Top Quark at LHC

2012-2013 Intercollegiate PostGraduate Course in Elementary Particle Physics

London, UCL Bloomsbury Campus
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Outline

- **Why top quark?**

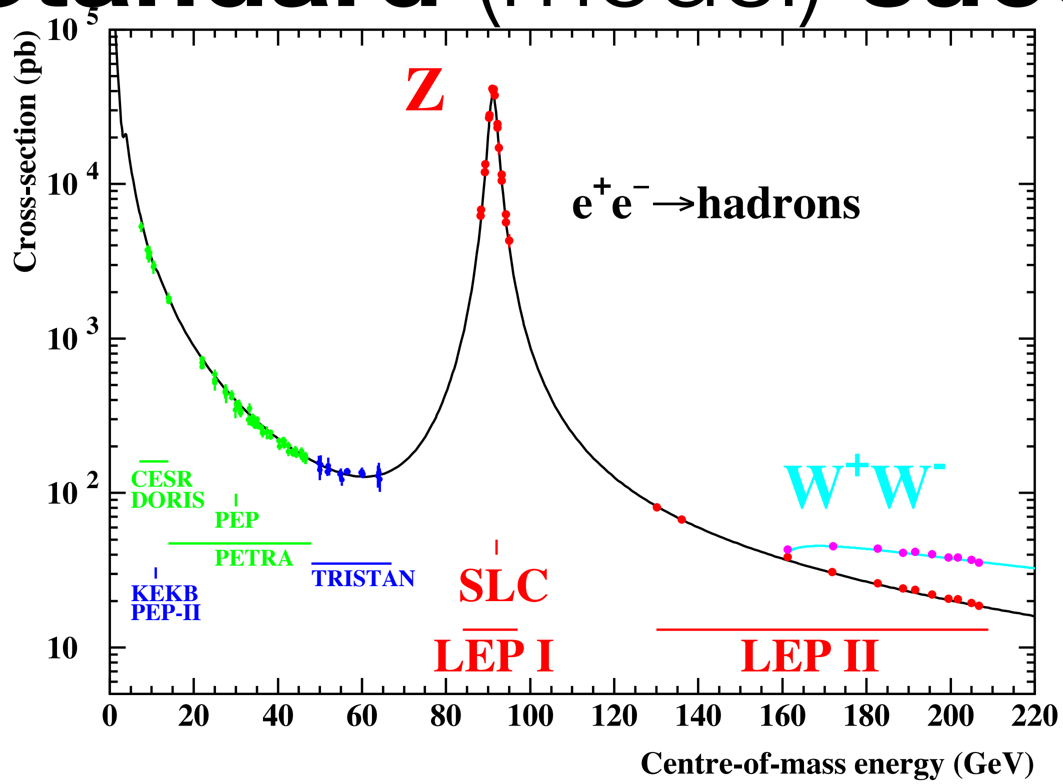
- **The tools of the trade**
  - **LHC:** a top factory at work
  - **The ATLAS and CMS detectors**: top observers

