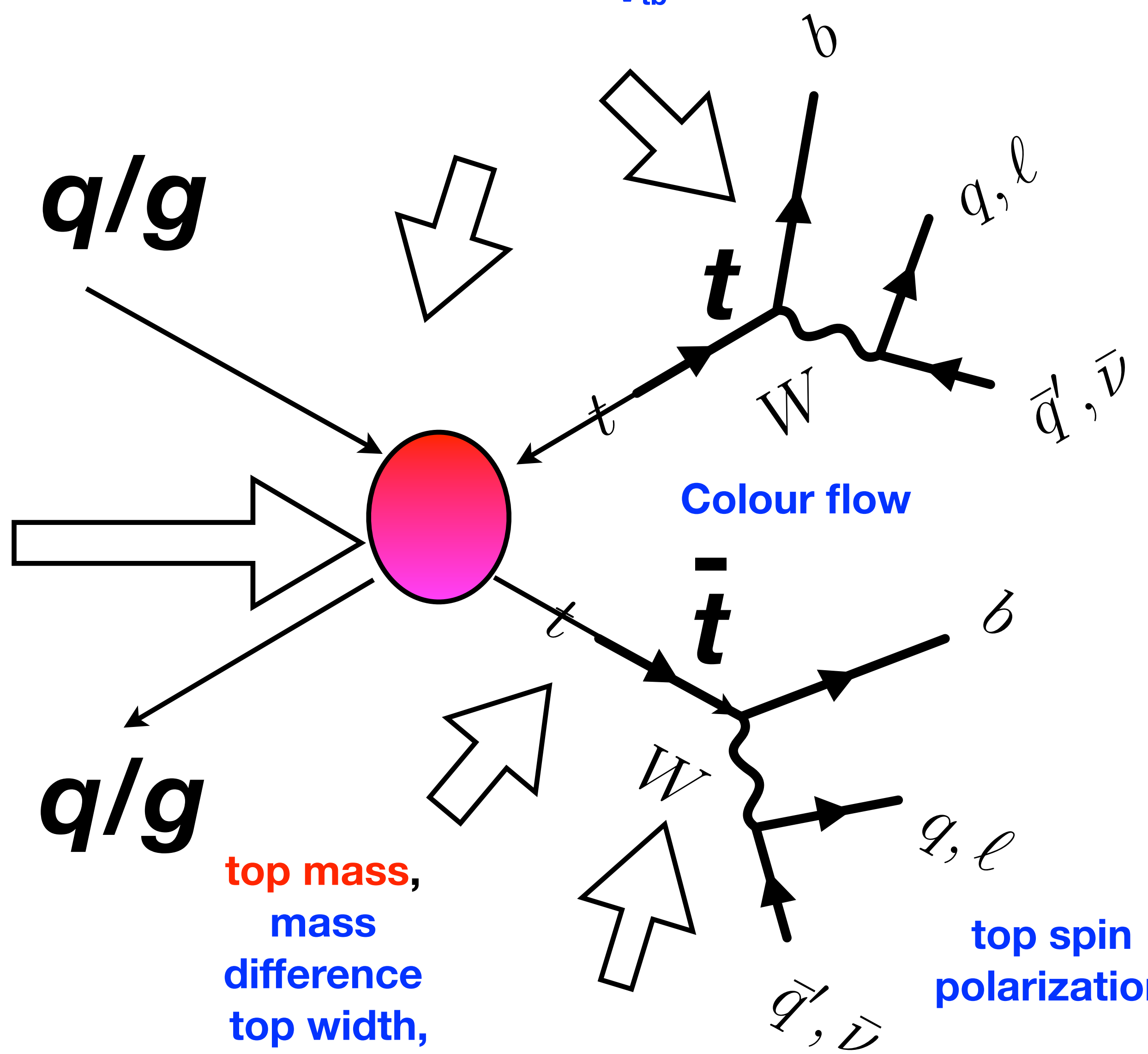
Discuss Today

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, 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

$n_{sig} = n_{bkg} + \int L dt * \sigma_{tt \text{ or } t} *$ detection/extrapolation efficiency

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

- ***Cut and Count*** i.e. maximum likelihood solution for poisson hypothesis
- ***Using 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**
- Towards definition in fiducial phase space
- Many top quarks: going differential!

Final states:

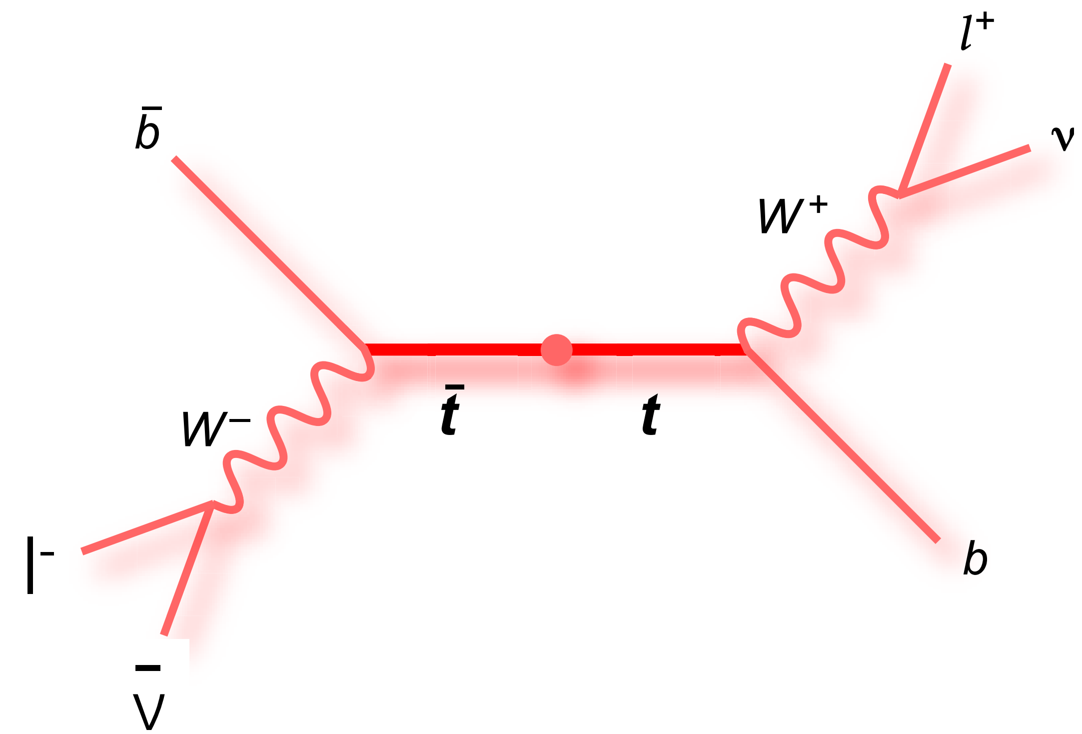
- dilepton — low bkg, low prob
- l+jets — compromise between, prob & bkg
- fully hadronic — large prob, large bkg

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

$\int L dt$ = **~2.4 fb^{-1}** *(2012)*

- Vertex and quality cuts
- After di-lep trigger **exactly two opposite sign** high p_T central **leptons (ee, eμ, μμ)**
- **≥ 2 central** high p_T **jet**
- High **E_T^{miss} for (ee, μμ)** *(>40 GeV)*
- **For (ee, μμ) veto low di-lep mass***(<15 GeV)* & **Z-like** *(20 GeV mass window)* **events**
- **≥ 1 b-tag,**

CMS-PAS-TOP-12-007



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

Cut and count: σ_{tt} @ 8 TeV - *di-lepton channel*

$$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A} \cdot \mathcal{L}}$$

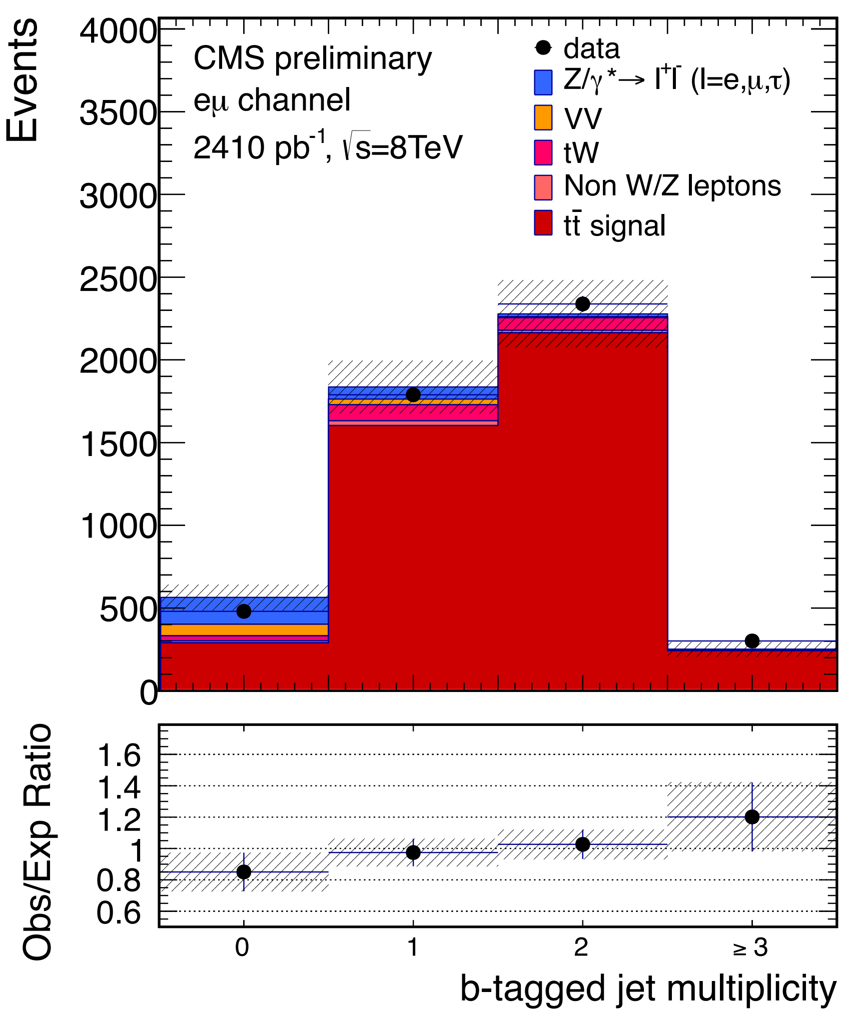
- **Subtract background and get N_{tt}**
- **Extract cross section**
  - combining channels with best linear unbiased estimator including correlations and systematics

$\delta\sigma/\sigma \sim 7\%$

$$\sigma_{t\bar{t}} = 227 \pm 3 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 10 \text{ (lumi) pb}$$

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

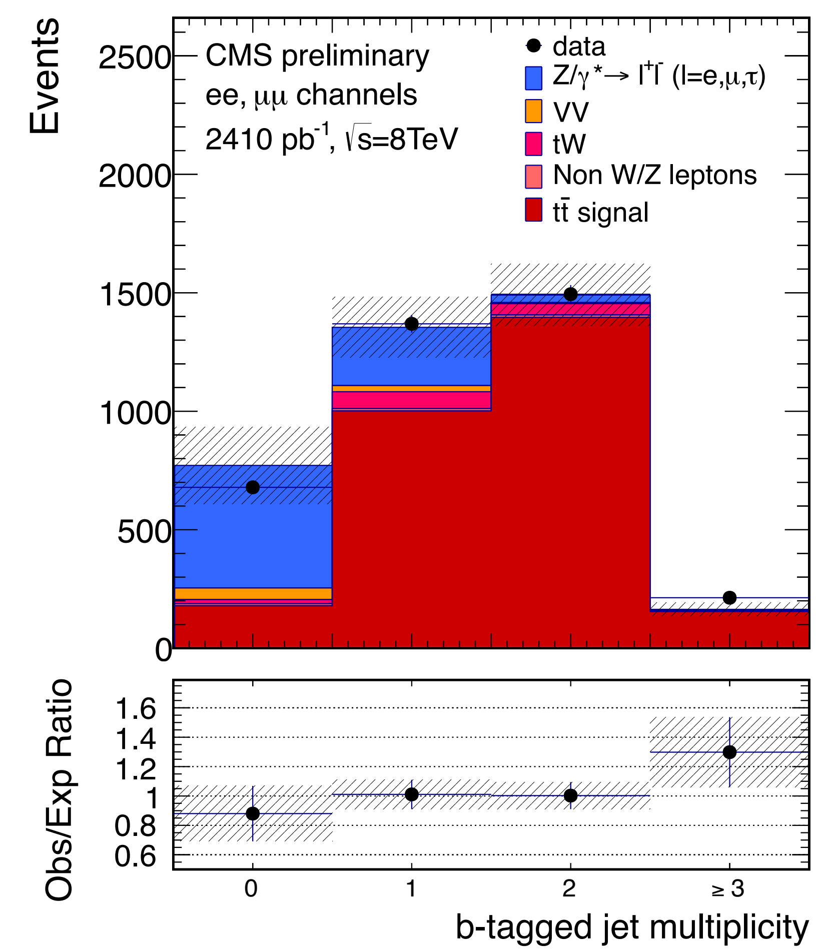
CMS-PAS-TOP-12-007



distributions after all cuts, except Ntagged jets

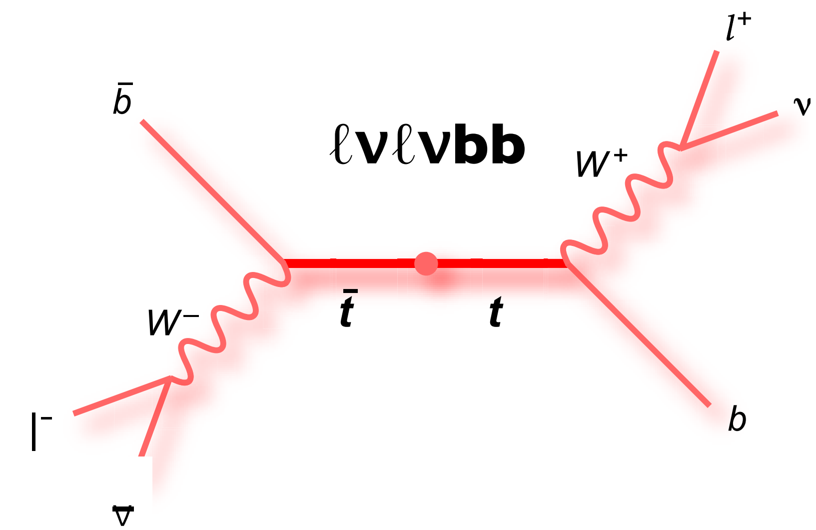
syst dominated!

JES~2.5%), lept eff~1.8% luminosity (~4%)



"Cut & count" σ_{tt} : dilepton - $\sqrt{s}$ = 8 TeV $\int Ldt \sim$ **20.3 fb^{-1}** *(2012)*

freshly presented at TOP2013 in September



- **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), fake leptons, reduced Z+jets

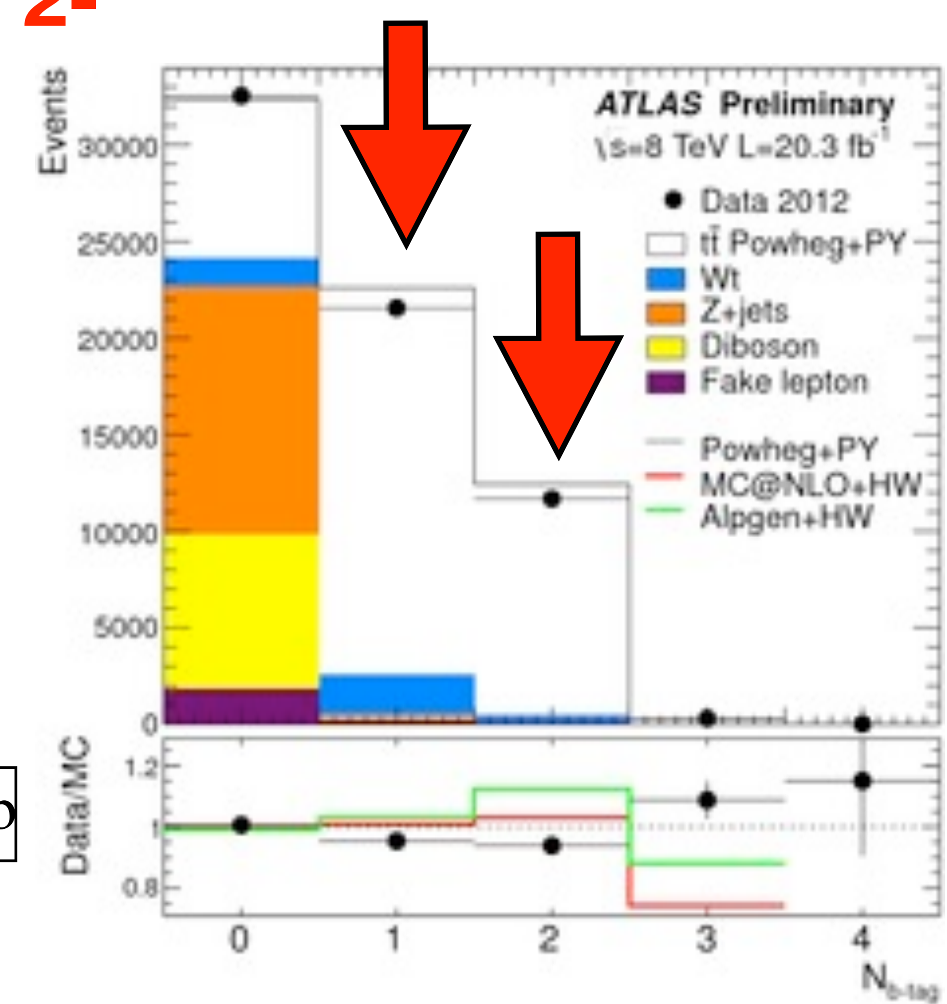
ATLAS-CONF-2013-097

- **Maximum likelihood 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**

efficiency terms

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

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



- **"External" Syst dominated:** *Lumi ~3.1%, E_b~1.7%, tt modelling ~1.5% Elec. ID/isol ~1.4%*

$$\sigma_{t\bar{t}} = 237.7 \pm 1.7\ (\text{stat}) \pm 7.4\ (\text{syst}) \pm 7.4\ (\text{lumi}) \pm 4.0\ (\text{beam energy})\ \text{pb}$$

$\delta\sigma_{tt}/\sigma_{tt}$ ~4.8%

Most precise LHC $\sigma_{t\bar{t}}$ @ 8 TeV!

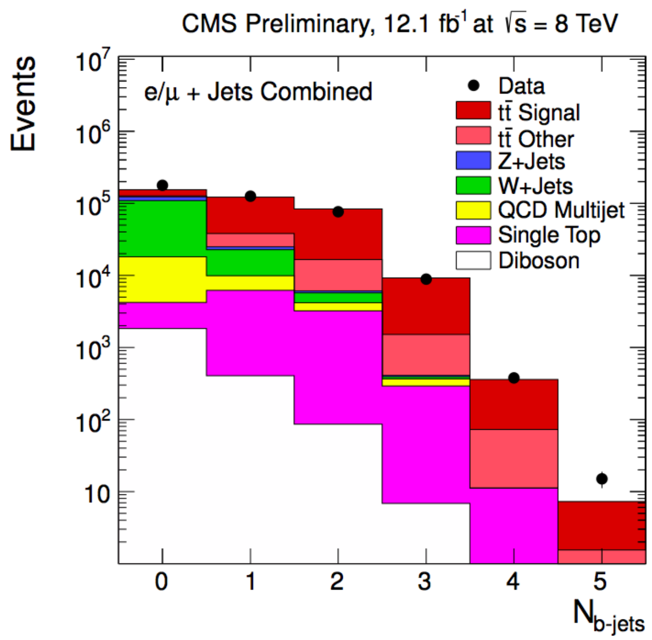
Going differential for σ_{tt} !