- Measuring **top quark production**
  - top pair
  - single top

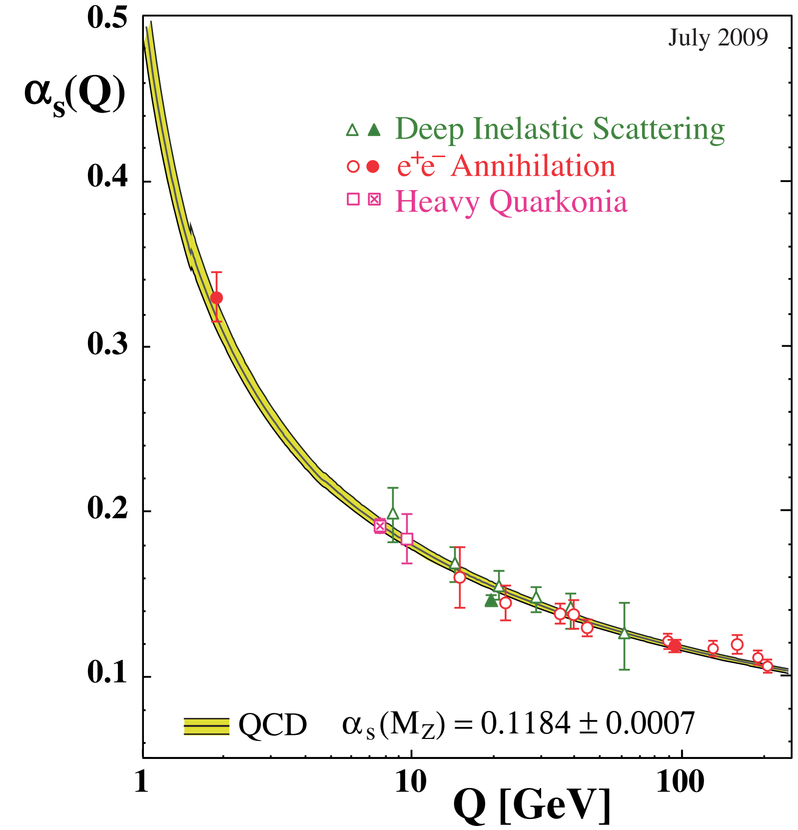
- Top Properties
  - Top mass
  - Differential cross sections

- Top pair production as a **window on new physics**
  - **The emergence of boosted tops:** Resonances in $t\bar{t}$