- Differential tt cross sections
  - → *test of SM QCD tt production & kine (generators & had scheme)*
  - → *complementary in searches for new forces, dimensions*
  - → *provide info on Parton Dist Functions*

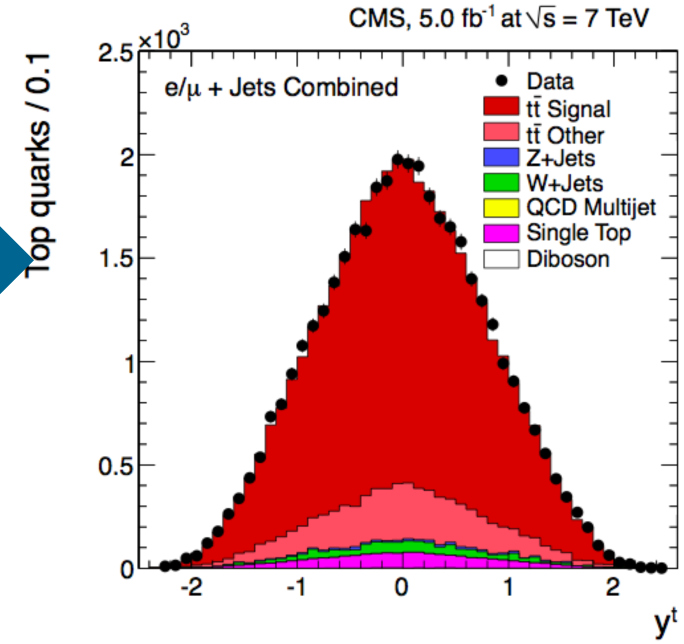
Going differential for σ_{tt} !

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

(1) Event selection



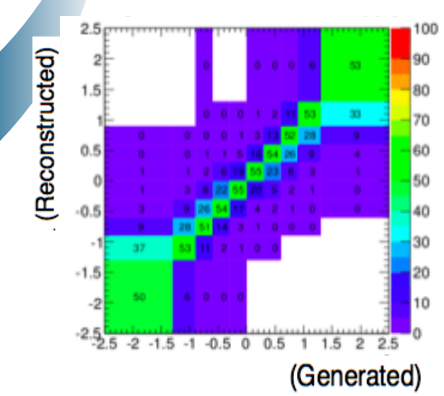
(2) tt̄ kinematic reconstruction



(3) Bin-wise cross section measurement

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

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

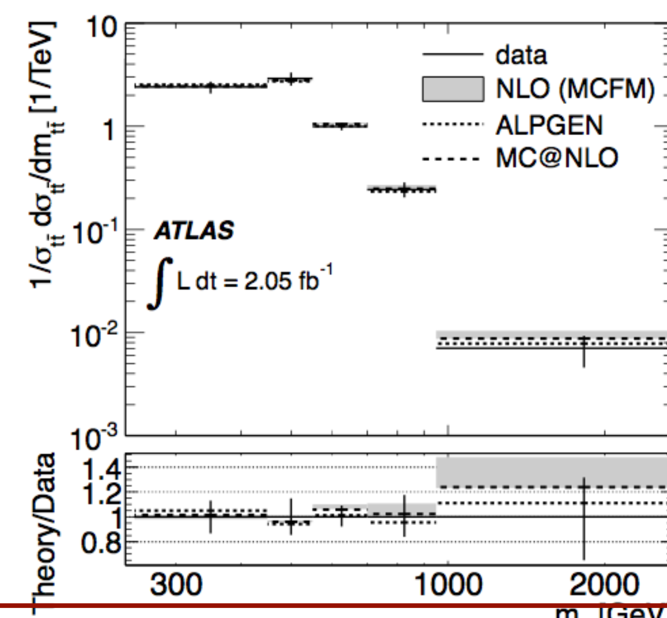


Response matrix

Migrations due to det resolution & biases

(4) Differential tt̄ cross sections

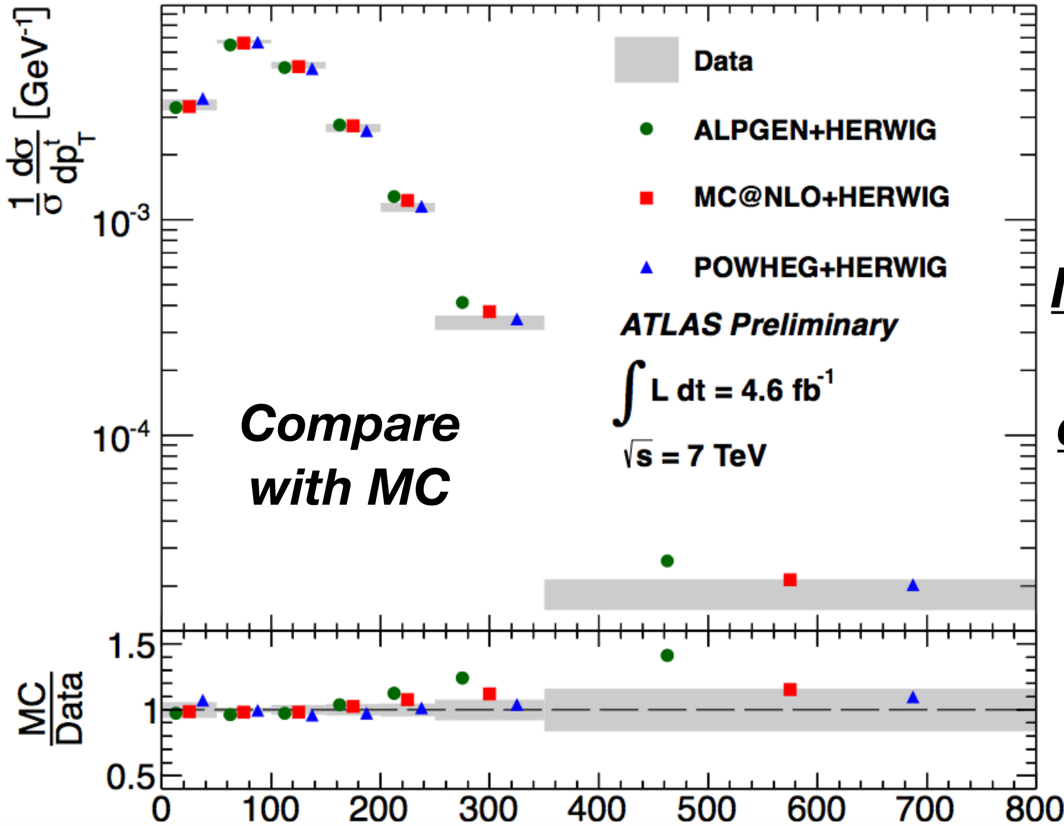
- Normalised to in-situ measured σ(tt̄)
- 'Visible' or extrapolated to full phase space
- Compare to theory predictions



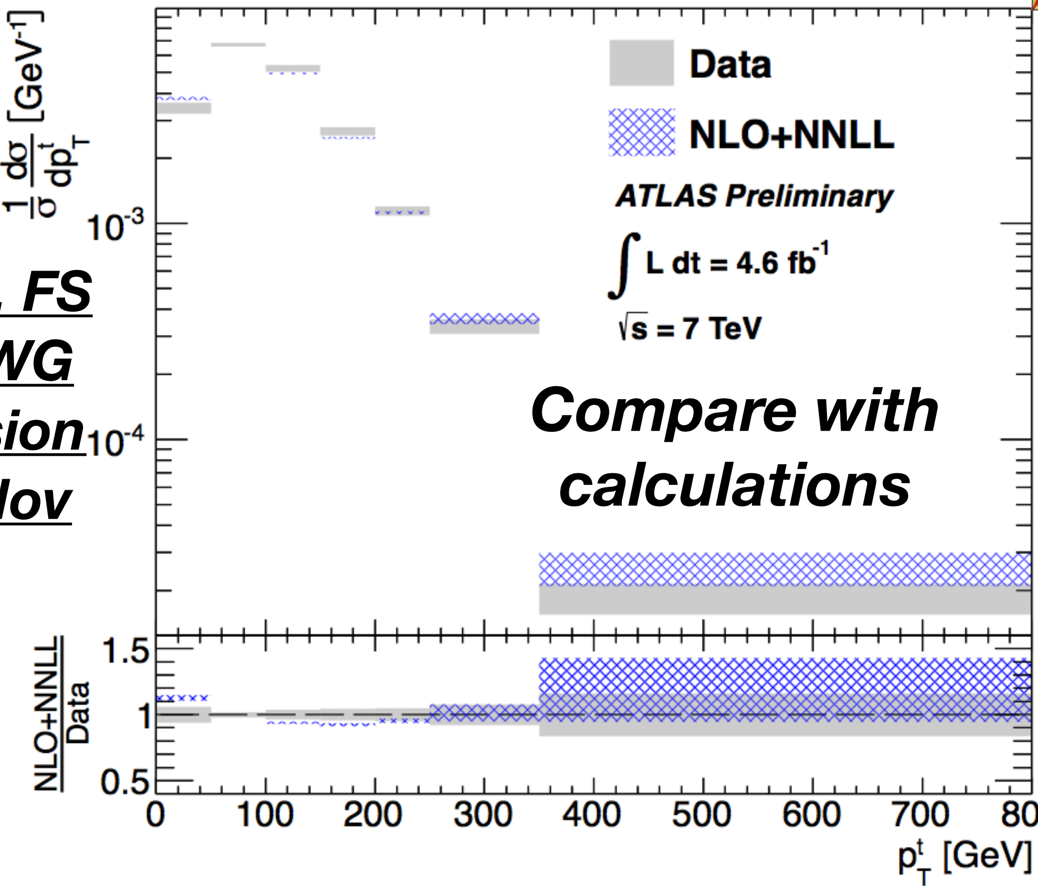
M. Aldaya — TOPLHCWG, 28.11.13 — 4

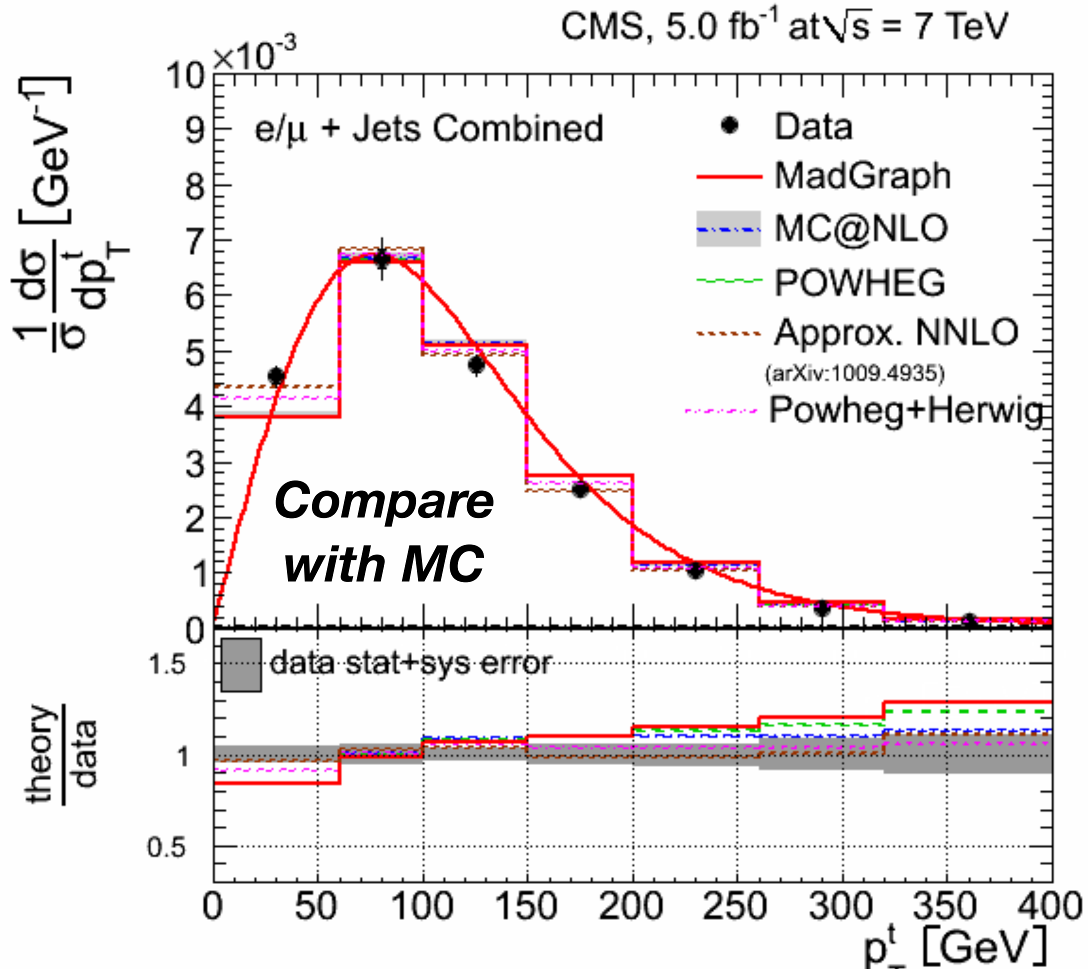
M. Aldaya, FS TOPLHCWG open session 28-29th Nov. 2013

Differential σtt ATLAS & CMS (7 TeV, ℓ+jets) – p_T(top)



M. Aldaya, FS
TOPLHCWG
open session
28-29th Nov 2013

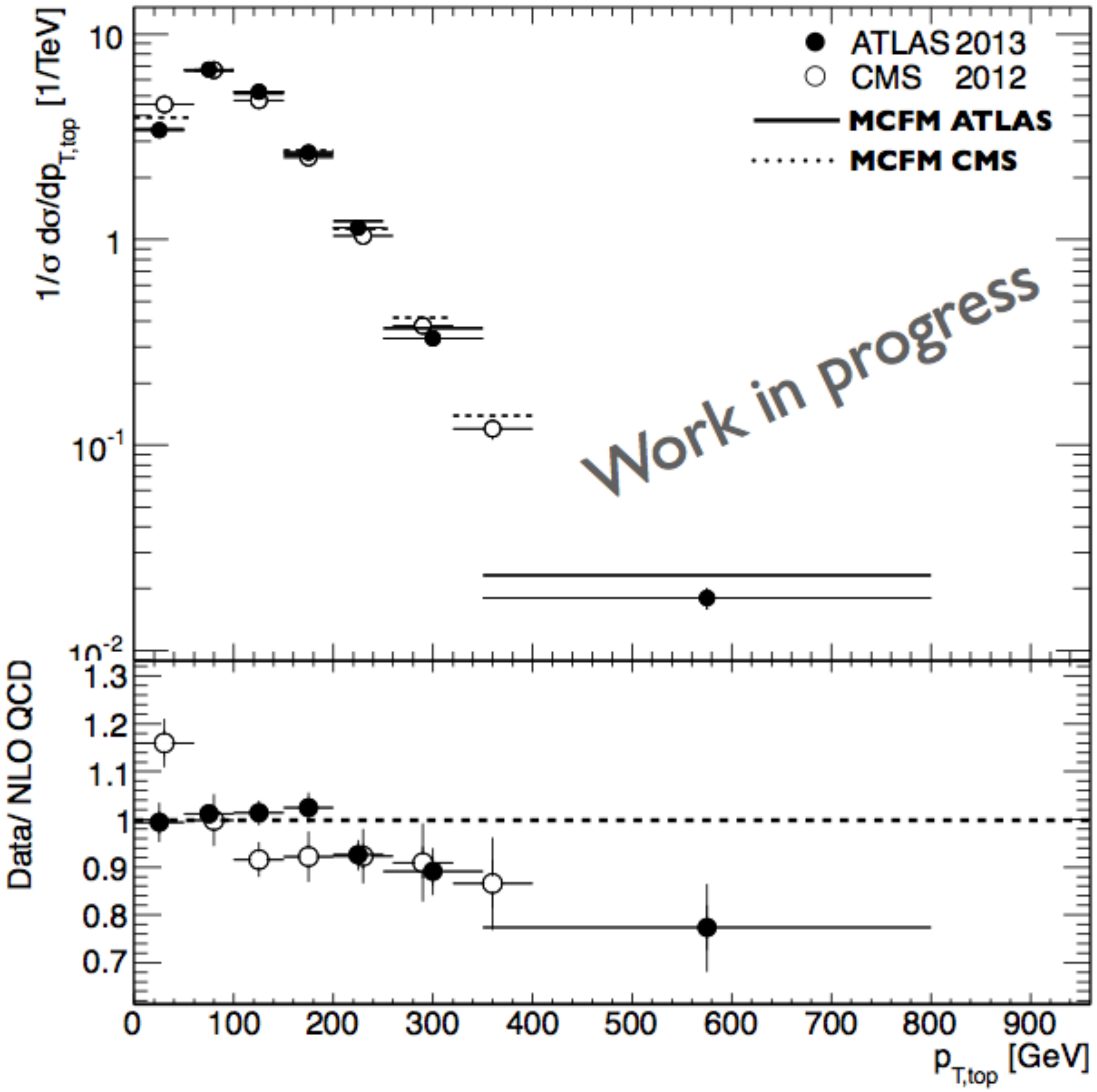




- Powheg+Herwig describes ATLAS & CMS data reasonably well over the full p_T range
- **p_T(top) < 200 GeV: disagreement btw ATLAS & CMS**
  - CMS: softer spectrum in data, best described by Approx. NNLO
  - ATLAS: disagreement with Approx. NNLO
- CMS: Similar behaviour for dileptons, both at 7 & 8 TeV

Differential σ_{tt} ATLAS & CMS (7 TeV, ℓ+jets) – p_T(top)

- First attempt at direct data comparison: data/NLO prediction (MCFM)



p_T(top) < 200 GeV:

- Disagreement between ATLAS & CMS data
- ATLAS result in agreement with MCFM

p_T(top) > 200 GeV:

- Good agreement between ATLAS & CMS data
- ATLAS & CMS in disagreement with MCFM

Results under comparison

M. Aldaya, FS TOPLHCWG open session 28-29th Nov 2013

M. Aldaya 17 TOPLHCWG, 28.11.13

How is combination of results carried out?

The simplest combination: weighted average for uncorrelated meas.

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

for differet distr and known variances

$$w_i = \frac{1}{\sigma_i^2}.$$

essential clues

- Generalized to BLUE

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

- Find linear combination of available measurements x = ∑i wi 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:

$$\sigma_x = \sqrt{\frac{\sigma_1^2\sigma_2^2(1-\rho^2)}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2}}$$

- Likelihood ATLAS-CONF-2012-024

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

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

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

now think about combining differential cross sections..

(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

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{pmatrix}$$

uncertainties on input measurements

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

correlations of uncertainties on input measurements

essential clues

- Output

combined measurement

$$\hat{x} = \sum_{i=1}^{N} w_i x_i$$

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

find set of weights that minimize the variance

- where

$$w = M^{-1}U/(U_T M^{-1}U)$$

method of Lagrangian multipliers

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(\hat{x}-x_i)(\hat{x}-x_j)M_{ij}^{-1}$$

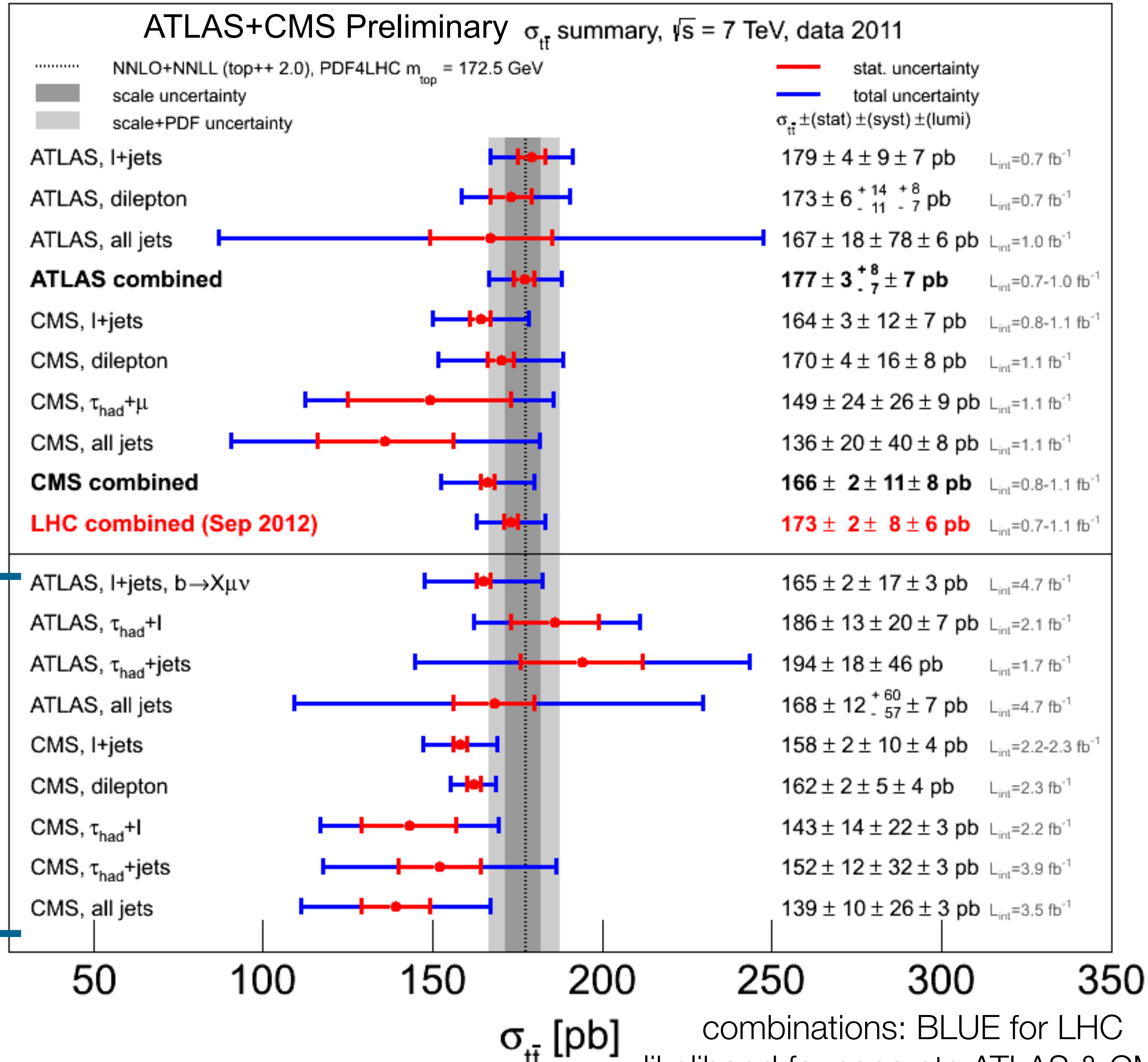
equivalent to χ^2 method

Sept 18, 2012 E.Shabalina -- TOP 2012 5

Summary of LHC σ($t\bar{t}$) results @ 7 TeV

Using
m_{top} = 172.5 GeV
as a temporary fix until experiments provide parametrisation for the mass dependence

New or updated measurements, not included in current LHC combination



combinations: BLUE for LHC
likelihood for separate ATLAS & CMS

Plan for future combinations:

- Provide LHC combination at 7 TeV with updated results

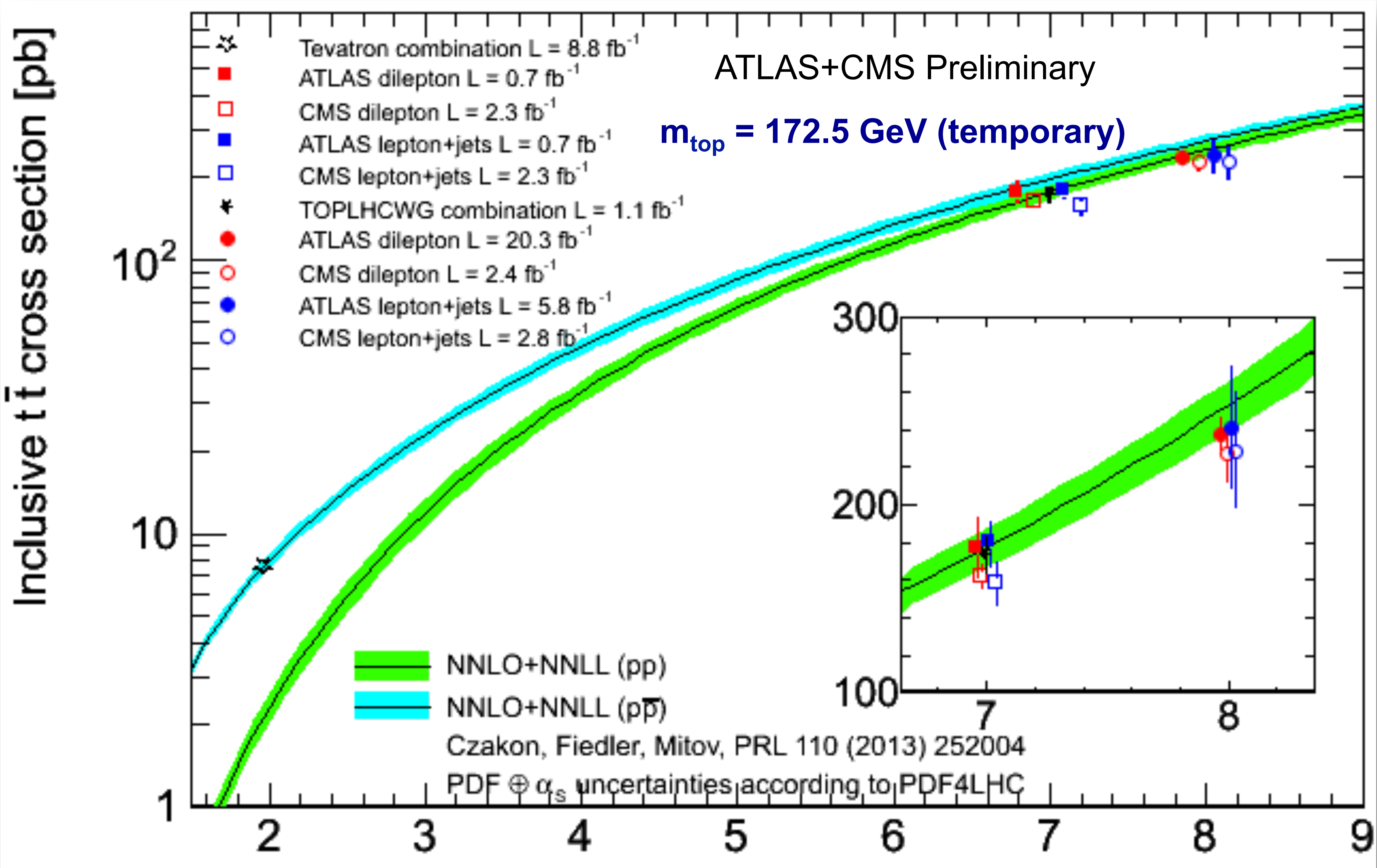
- Combine 8 TeV results as soon as updated CMS measurement is released

M. Aldaya

M Aldaya, J Ferrando, TOPLHCWG 28th-29th Nov 2013

TOPLHCWG, 28.11.13

σ($t\bar{t}$) as a function of √s



M Aldaya, J Ferrando, TOPLHCWG 28th-29th Nov 2013

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 exp in another's
    - ❖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.

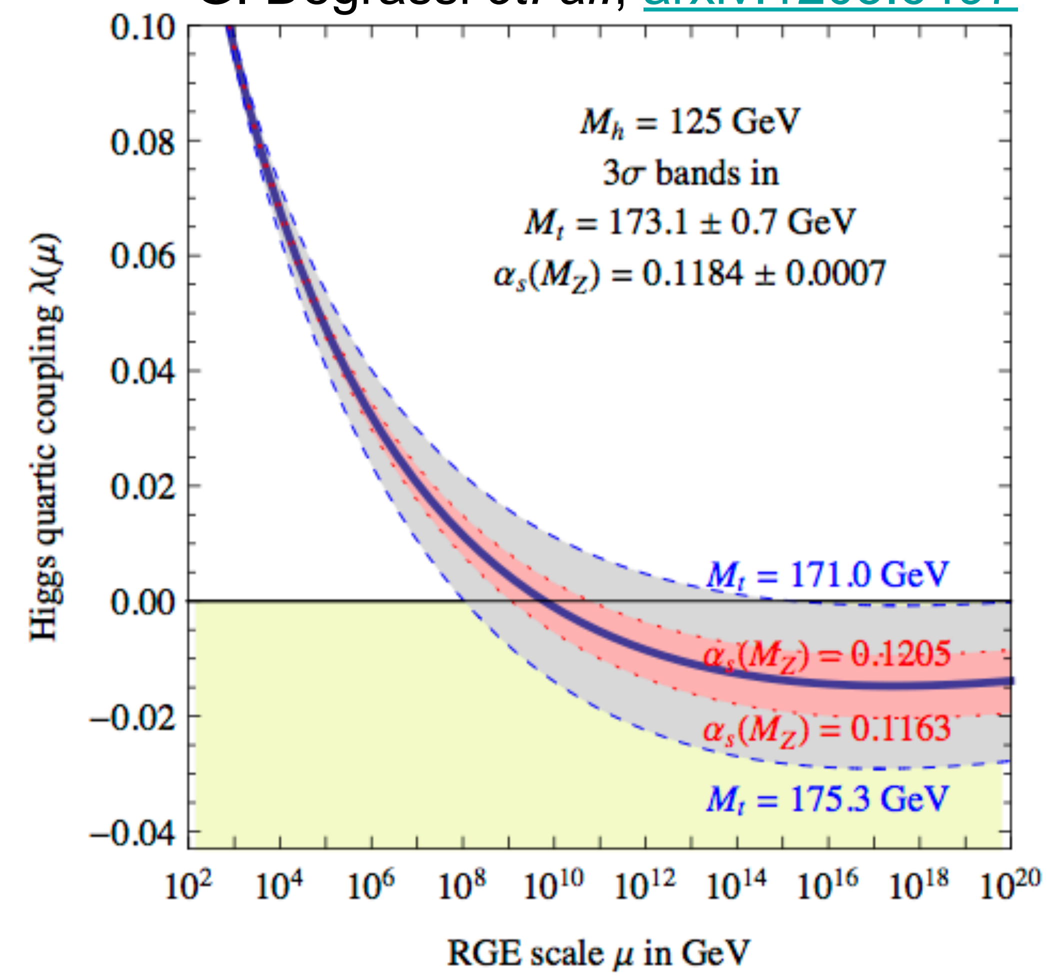
the defining property

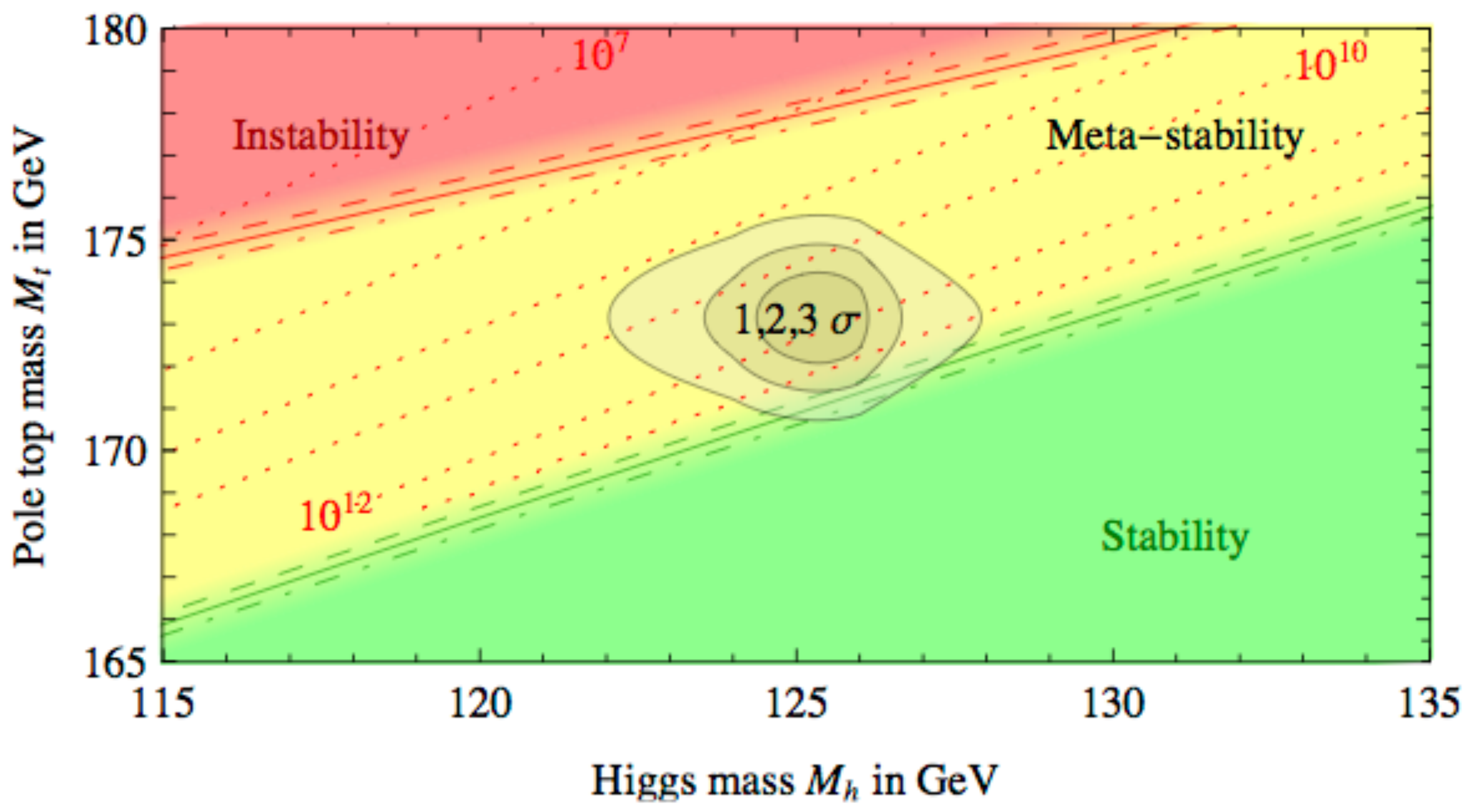
Higgs potential stability

- 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



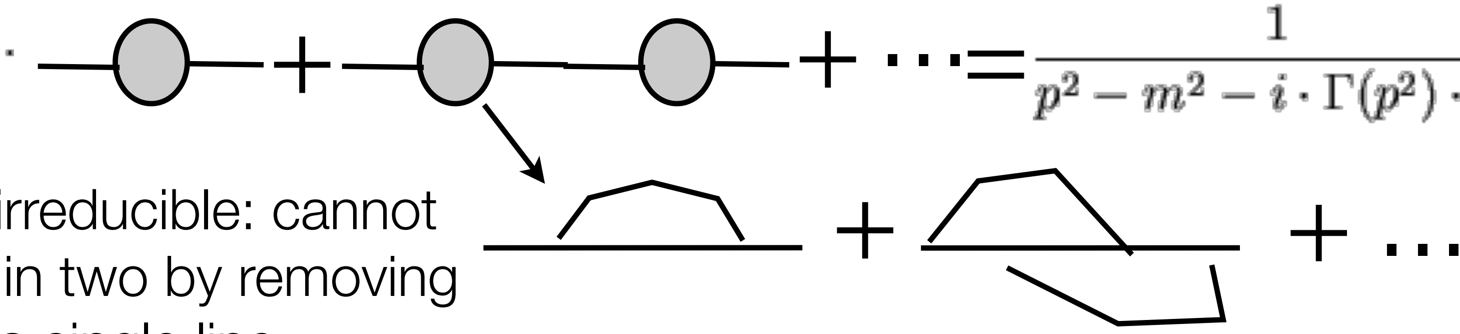


- Even in the absence of direct evidences for new physics at the LHC, the experimental information on m_H and m_{top} gives us useful hints on the structure of the theory at very short distances
- Renewed interest for precision m_{top} measurements

What is top mass and how is it measured?

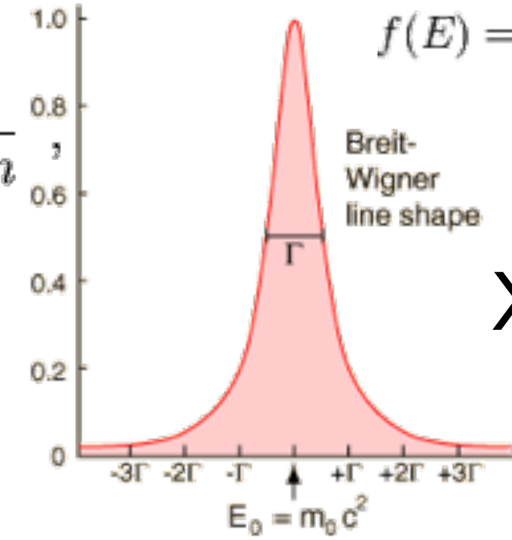
propagator to amplitude: higher order corrections

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



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

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



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

X Detector

Definition

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

Techniques

essential clues

- Variety of techniques: **compare a predicted shape with measured. Calculate likelihood of sample as a function of top mass**: distance "measured" by likelihood.
  - template method, ideogram method, matrix element..

Top specific! ***Uncertainties***

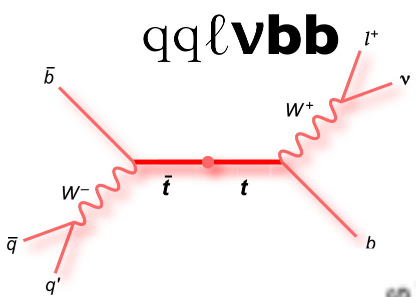
- Systematics dominated : mostly jet & theory related
- Precision measurement: detailed understanding of each uncertainty develop techniques to constrain uncertainty from data or make analysis less sensitive or insensitive

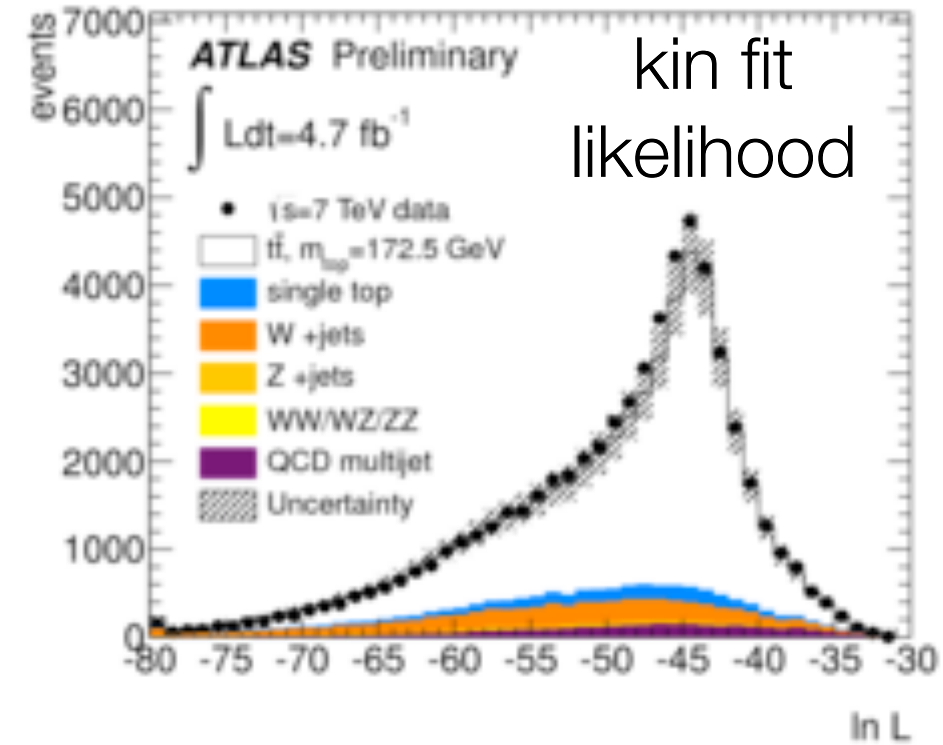
Measuring top mass

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

ATLAS-CONF-2013-046

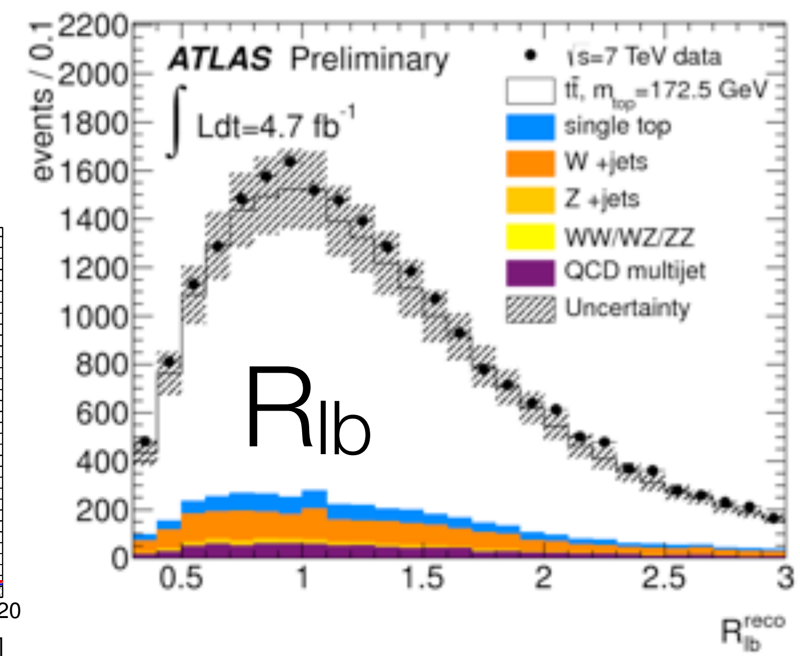
- **Standard single lepton selection**
  - *good quality objects, 1 lepton, cuts on E_T, m_T^W, ≥4 jets, at least 1 b-tagged jet*
  - *channel dep analytic shape for bkg,*
  - *W+jets and QCD from data*