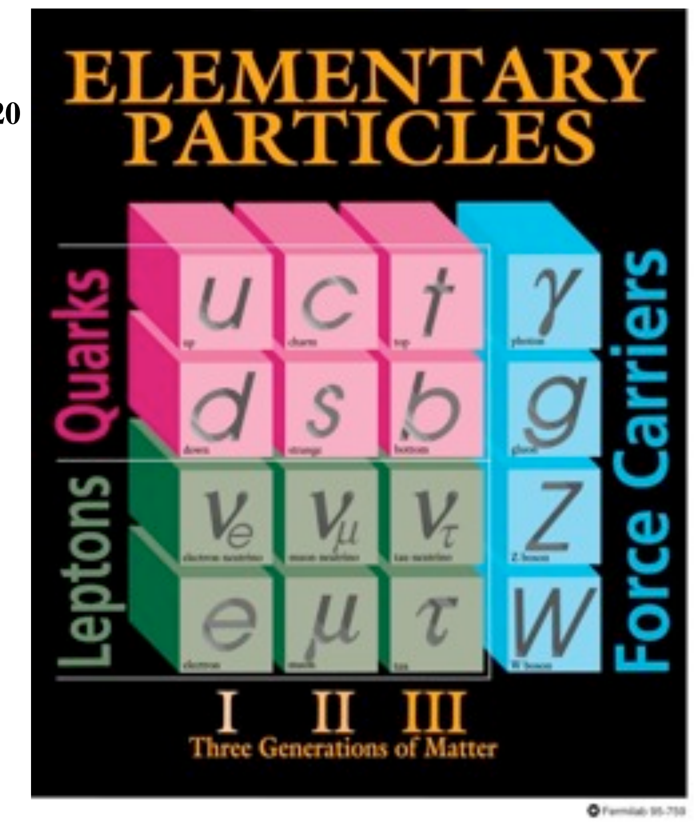
Standard (model) **successes**

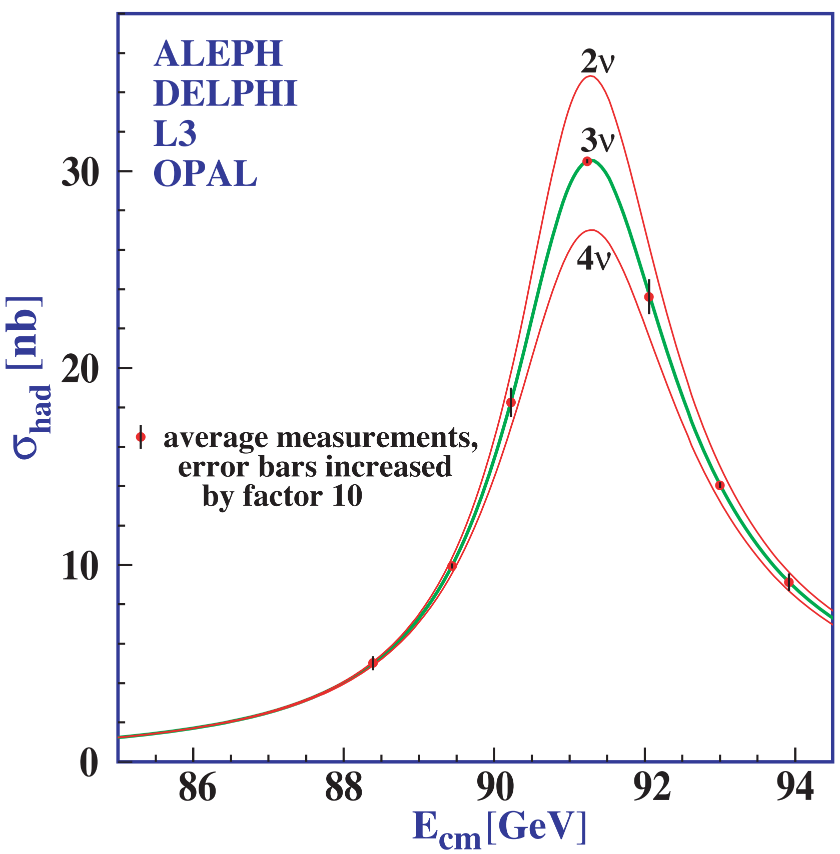


W, Z, bosons unify Electro-weak force



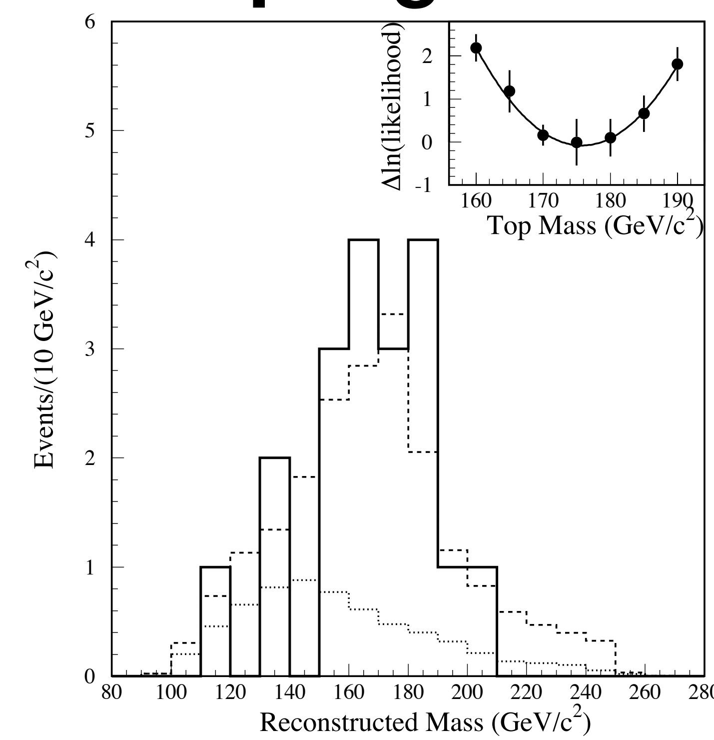
Strong coupling runs





only 3 standard neutrinos

a quick (biased) selection..