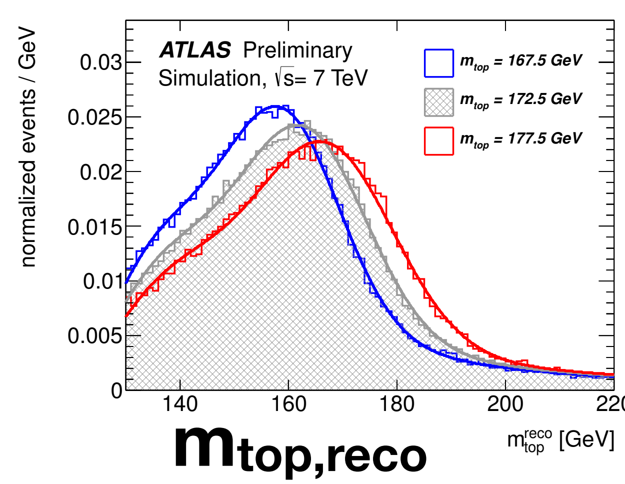


- **Reconstruct m_{top}-sensitive variables Reconstruct LO tt picture with kinematic likel. fit** *($m_{top,HAD}$= $m_{top,LEP}$ + weight for b/mis-tag ,m_W constraint)* → assign jets
  - **$m_{top,reco}$ from fit-assigned & constrained jets**
  - **$m_{W,reco}$ from fit-assigned but unconstrained jets**
  - **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



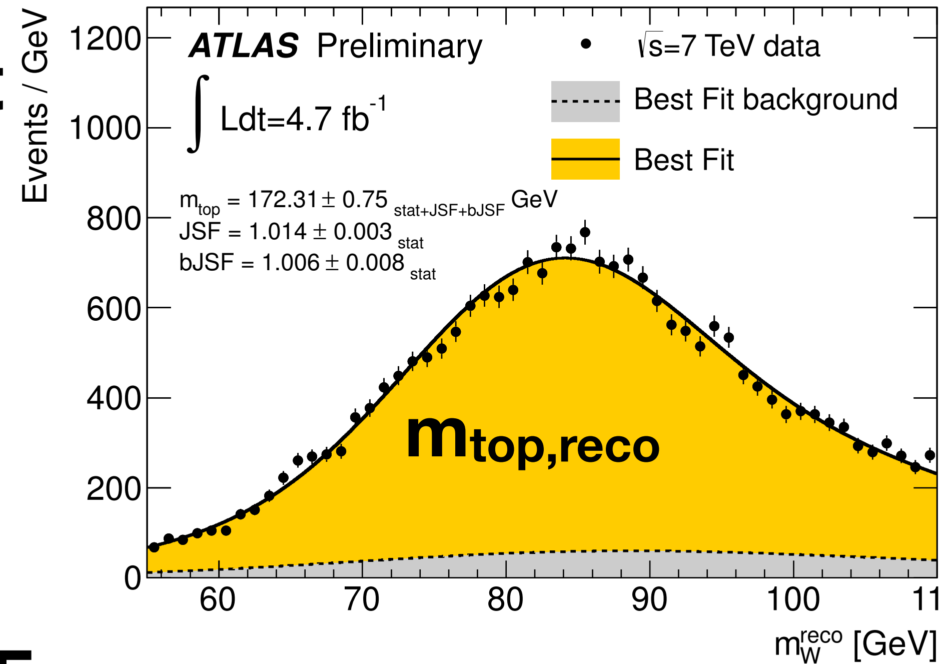
- *Jet energy scale is crucial: different reduction*

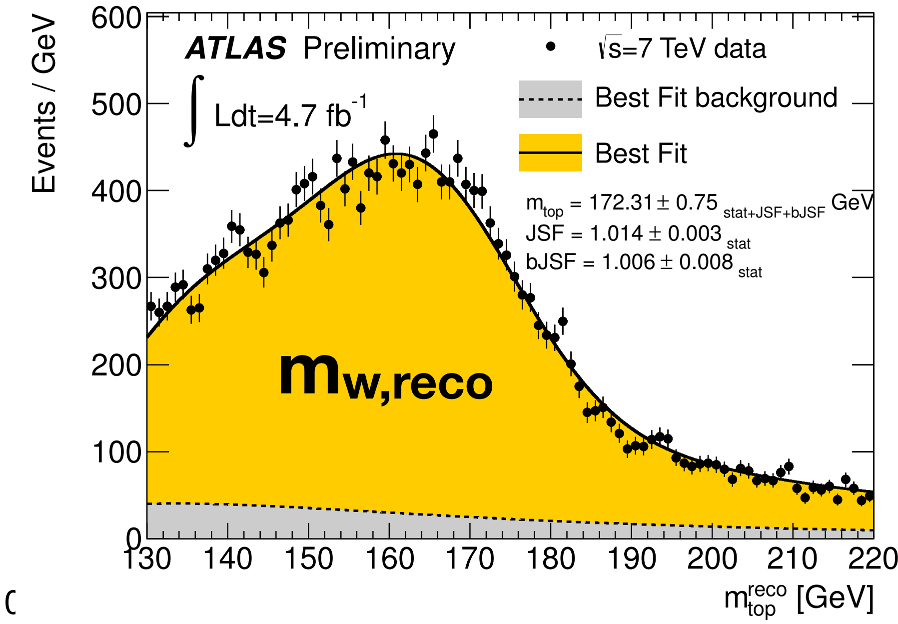
Measuring top mass

$\int Ldt$ = **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**

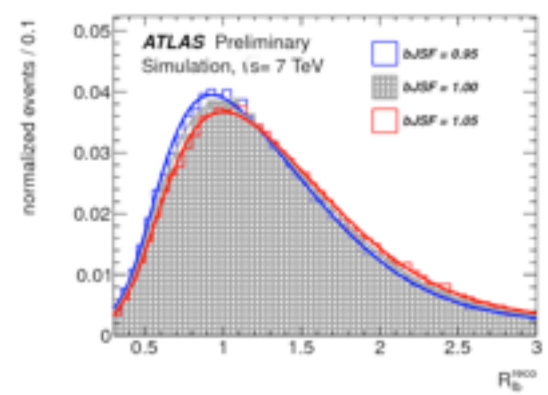


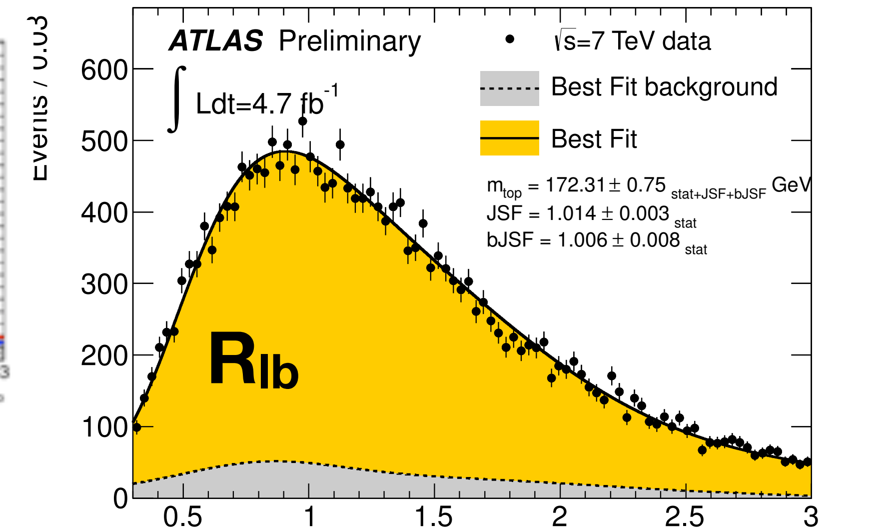


Template dependence

- **$m_{top,reco}$: 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*

$$m_t = 172.31 \pm 0.75(\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35(\text{syst})\text{GeV}$$
$$\text{JSF} = 1.014 \pm 0.003(\text{stat}) \pm 0.021(\text{syst})$$
$$\text{bJSF} = 1.006 \pm 0.008(\text{stat}) \pm 0.020(\text{syst})$$

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)

- 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

set b-JES to 1

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
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

reduced

reduced

reduced

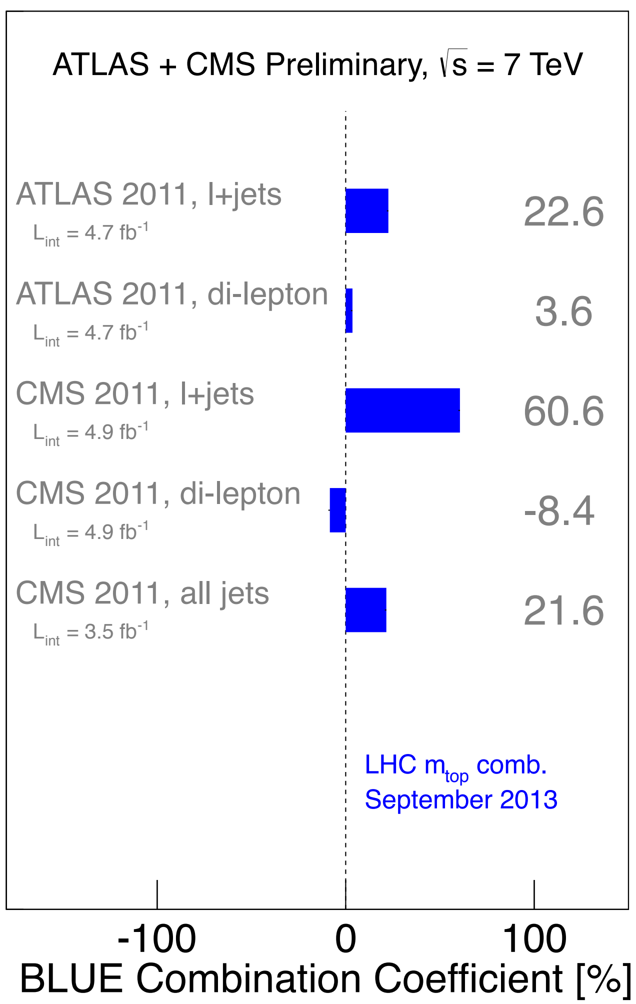
reduced

Combined m_{top} @ LHC (Oct 2013): use BLUE

from fit of $m_{w,rco}$ $m_{top,reco}$ $R_{l,b}$

sample size, detector, pile-up, close-by

from γ/Z, di-jets, multi-jets



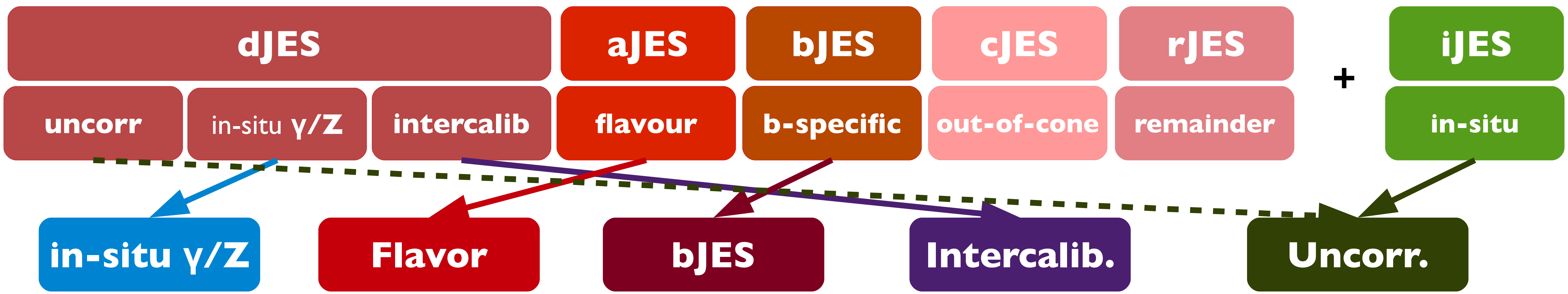
ATLAS-CONF-2013-102

	ATLAS comb.	CMS comb.	LHC comb.
Measured m_{top}	172.65	173.59	173.29
iJES	0.41	0.27	0.26
uncorrelated JES comp.	0.66	0.32	0.29
in-situ JES comp.	0.30	0.08	0.10
intercalib. JES comp.	0.28	0.02	0.07
flavour JES comp.	0.21	0.19	0.16
b-jet energy scale	0.35	0.56	0.43
Monte Carlo simulation	0.40	0.06	0.14
Radiation modelling	0.42	0.28	0.32
Colour reconnection	0.31	0.48	0.43
Underlying event	0.25	0.17	0.17
Proton PDF	0.15	0.07	0.09
Detector modelling	0.22	0.25	0.20
b-tagging	0.66	0.11	0.25
Lepton reconstruction	0.07	0.00	0.01
Background from MC	0.06	0.10	0.08
Background from Data	0.06	0.03	0.04
Method	0.08	0.07	0.06
Multiple Hadronic Interactions	0.02	0.06	0.05
Statistics	0.31	0.29	0.23
Systematics	1.40	0.99	0.92
Total Uncertainty	1.43	1.03	0.95

- **Systematics dominated:** *(b)JES, signal model(CR, radiation), b-tagging*

Most relevant correlations: JES

- **Correlation of JES between ATLAS and CMS is split into four groups:**

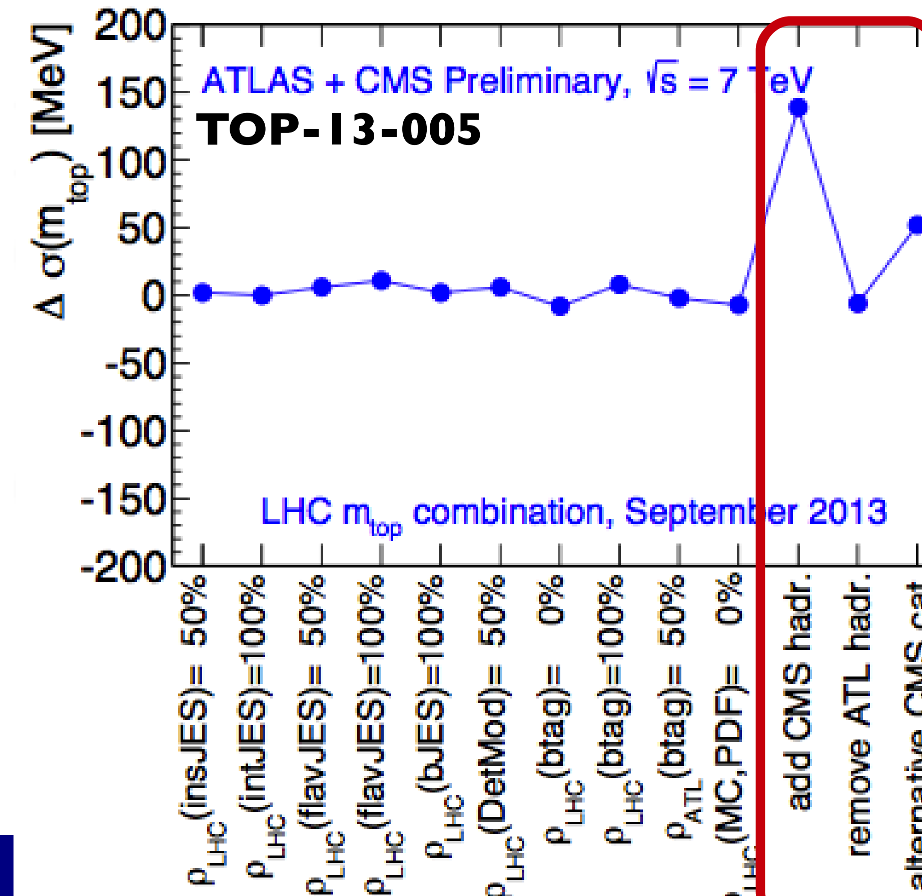


in-situ γ/Z	Flavor	bJES	Intercalib.	Uncorr.
$\rho_{exp}=1$, $\boldsymbol{\rho_{LHC}=0}$ vary 0 → 0.5	$\rho_{exp}=1$, $\boldsymbol{\rho_{LHC}=0}$ vary 0 → 1	$\rho_{exp}=1$, $\boldsymbol{\rho_{LHC}=0.5}$ vary 0.5 → 1.0	$\rho_{exp}=1$, $\boldsymbol{\rho_{LHC}=0.5}$ vary 0.5 → 1	$\rho_{exp}=0$ or 1, $\boldsymbol{\rho_{LHC}=0}$

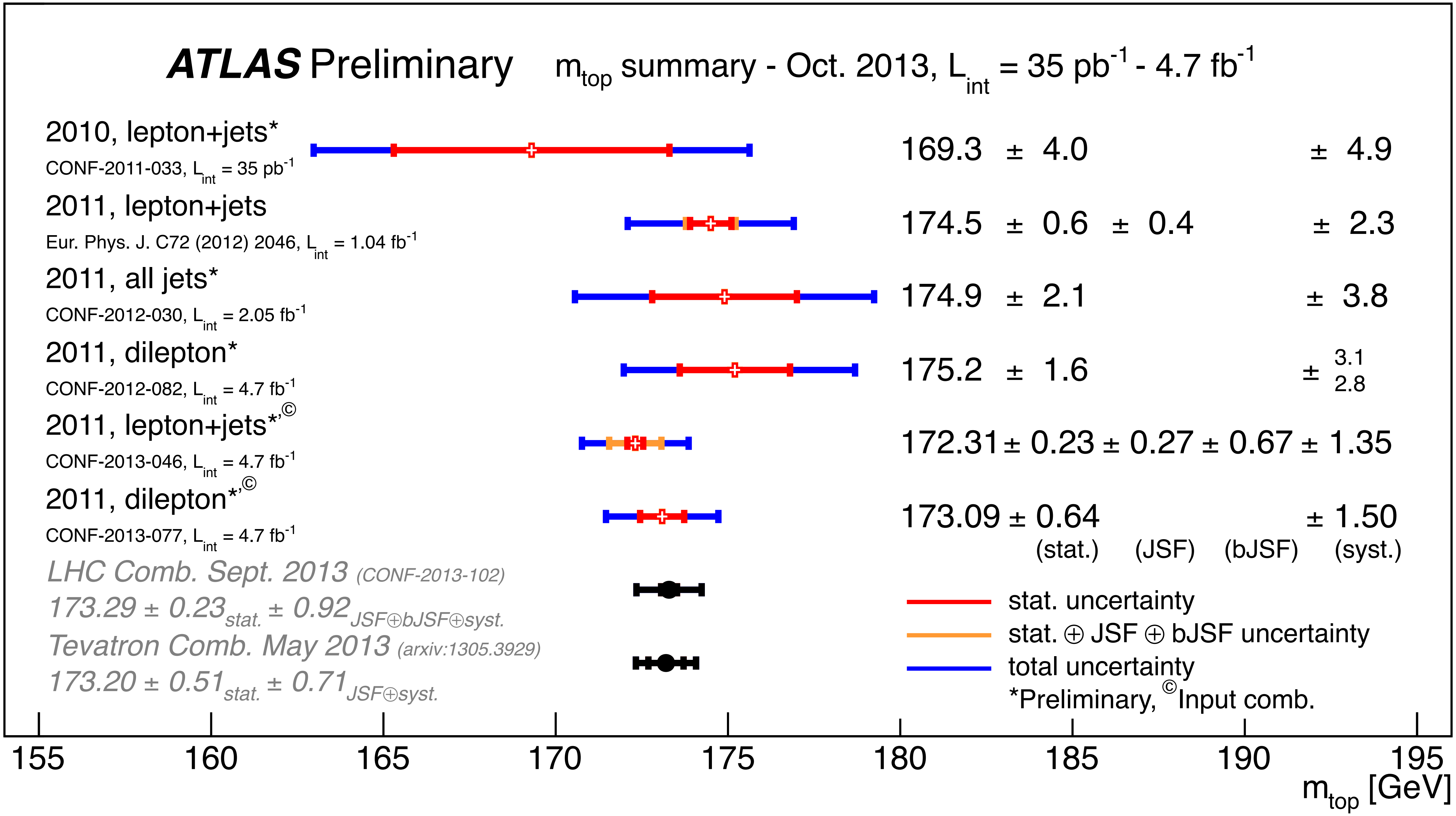
- Robust combination with respect to most variations ▶