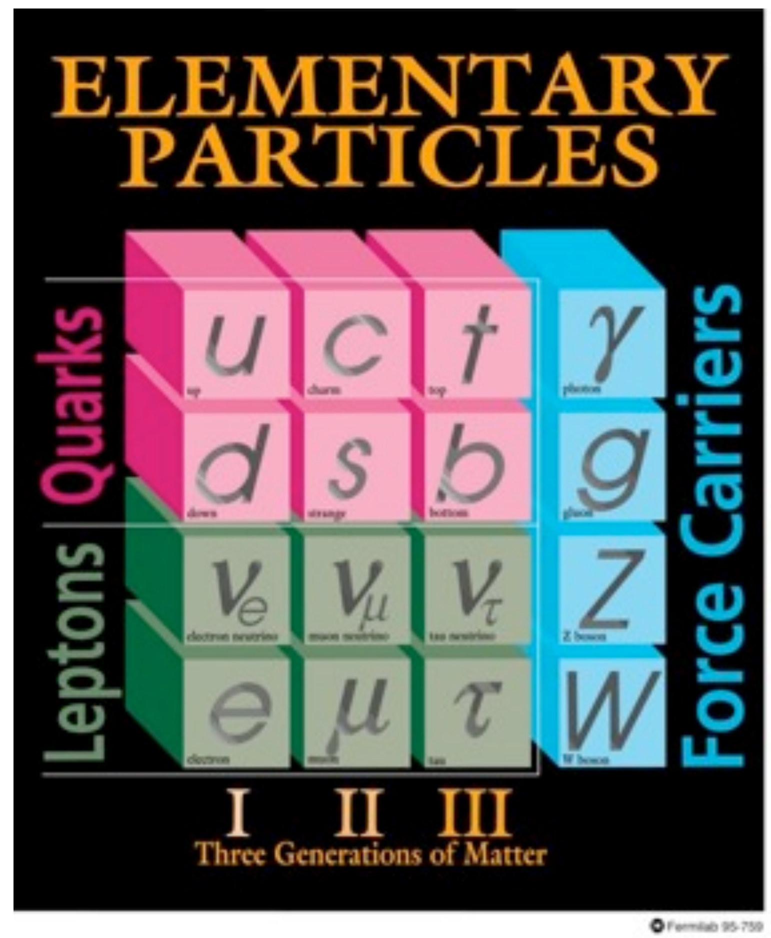


Top quark is found

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?**

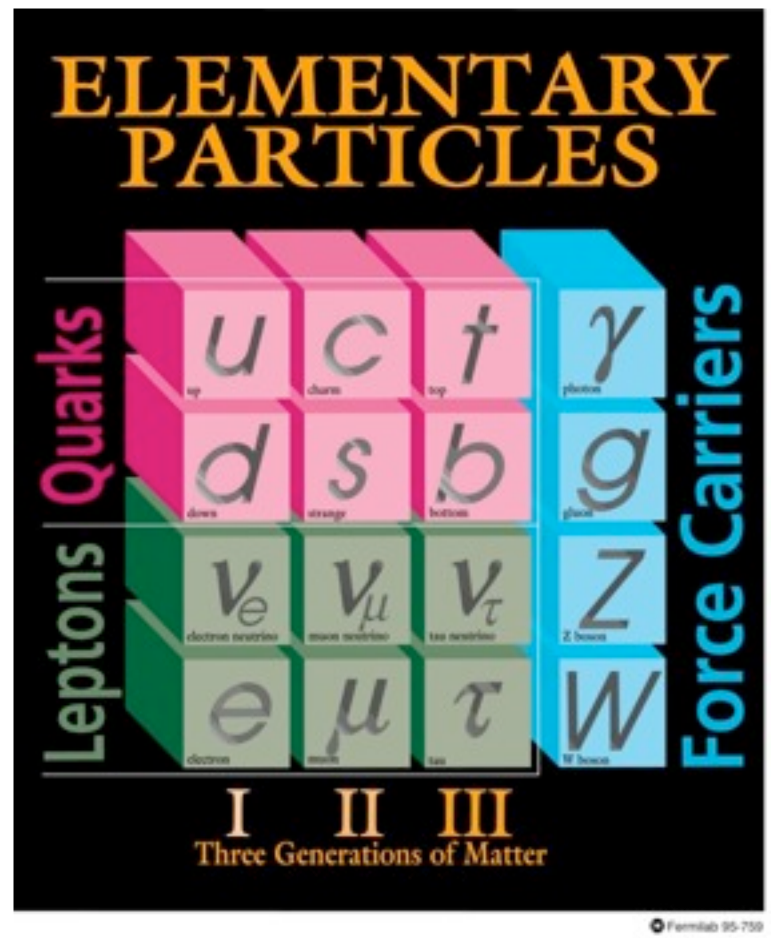
Higgs, SuperSymmetry, New Strong forces..