- **Three additional cross-checks:**
  - add ttbar-specific hadronization uncertainty in CMS measurements comparing Powheg Pythia vs Herwig
  - remove ATLAS tt-specific hadronization
  - re-categorize CMS bJES uncertainty varying b-fragmentation, semi-leptonic BR, hadronization model

(P. Silva, TOP2013)



Status/history on m_{top}



bJSF has stat nature relative to in-situ JES calib

Sept 2013 combinations

ATLAS	$172.65 \pm 0.31_{stat} \pm 1.40_{(b)JSF\oplus\, syst}$
CMS	$173.59 \pm 0.29_{stat} \pm 0.99_{JSF\oplus\, syst}$
LHC	$\mathbf{173.29 \pm 0.23_{stat} \pm 0.92_{JSF\oplus\, syst}}$

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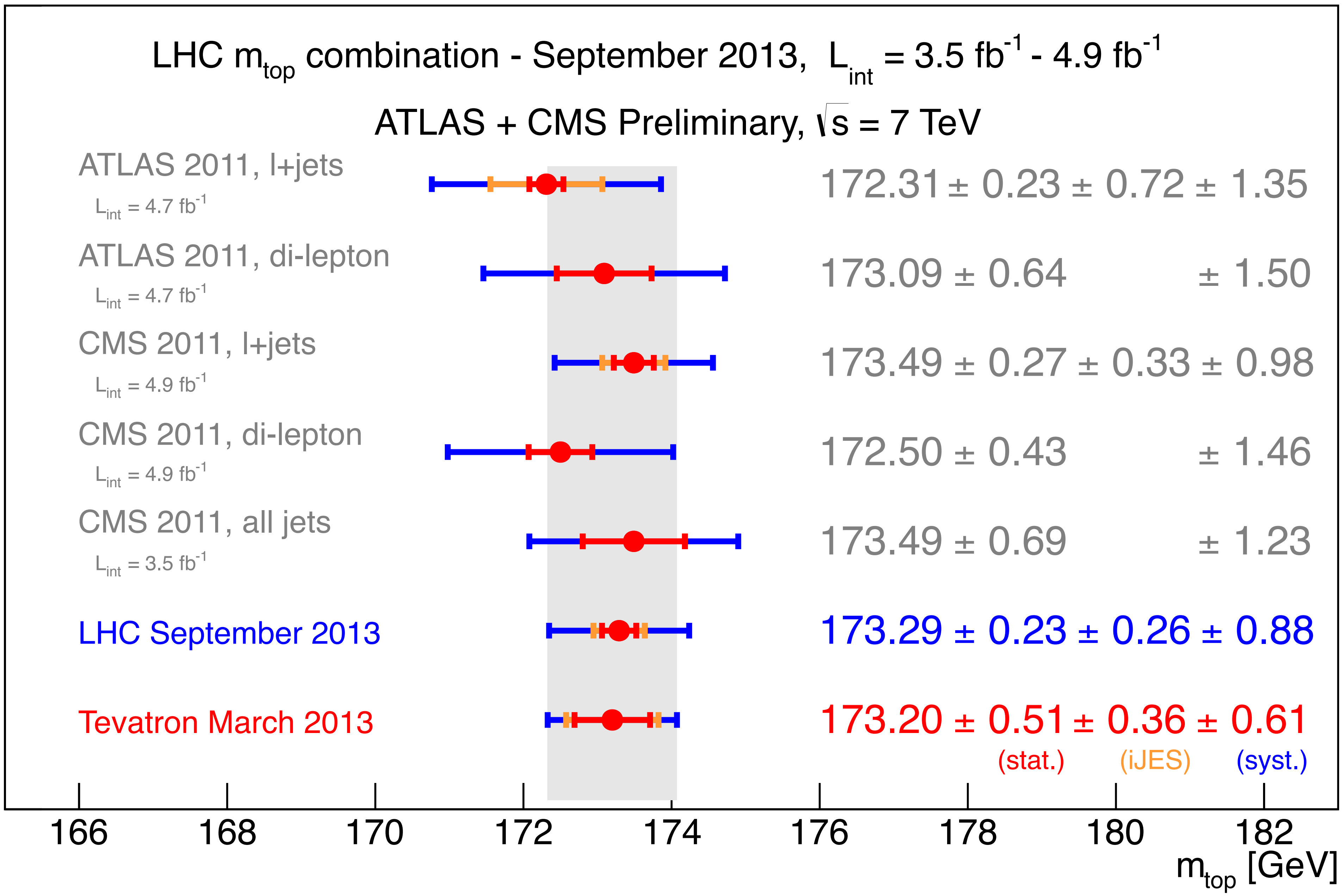
CMS-PAS-TOP-13-005

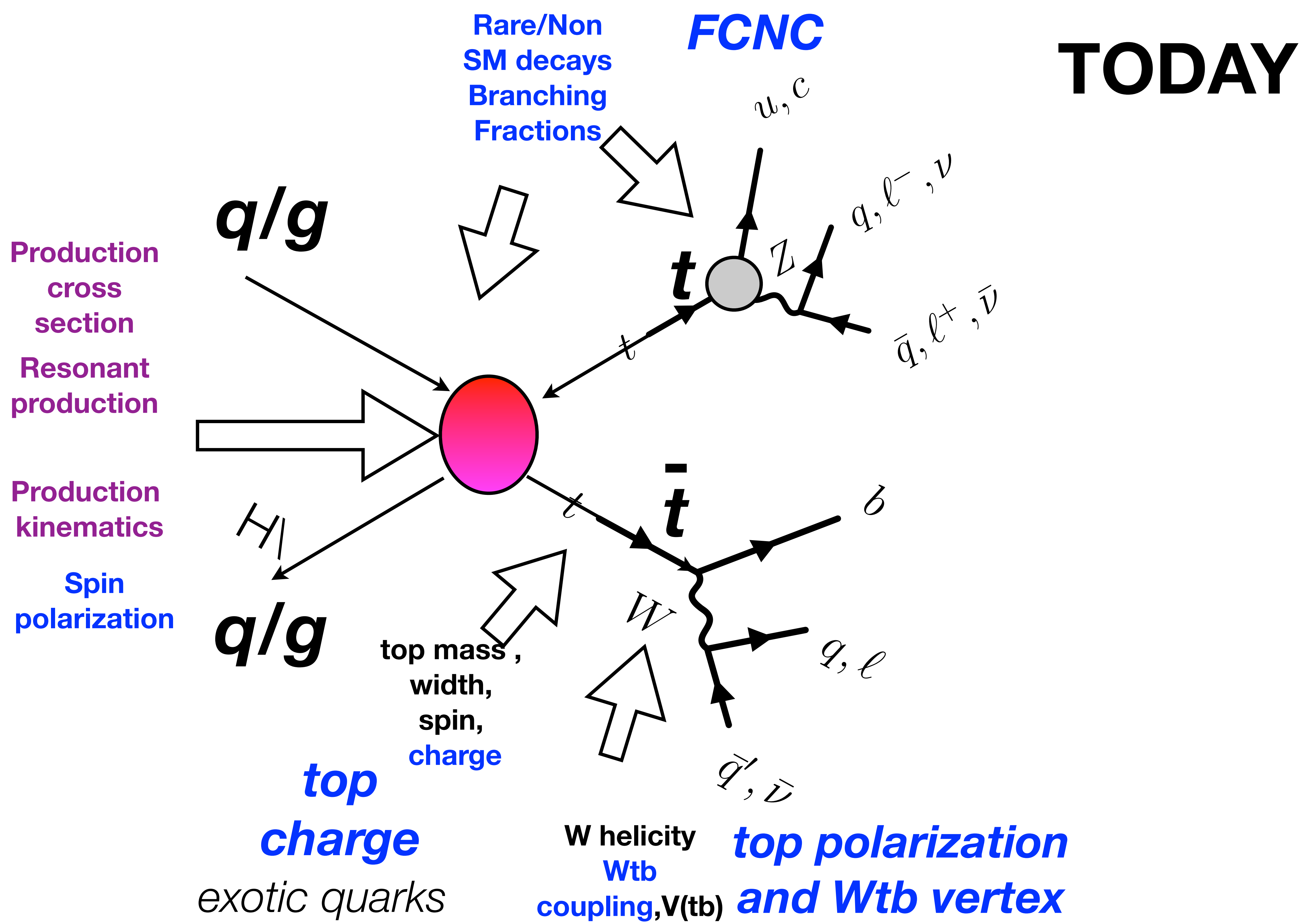
m_{top} @ LHC (Oct 2013)



ATLAS-CONF-2013-102

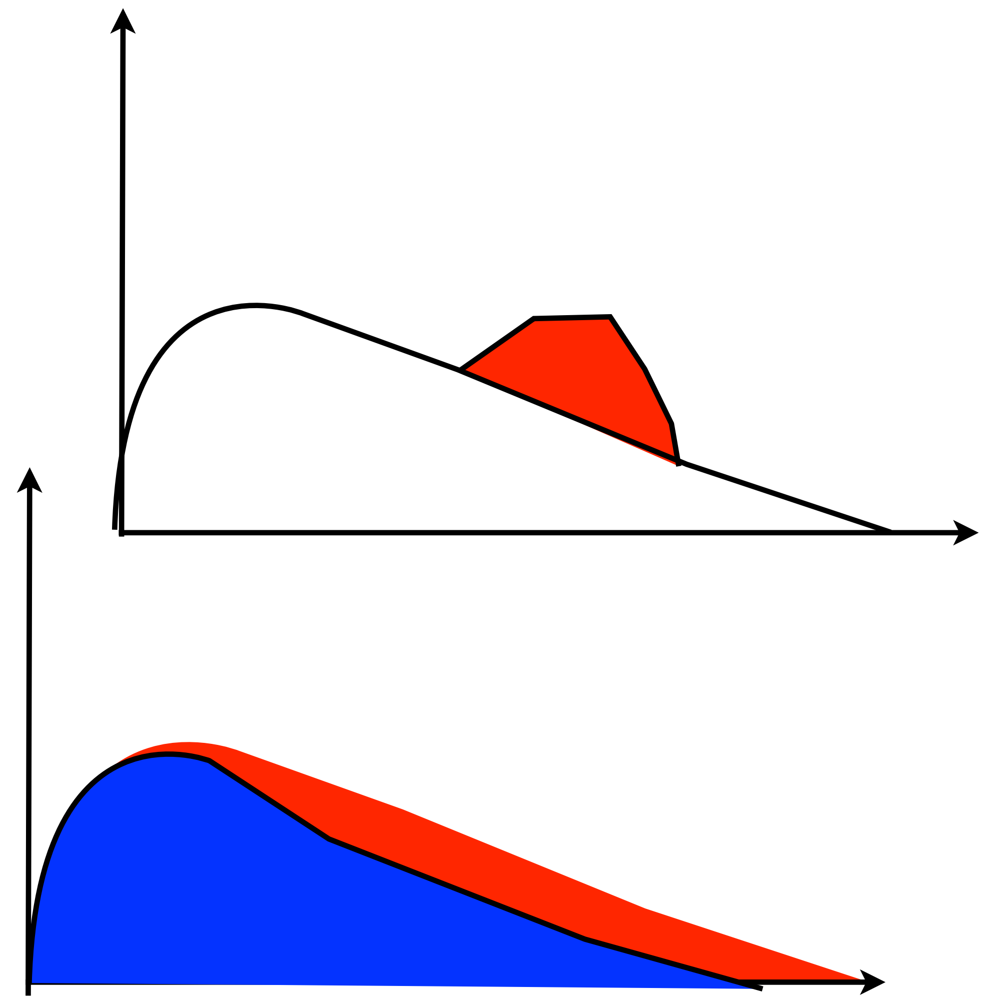
Top quark as a window on new physics

inspired by figure
by D Chakraborty



i.e.
Beyond the Standard model

Top and BSM



- Searches look for **deviations from SM**
  - **direct enhancements**
  - **indirect shape distortions**

Top Specific

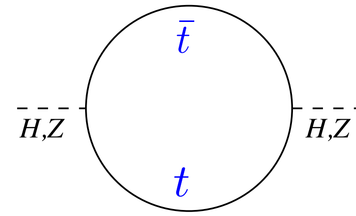
- Understanding **bkg is crucial** to claim deviation:
  - **Top pair or single top events are usually the main background**
  - Special regions of phase space: **require new reconstruction** and **recognition schemes**
- Statistical treatment need to determine limits. Systematics & correlations broadly reduce significance of observation

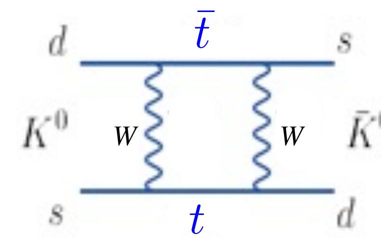
Top and BSM: a "natural" view

Standard Model (SM): top coupling to Higgs is perturbative but LARGE: $y_t \simeq 1$

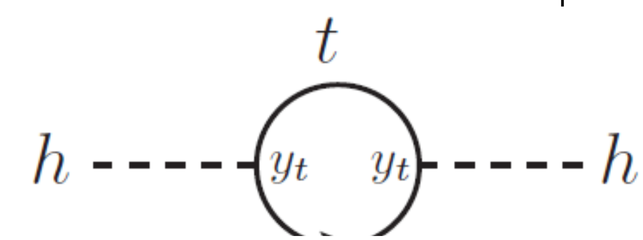
Quantum effects (virtual tops) => dramatic impact on EW & flavor phys.: $\frac{2N_c\, {y_t}^2}{16\pi^2} \simeq 5\%$

(Gilad Perez, CKM2012)





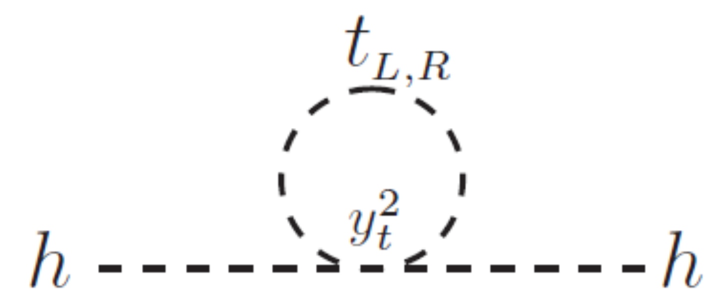
Higgs mass has quantum corrections



(Gian Giudice: arXiv 1307.7879)

$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \mathrm{GeV}}\right)^2$$

top quark has largest contrib $\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$



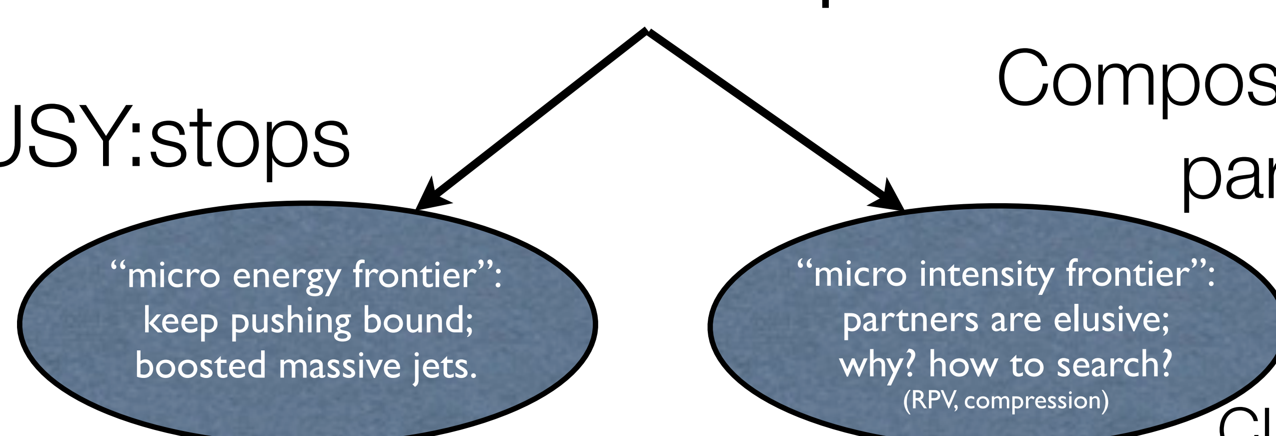
UV corrections from particles coupling to HIggs are additive and uncorrelated with M_h so scale is about 500 GeV they are larger than M_h

If naturalness is a guide: need top partners to keep mh stable

LHC8: where are the partners ⁇

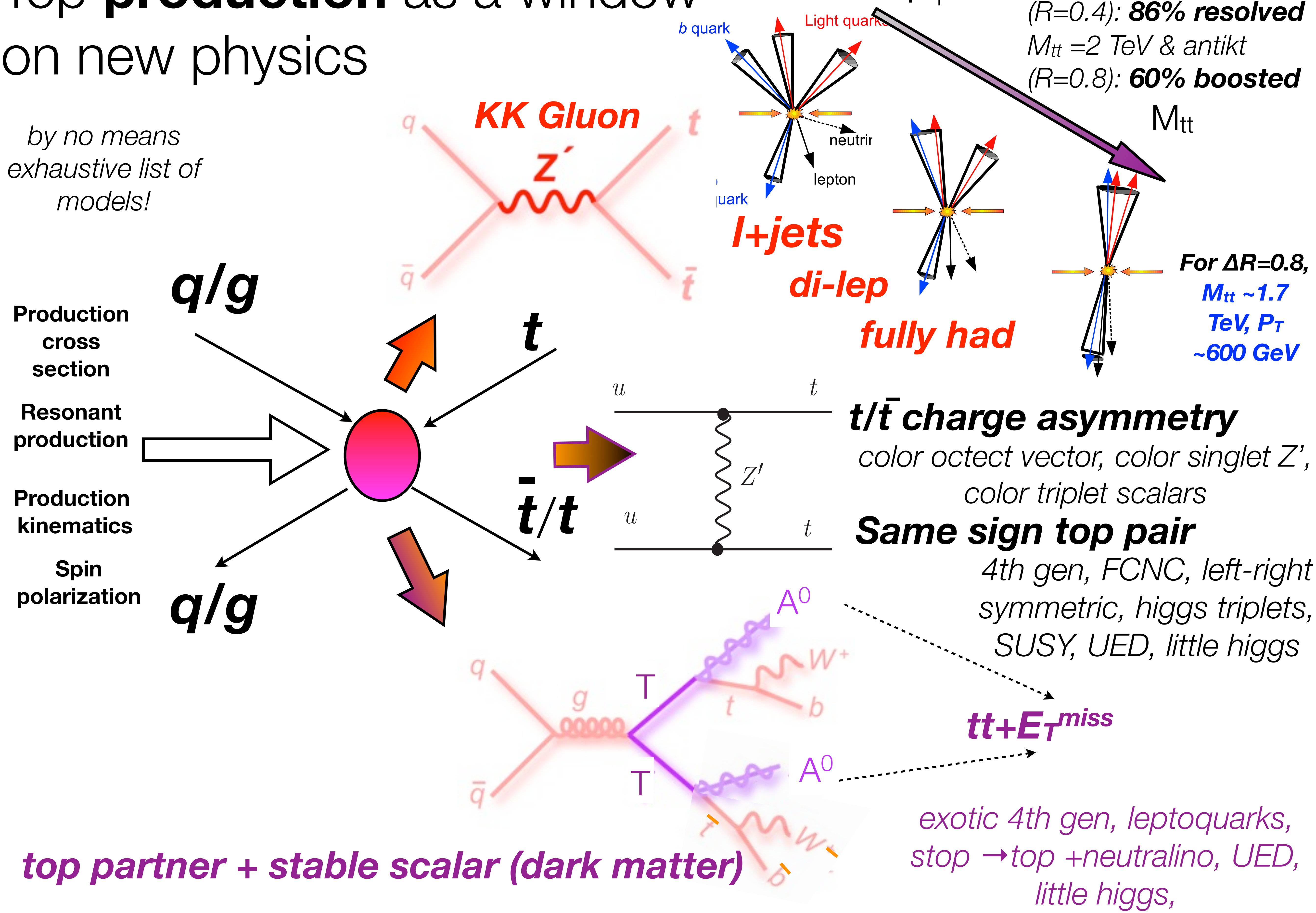
SUSY:stops

Composite Higgs:T partners

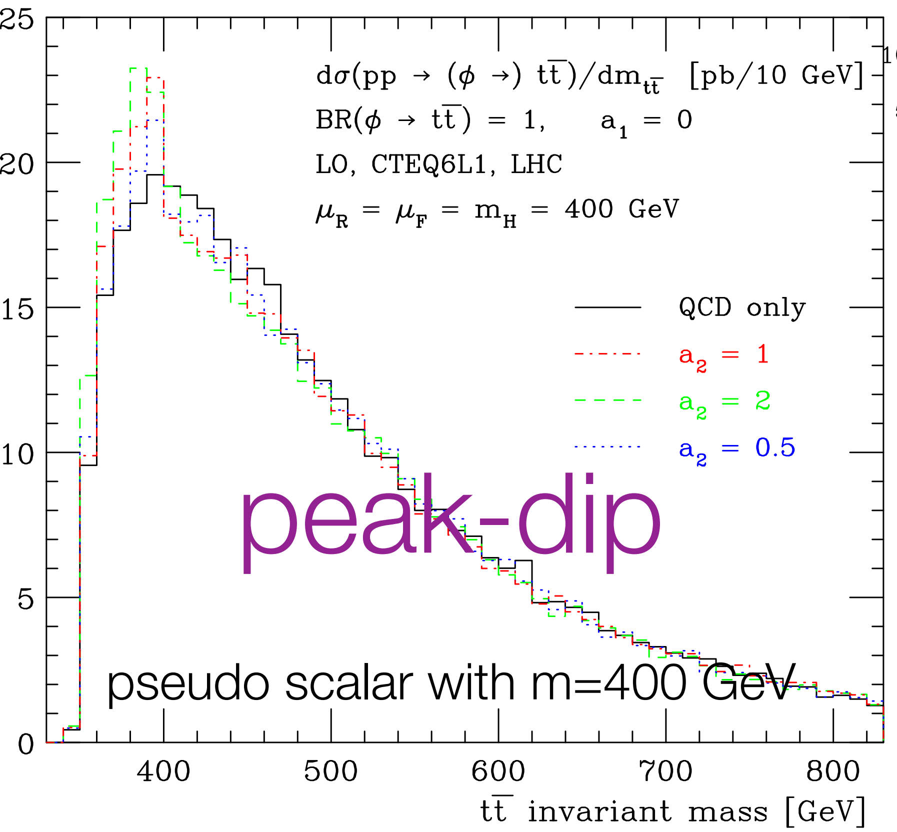


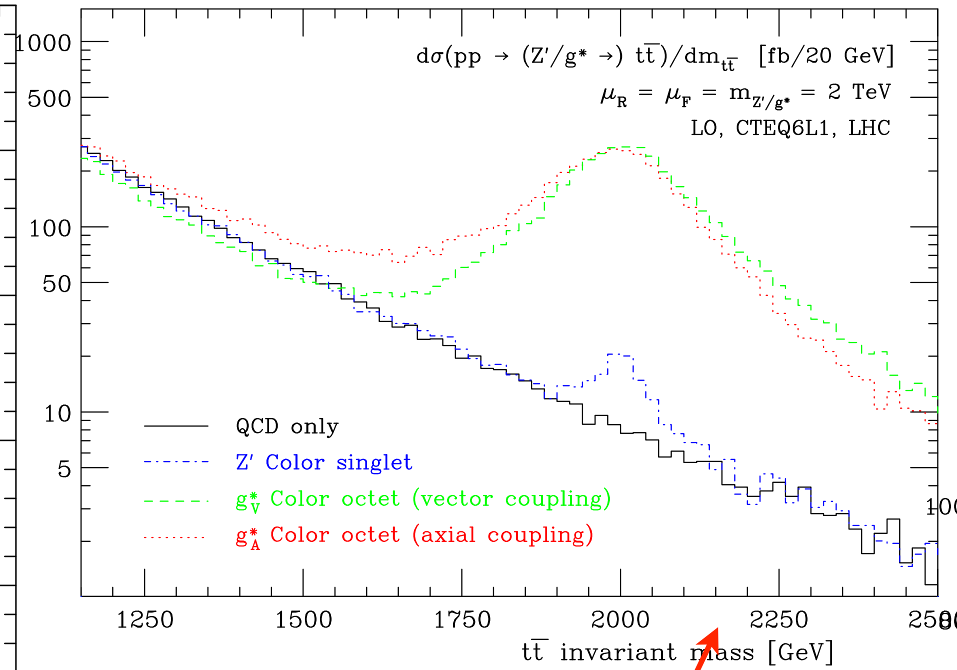
(figure from Gilad Perez, CLICMeeting, Oct2013)

Top **production** as a window on new physics



Example: new phys in ttbar mass





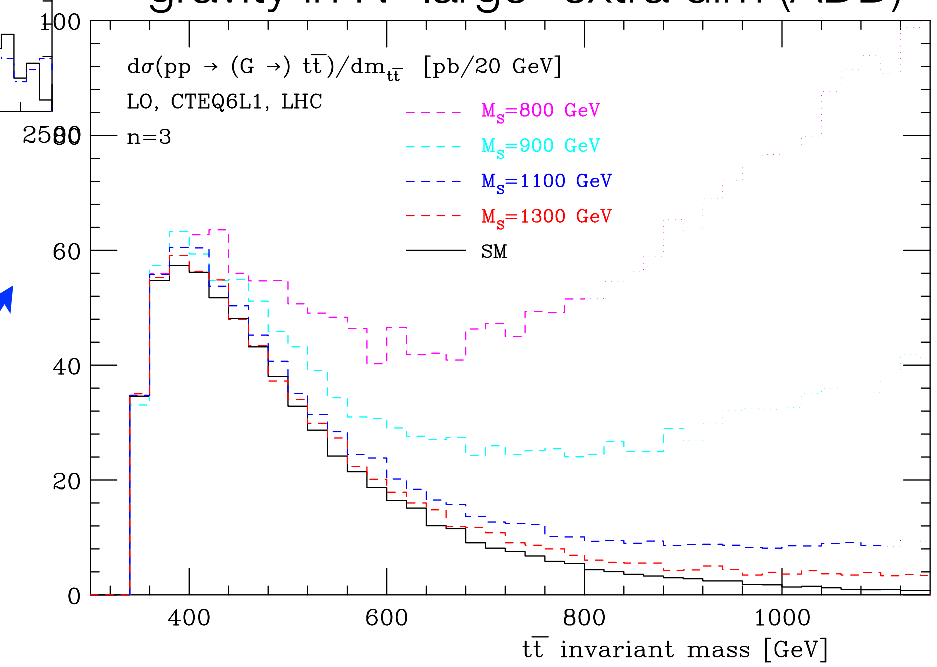
one peak

Z' or

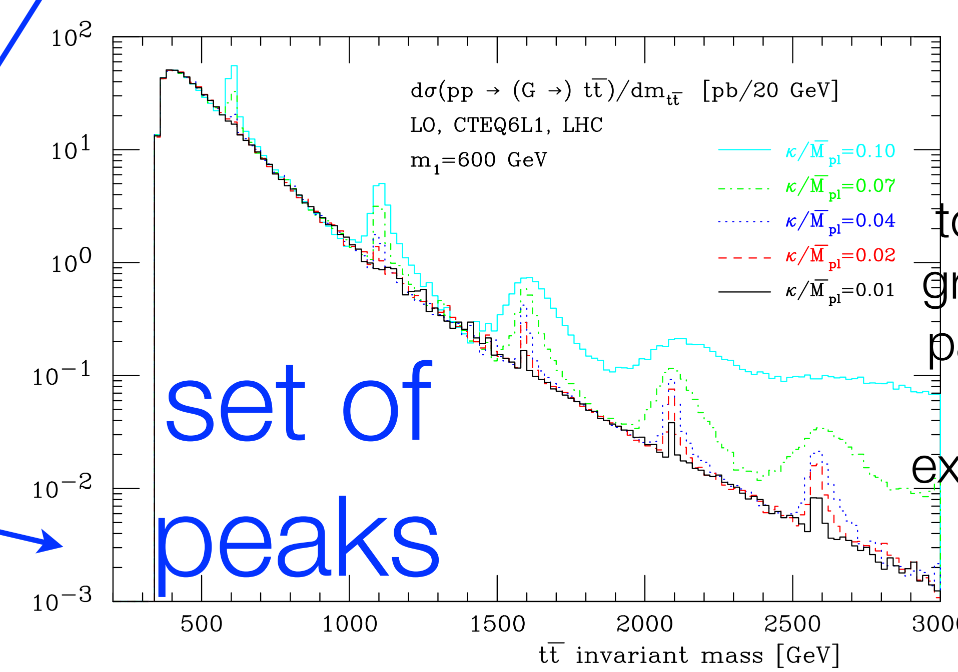
new strong bosons

enhancements

tower of degenerate KK gravitons ; only gravity in N “large” extra dim (ADD)



Spin	color	parity $(1,\gamma_5)$	some examples/Ref.
0	0	(1,0)	SM/MSSM/2HDM, Ref. [51, 52, 53]
0	0	(0,1)	MSSM/2HDM, Ref. [52, 53]
0	8	(1,0)	Ref. [54, 55]
0	8	(0,1)	Ref. [54, 55]
1	0	(SM,SM)	*Z′*
1	0	(1,0)	vector
1	0	(0,1)	axial vector
1	0	(1,1)	vector-left
1	0	(1,-1)	vector-right
1	8	(1,0)	coloron/KK gluon, Ref. [56, 57, 58]
1	8	(0,1)	axigluon, Ref. [57]
2	0	–	graviton “continuum”, Ref. [17]
2	0	–	graviton resonances, Ref. [18]



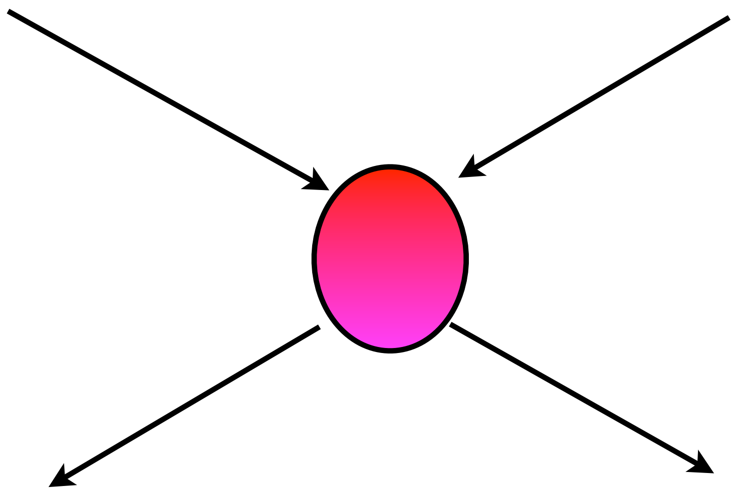
tower of KK gravitons ; all particles in 1 “warped” extra dim (RS)

arxiv:0712.2325

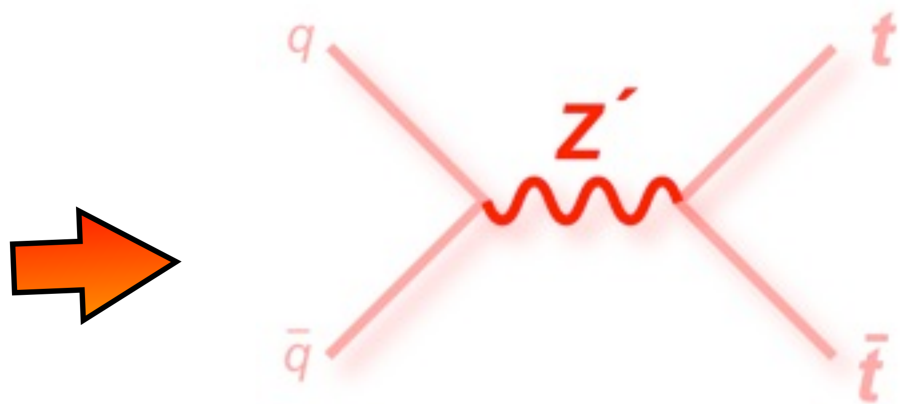
The emergence of boosted tops

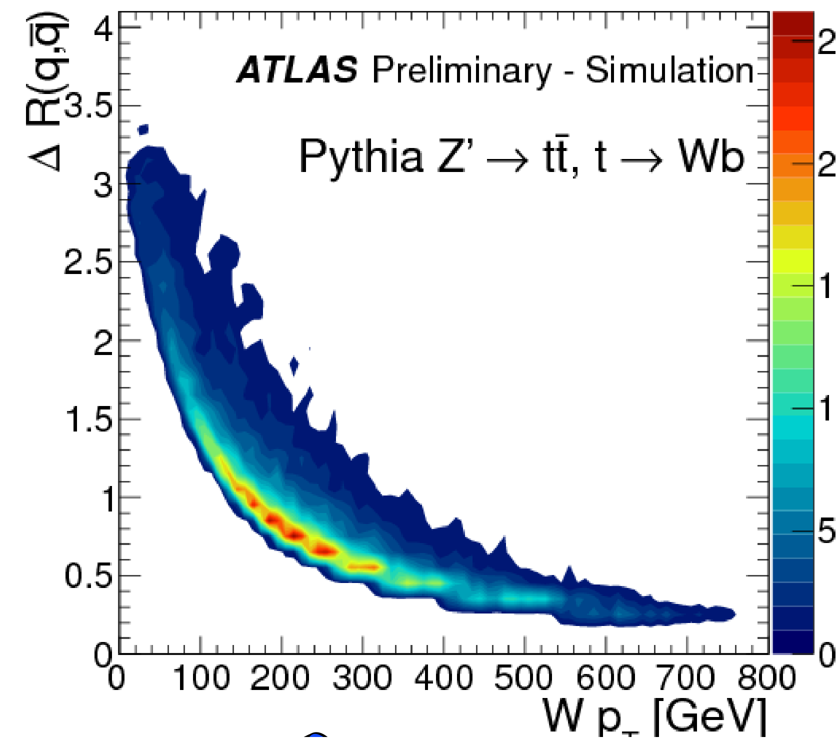
ATLAS-CONF-2012-065

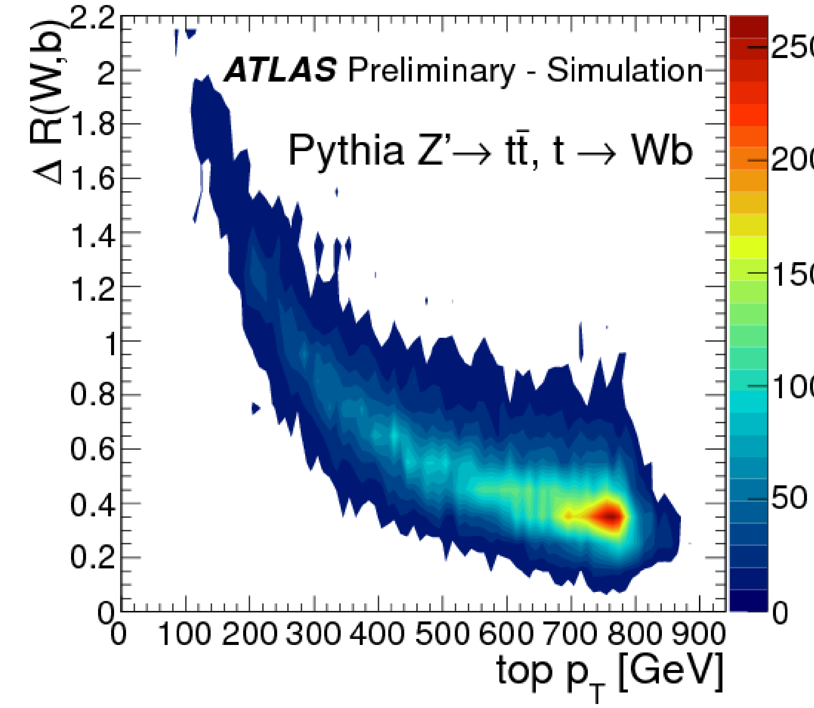
q/g



q/g



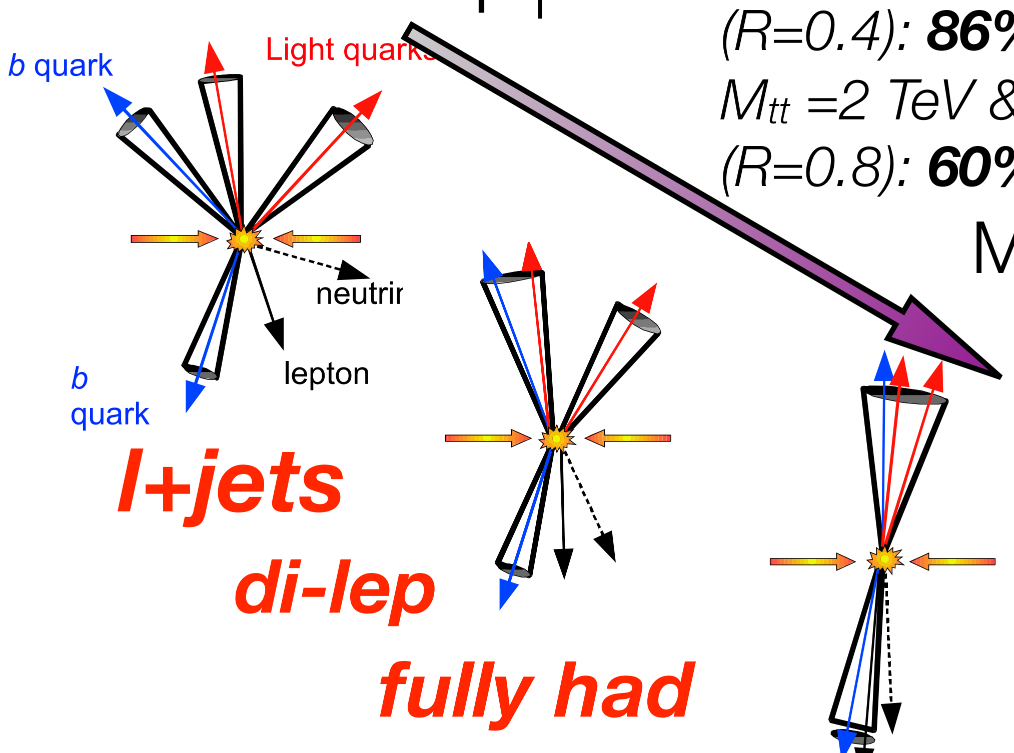




P_T^{Top}

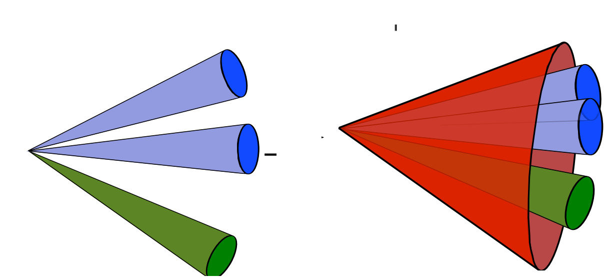
M_{tt} =1 TeV & anti-k_T (R=0.4): ***86% resolved***