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

Quantum gravity
Extra dimensions...

- ***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...

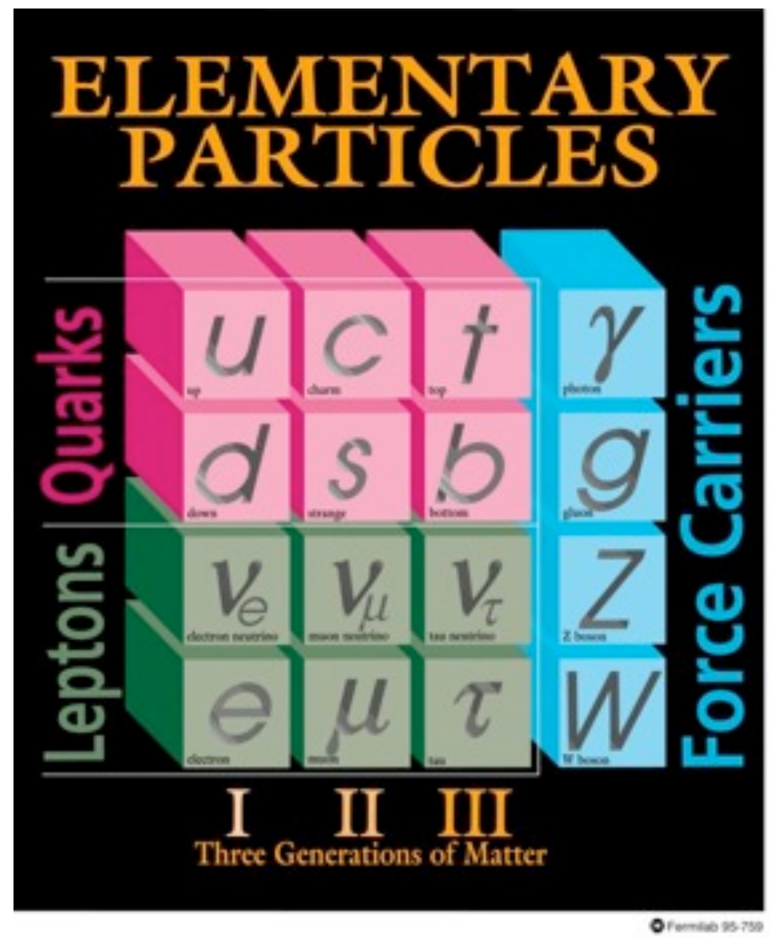
Standard (model) **questions**

- ***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...?

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

String theory..

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

Dark matter, Dark energy...