M_{tt} =2 TeV & antikt (R=0.8): ***60% boosted***



For ΔR=0.8, M_{tt} ~1.7 TeV, P_T ~600 GeV

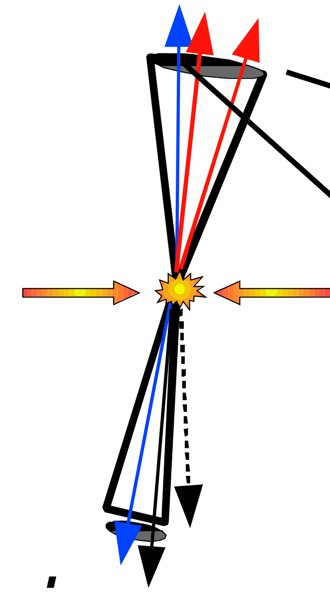
$\Delta R = 2m/p_T$

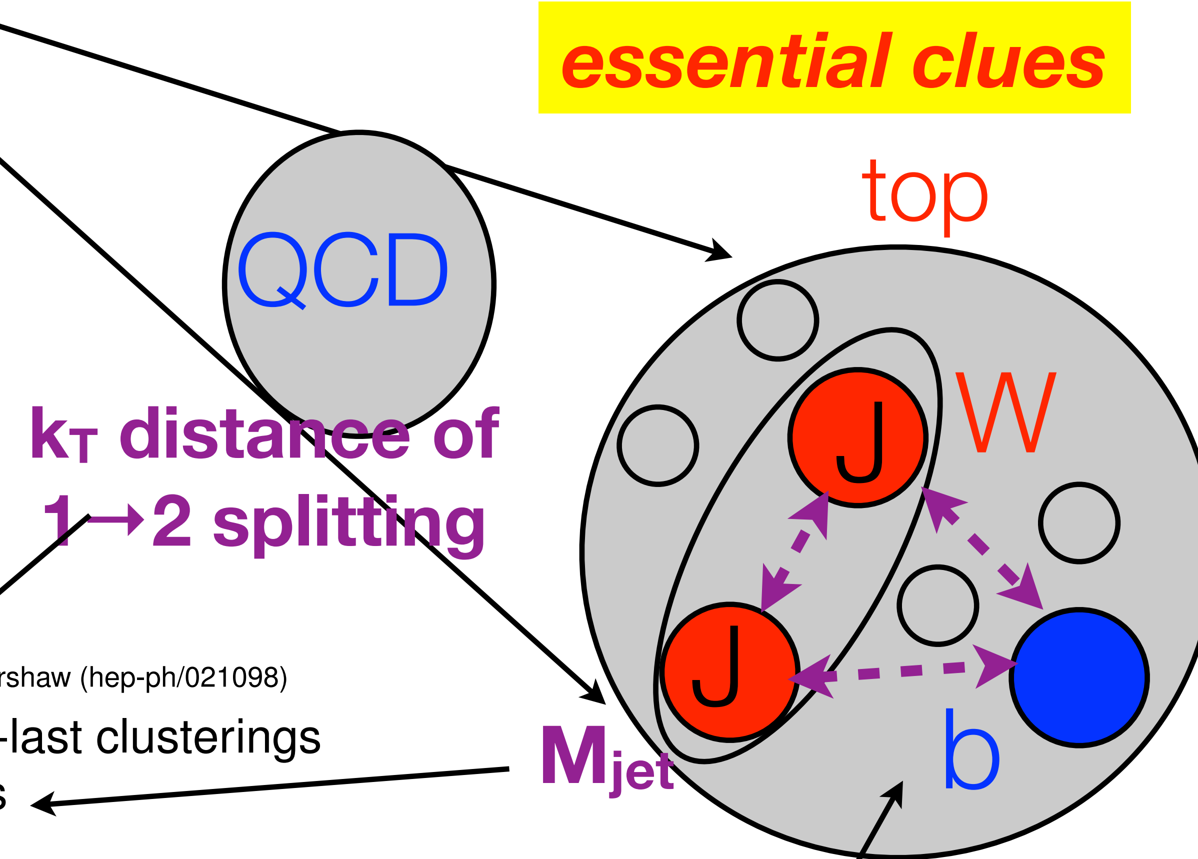


1) reduced efficiency for standard reco

2) di-jet bkg overwhelming for fully had decays

How to tag a boosted hadronic top quark?





Look into the jet substructure

(see Jose Juknevich, TOP2013)

Basic

- 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 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

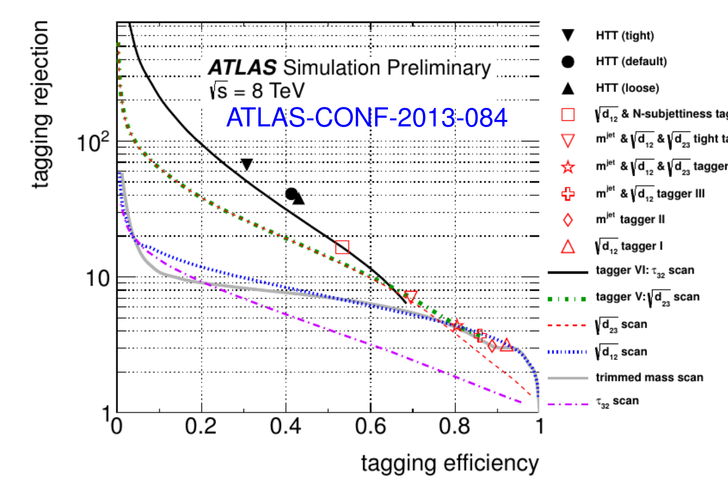
Example

- 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 select partonic decays (templates)

Performance figures of merit

efficiency to tag top jet vs **rejection against QCD jet**
sensitivity to pile-up

efficiency to **select the top final state** vs bkg



Top Template Tagger

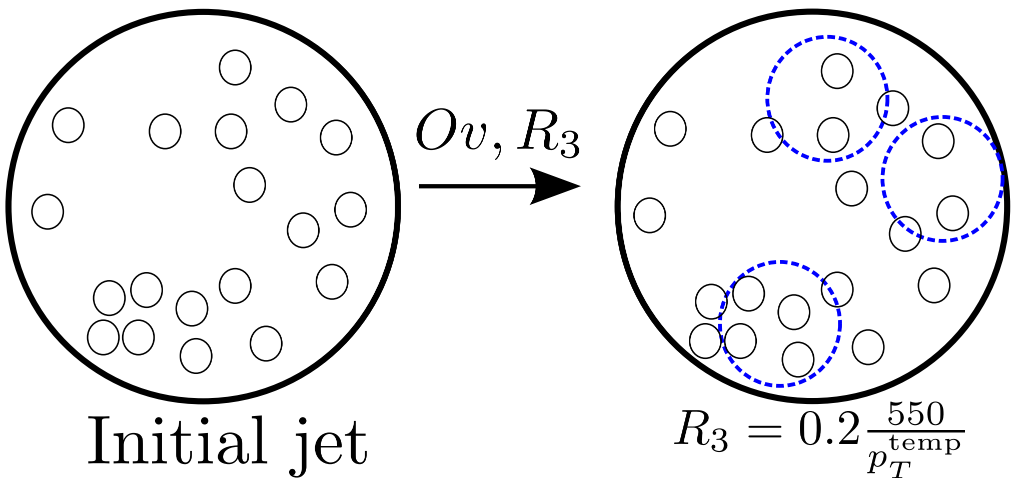
arXiv:1006.2035
Almeida, Erdogan, JJ, Lee, Perez, Sterman ’11
Backovic, JJ, Perez ’12
Backovic, JJ, Perez, Soreq, in preparation

1. Consider partonic phase space for boosted top decays

$$\{(p_1,p_2,p_3)\} : \left\{ \begin{array}{rcl} (P-p_1-p_2)^2 & = & 0, \quad P^2 = m_{\rm top}^2 \\ (p_1+p_2)^2 & = & m_W^2 \end{array} \right.$$

2. Pick out one configuration and evaluate overlap

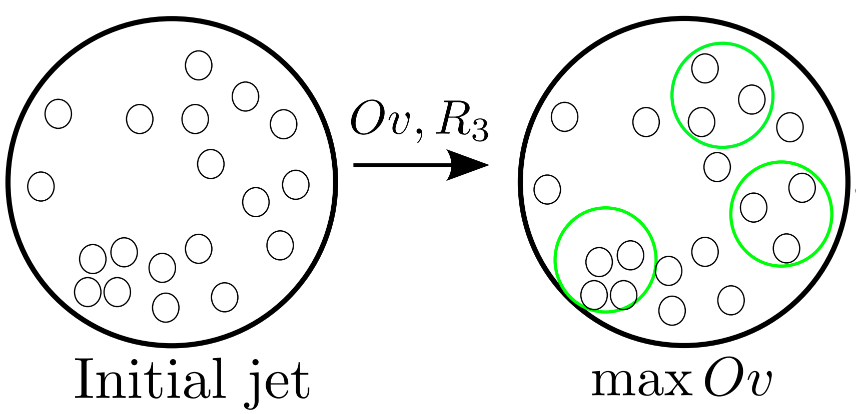
example



$$\exp\left[-\sum_{i=1}^{3} \left(E_i - \sum_{\Delta(topo,i)<R_3} E_{\rm topo} \right)^2 \right]$$

(Jose Juknevich, TOP2013)

3. Find configuration with best match to a given jet



$$\left\{ \begin{array}{l} Ov = \max_{\tau_n} \exp\left[-\sum_{i=1}^{3} \left(E_i - \sum_{\Delta(topo,i)<R_3} E_{\rm topo} \right)^2 \right] \\ \tau_n^{\max} = (p_1, p_2, p_3) \end{array} \right.$$

"Boosted" Search for excess in $t\bar{t}$ production vs M_{tt} - *single-lepton*

$\int L dt$ = **14.3 fb^{-1}** *(2012)* ***$\sqrt{s}$=8 TeV***

ATLAS-CONF-2013-052

$qq\ell\nu bb$

Resolved selection

- *single lepton trigger*

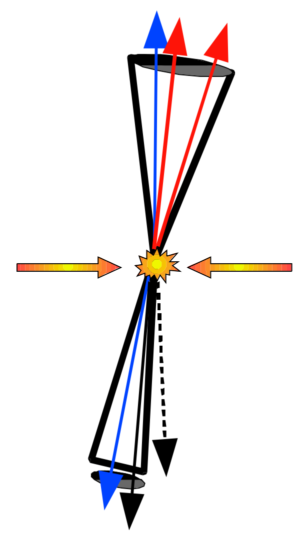
(Fully) Boosted selection

- *trigger on R=1.0 anti-k_T jet with p_T > 240 GeV (~100% eff > 350 GeV)*

- *exactly **1 good, high p_T central lepton (e,) with $p_{T\,dep}$ isolation***

- *≥ 3 (4) good anti-k_T (R=0.4) jets if ≥ 1 (no) jet with m_{jet} > 60 GeV*

lep top

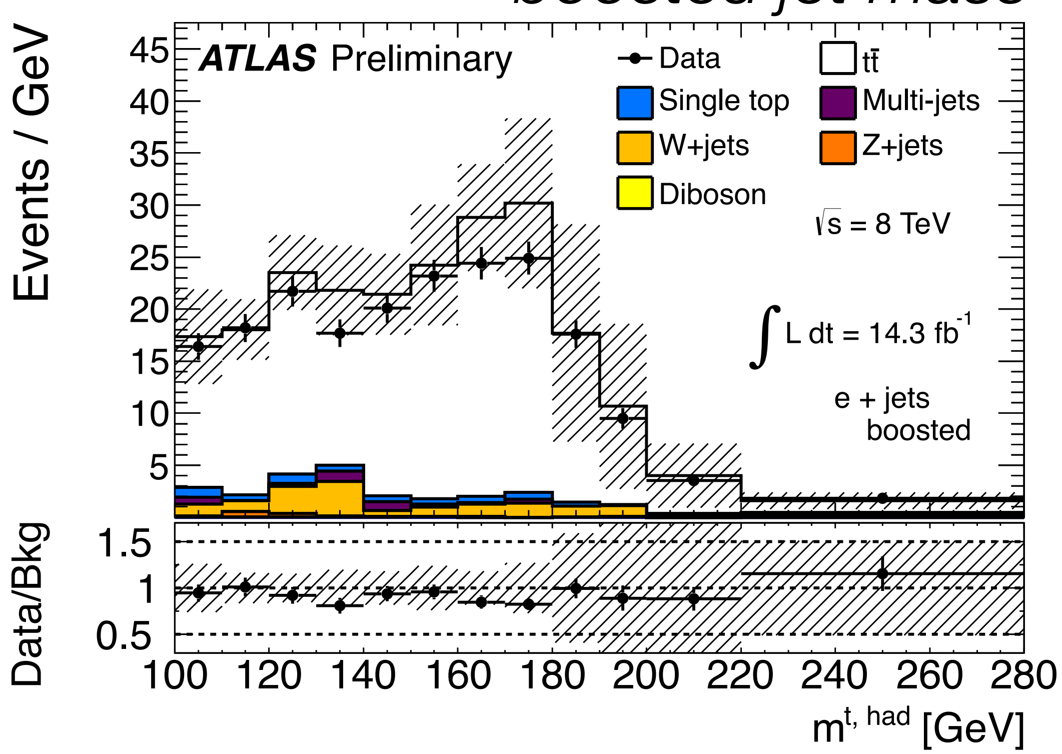


had top

- *≥ 1 anti-k_T (R=0.4) jet with ΔR(lep,jet)<1.5, closest jet → **b-jet for leptonic top***

- *anti-k_T (R=1.0) jet with **large (jet,jet for lep top)** ≥ 1.5, **large p_T** ≥ 300 GeV, **large m_{jet}**>100 GeV, **large k_T (1 → 2) scale** (> 40 GeV) after **shedding soft rad (trimming)** → **lead "fat" jet is had top***

boosted jet mass



- ***tops in opposite hemisphere** → Δϕi(lep,had t-jet)>2.3, ΔR(lept b-jet, had t-jet)>1.5*

- *≥ 1 anti-k_T (R=0.4) b-tagged jet*

2 exclusive samples: pass boosted , fail boosted & pass resolved

"Boosted" Search for excess in $t\bar{t}$ production vs $M_{t\bar{t}}$ -*single-lepton*

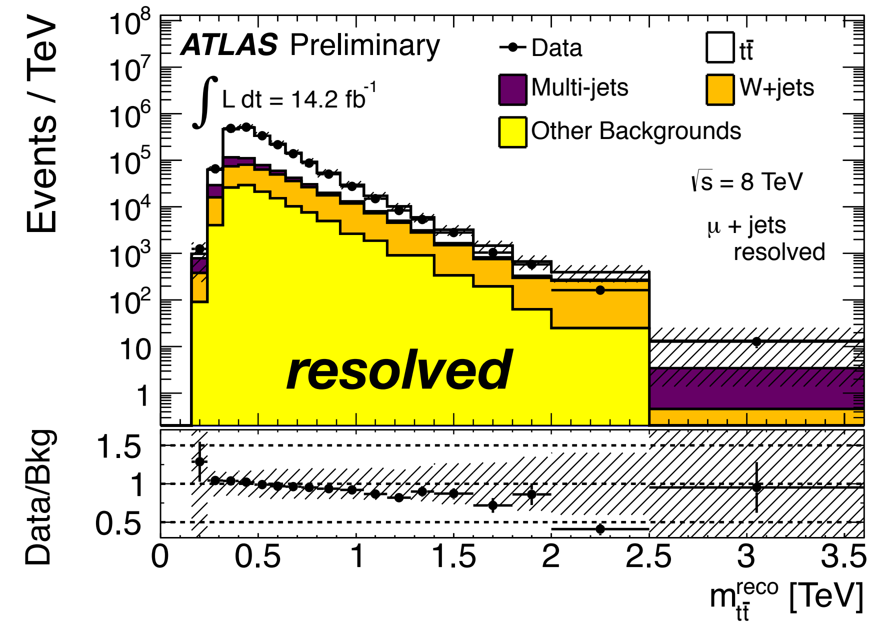
$\int Ldt$ = **14.3 fb^{-1}** *(2011)* $\sqrt{s}$=*8 TeV* ATLAS-CONF-2013-052

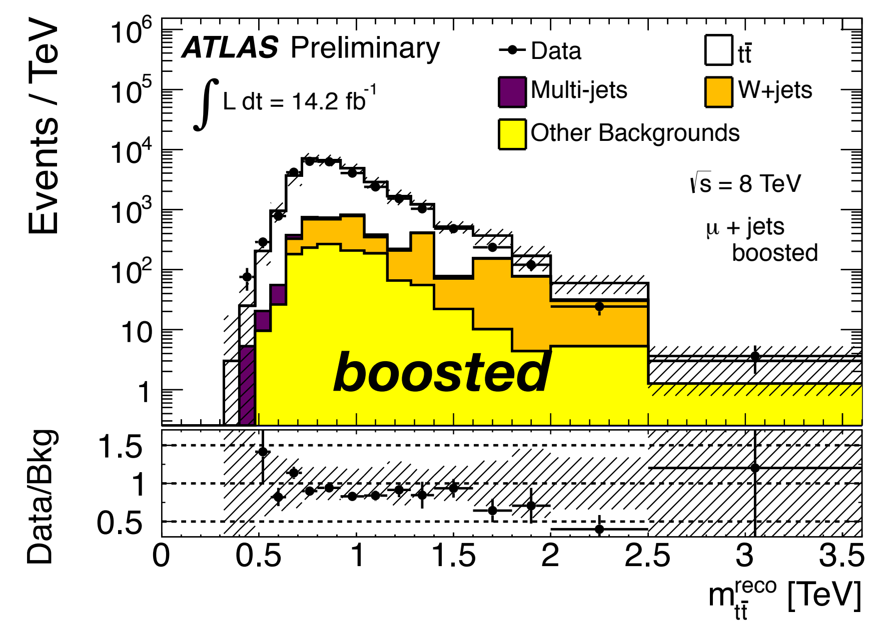
$qq\ell$**vbb**

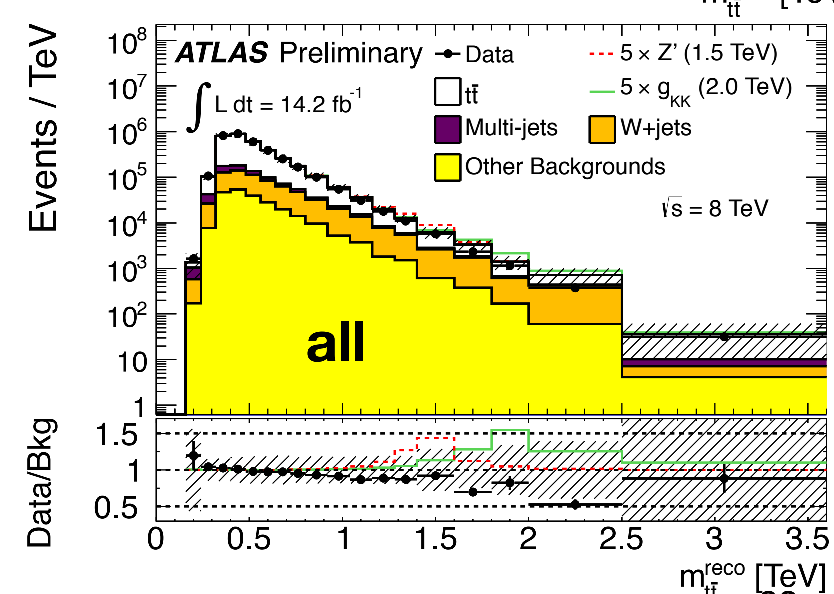
- Data-driven **QCD** (*matrix method, validated in low E_T^{miss}, $m_T(W)$ region, orthogonal to boosted*)**, W+jets normalization** (*from charge asymmetry of W production, relaxed p_T, b-tag and **k_T (1 → 2) cuts***)

- **Resolved M_{tt}: sum of top 4-momenta from** four jet assignment, lep and ν with minimal least squared sum, imposing W, top mass and similar $p_{T,top}$ constraints
  - ❖*p_z (ν) from W mass constraint*
  - ❖*all selected jets are used*
  - ❖*if jet with m_{jet} >60 GeV, allow qq and qb merging*

- **Boosted M_{tt}:** from had t-jet + high p_T lepton**,** p_z (ν) from W mass constraint, leptonic b-jet







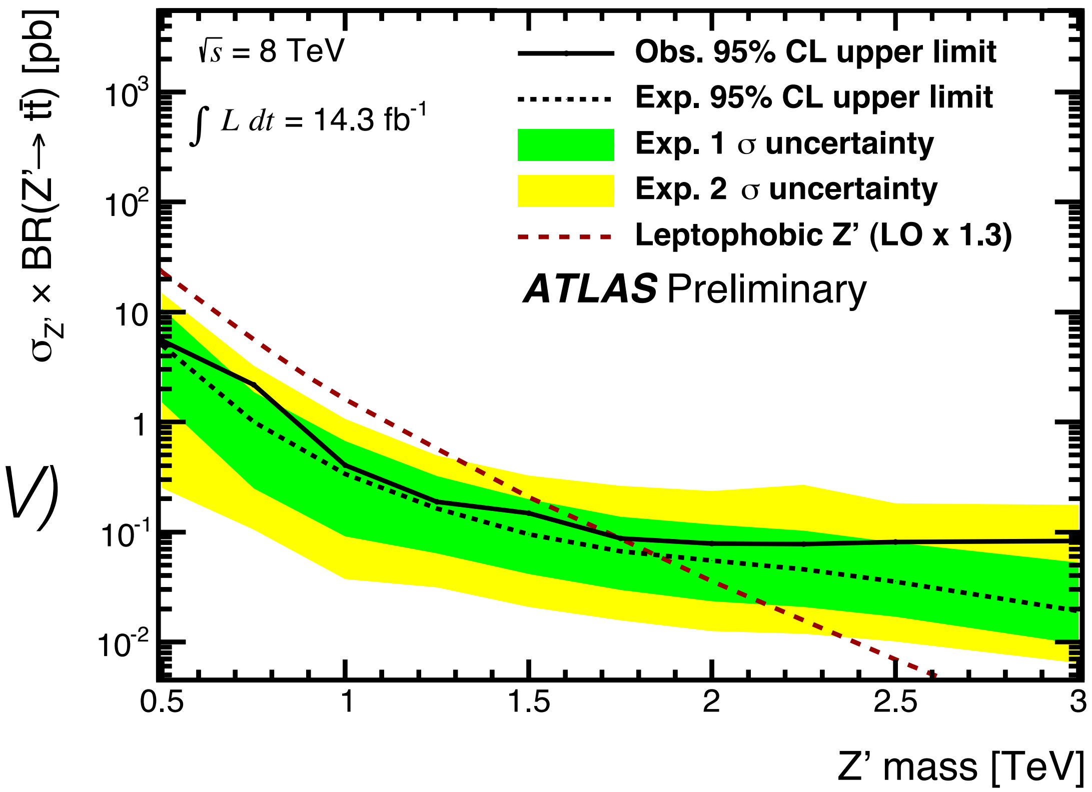
Search for excess in $t\bar{t}$ production vs M_{tt} -single lepton

$\int Ldt$ = **14.3 fb^{-1}** *(2011)* $\sqrt{s}$=8TeV

ATLAS-CONF-2013-052

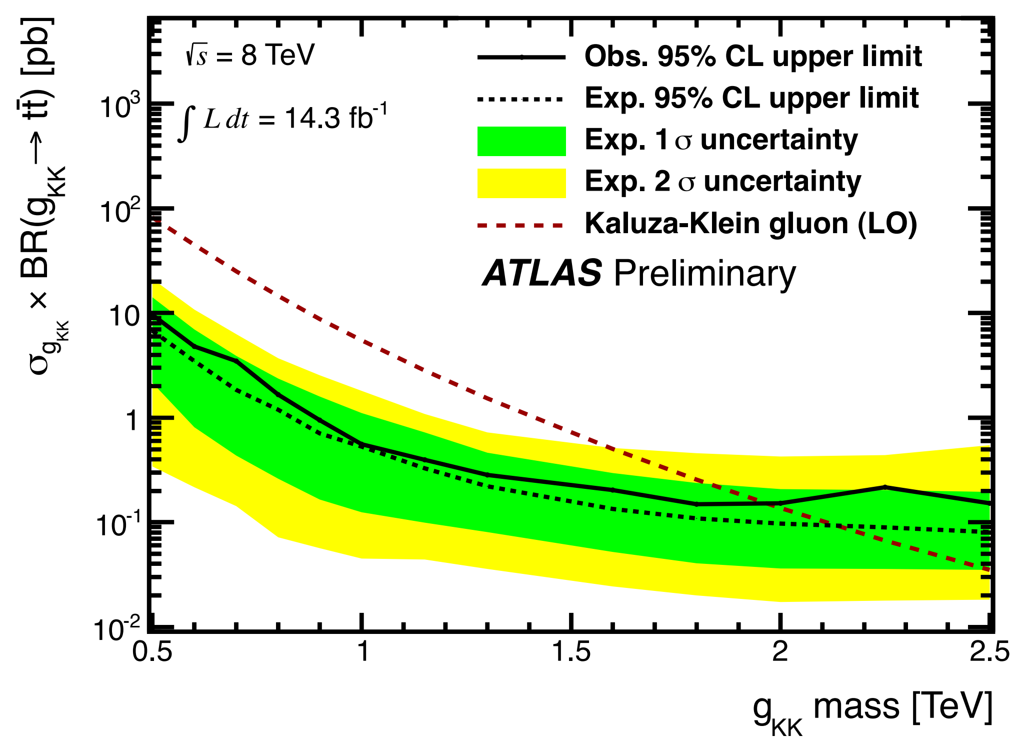
- No excess found → **95% upper observed limit (Bayesian credible interval) for Z' & RS KKGluon *σ*BR.* *Combine 4 spectra (2 chan x 2 sel)* including systematics** *as marginalized nuisance pars, flat prior.*

- **Limit on Topcolour Z' *σ*BR* (with $\Gamma_{Z'}/m_Z$ ~ 1%) : 5.3 pb** *($m_{Z'}$=500 GeV)* **to 0.08 pb** *($m_{Z'}$=3 TeV)*



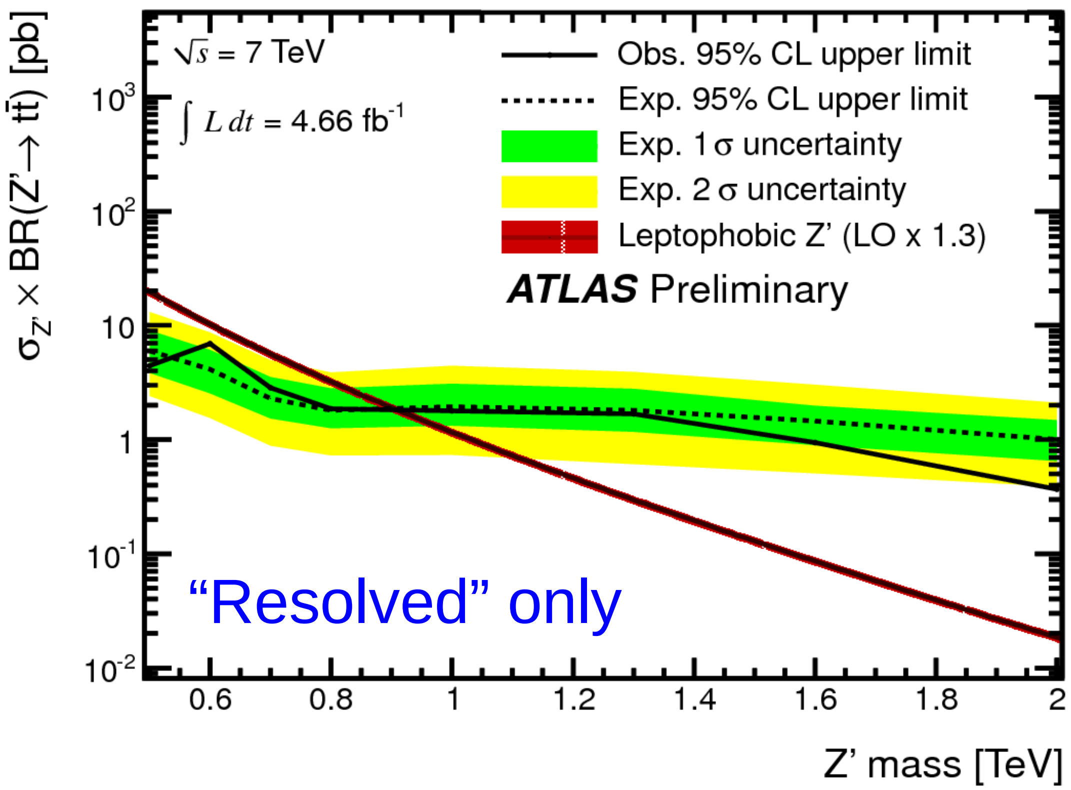
> *Z' with* **500 GeV <$m_{Z'}$ <1.8 TeV are excluded at 95% prob**

- Limit on **KKGluon *σ*BR* (with Γ_{KKG}/m_{kkG} ~ 15%): 0.56 pb** *($m_{kkG'}$= 1 TeV)* **to 0.15 pb** *($m_{kkG'}$=2.5 TeV)*



> KK Gluons with **500 GeV < m_{kkG} < 2.0 TeV are excluded with 95%prob**

ATLAS-CONF-2012-136



Semi-leptonic ttbar selection:

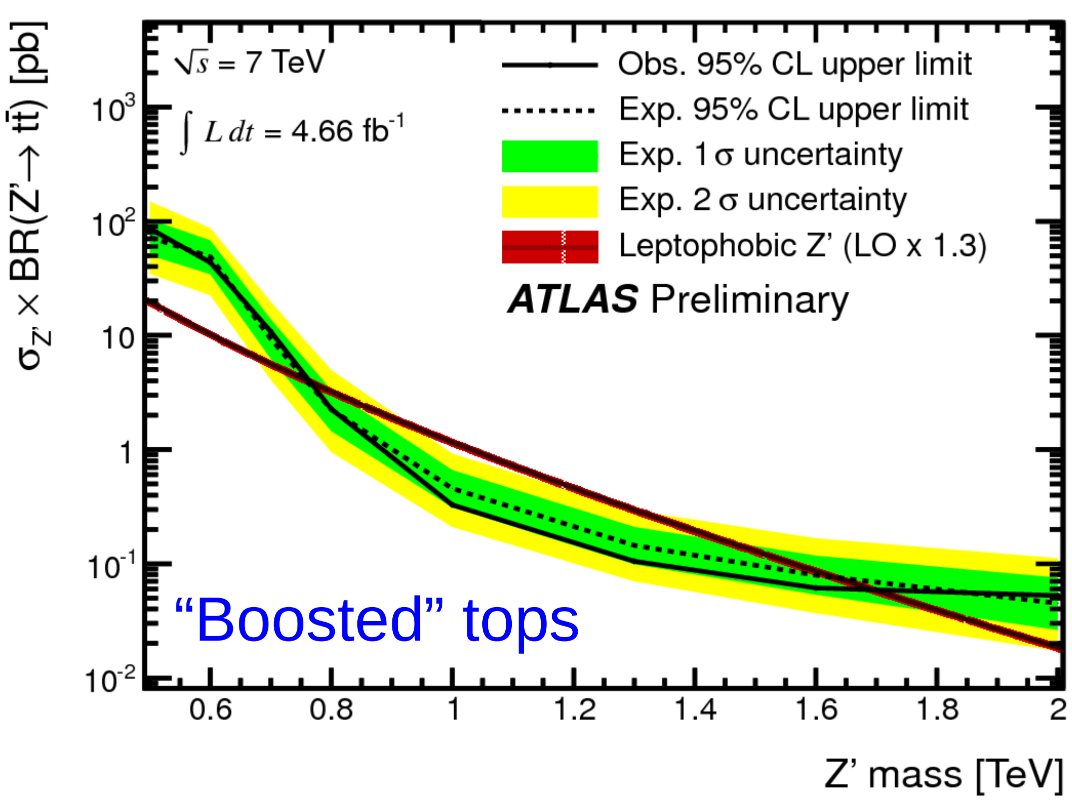
Resolved:

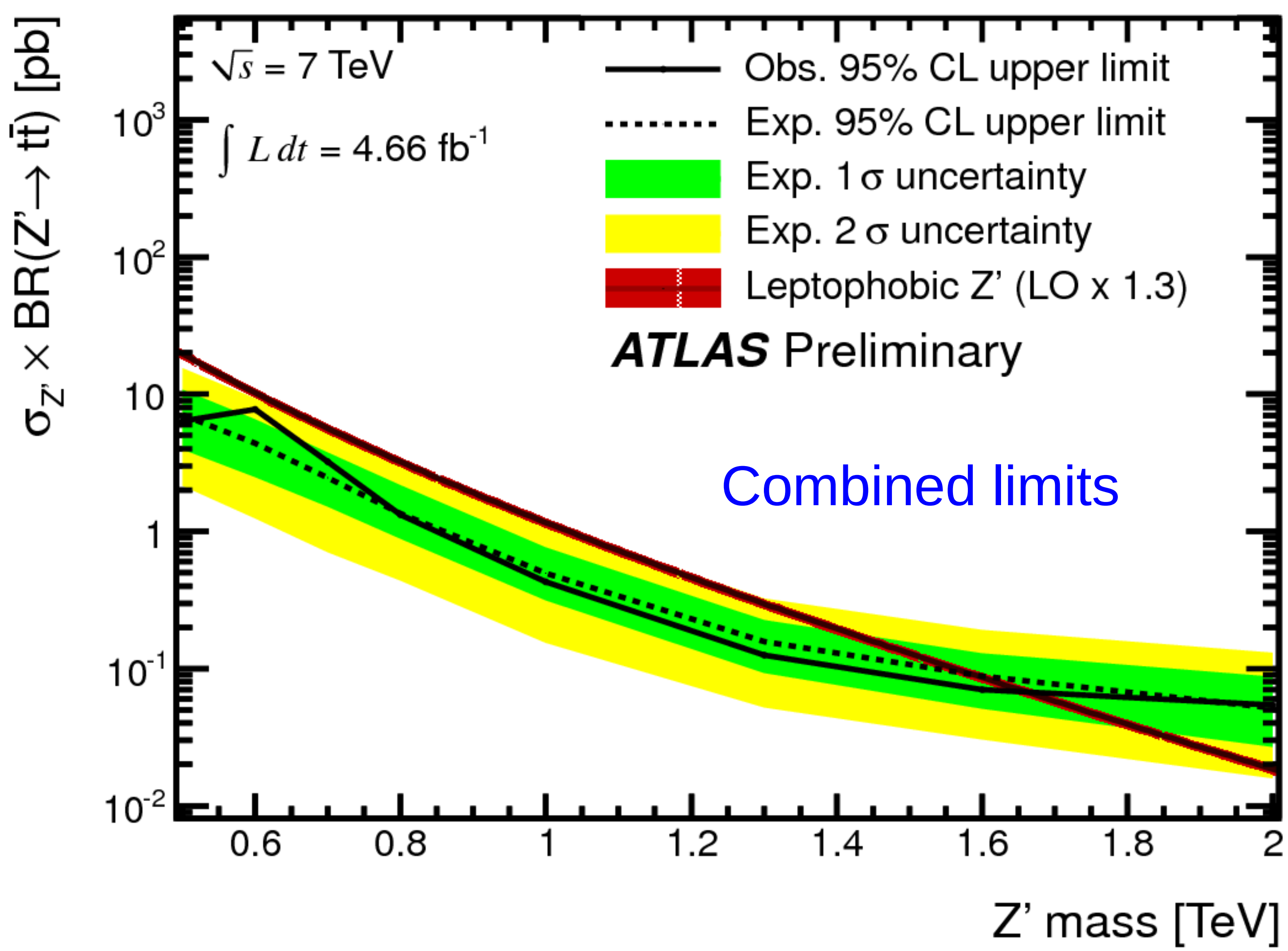
3 anti-kt R=0.4 jets, pt > 25 GeV

Boosted:

1 anti-kt R=1.0 jet

pT > 350 GeV, M > 100 GeV, sqrt(d12) > 40 GeV





(thanks to E.Thompson (Columbia))

Some words on prospects

- **Go for precision realm in tt cross section + observe single top** beyond t channel. Measurements are mostly **systematics dominated (that's where the work is).**

- **Perform higher statistic searches to extend limits well in the TeV/sub pb region**
  - **boosted top regime** will use new tagging/reconstruction techniques, associated syst uncertainties
  - consider jet triggers for boosted regime
  - pile-up understanding for standard and "fat jets"

- **Perform differential xsec measurements** ($d\sigma/dm_{tt}$, $d\sigma/dp_{T,tt}$, $d\sigma/dy_{tt}$, $d\sigma/dp_{T,top}$) to test SM and complement direct searches

Conclusions

- **Top analysis at LHC is in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is already underway.**
- **Top pair production cross section is measured** in nearly all expected final states. It is **consistent with the standard model at $\sqrt{s}$=7 TeV** and **most precise channels**/combination are
  - **systematics dominated**
  - entering the realm of **precision physics**: $\delta\sigma/\sigma$ <~10% comparable with theory uncertainty
- **Single top production is clearly observed** in the t-channel; need more data to observe it in Wt and s-channel.
- **Top properties** are rapidly reaching precision level with **m_{top} already syst dominated**
- The rapidly **increasing data-set and detector understanding** is quickly opening **unprecedented phase space for new physics searches linked to top production** *ranging from resonances to dark matter candidates*

References and useful tools

- 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

BACK-UP

Math Appendix : Mass, P_T and DR

As we know that for any 4-momentum $E = m_T \cosh y \; , \; p_x \; , \; p_y \; , \; p_z = m_T \sinh y$

where $m_T^2 = m^2 + p_x^2 + p_y^2 \, .$ and

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \ln \left(\frac{E + p_z}{m_T} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right) .$$

The invariant mass M of the two-particle system

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2)\cosh \Delta y - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \; ,$$

where $E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2} \; ,$

This can be re-written as

$M^2 = m_1^2 + m_1^2 + 2[\, E_T(1)\, E_T(2)\ \cosh(Dy) - p_T(1)\, p_T(2) \cos(DPhi)$

where DPhi =Phi(2)-Phi(1)is the angle between the two momenta in the transverse plane

Now if 1) the masses of the particles are small w.r.t. their momenta and 2) the splitting is quasi collinear i.e. cosDPhi ~1 - $(DPhi)^2/2$ and cosh(Dy)~1+$Dy^2/2$, so $E_T(I) \sim p_T(i)$

http://en.wikipedia.org/wiki/Hyperbolic_function

$M^2 \sim 2[\, p_T(1)\, p_T(2)\, (\, 1+Dy^2/2 \; - 1 + (DPhi)^2/2)] = p_T(1)\, p_T(2)\, (Dy^2/2 + (DPhi)^2) = p_T(1)\, p_T(2)(DR(1,2))^2$

So Labelling i and j such that $p_{tj} < p_{ti}$ and defining $z = p_{tj}/p_t$ $(p_t = p_{ti} + p_{tj})$,

$$m^2 \simeq z(1-z) p_t^2 \Delta R_{ij}^2 \, ,$$

$$d_{ij} = z^2 p_t^2 \Delta R_{ij}^2 \simeq \frac{z}{(1-z)} m^2 \, .$$