From bottom to top: a history of expectations

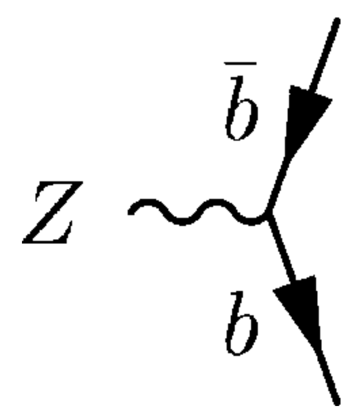
One needs top because

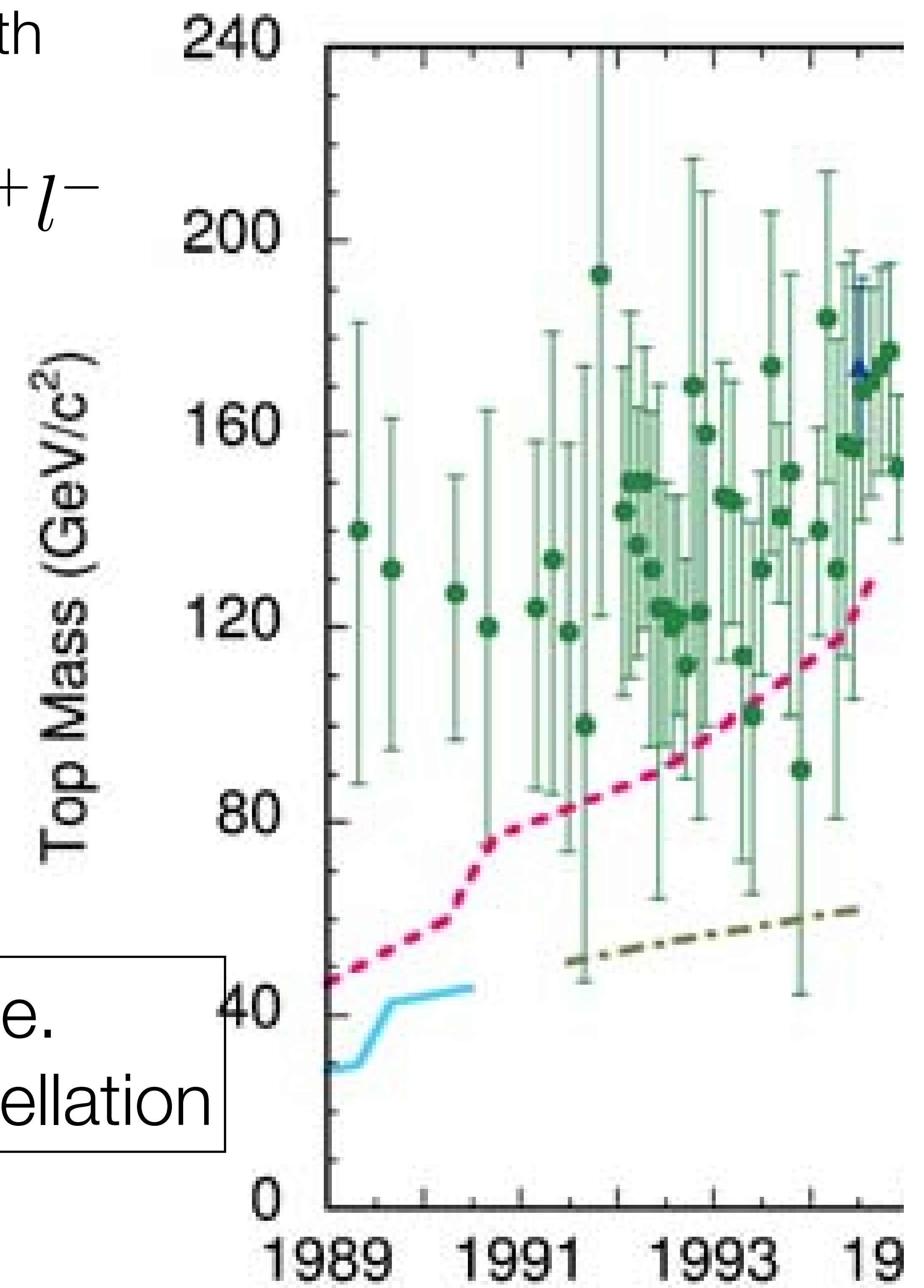
b couples to s only with neutral mediator

No flavour changing neutral currents: no b iso-singlet

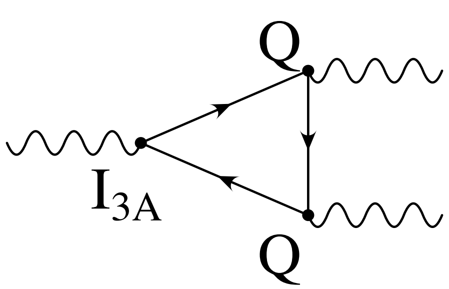
$$\begin{bmatrix} c \\ s' \end{bmatrix}_L \quad b'_L \qquad b \longrightarrow s + l^+ l^-$$

I_3 = -1.2 for b quark required by Z width in b$\bar{\text{b}}$ 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



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

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

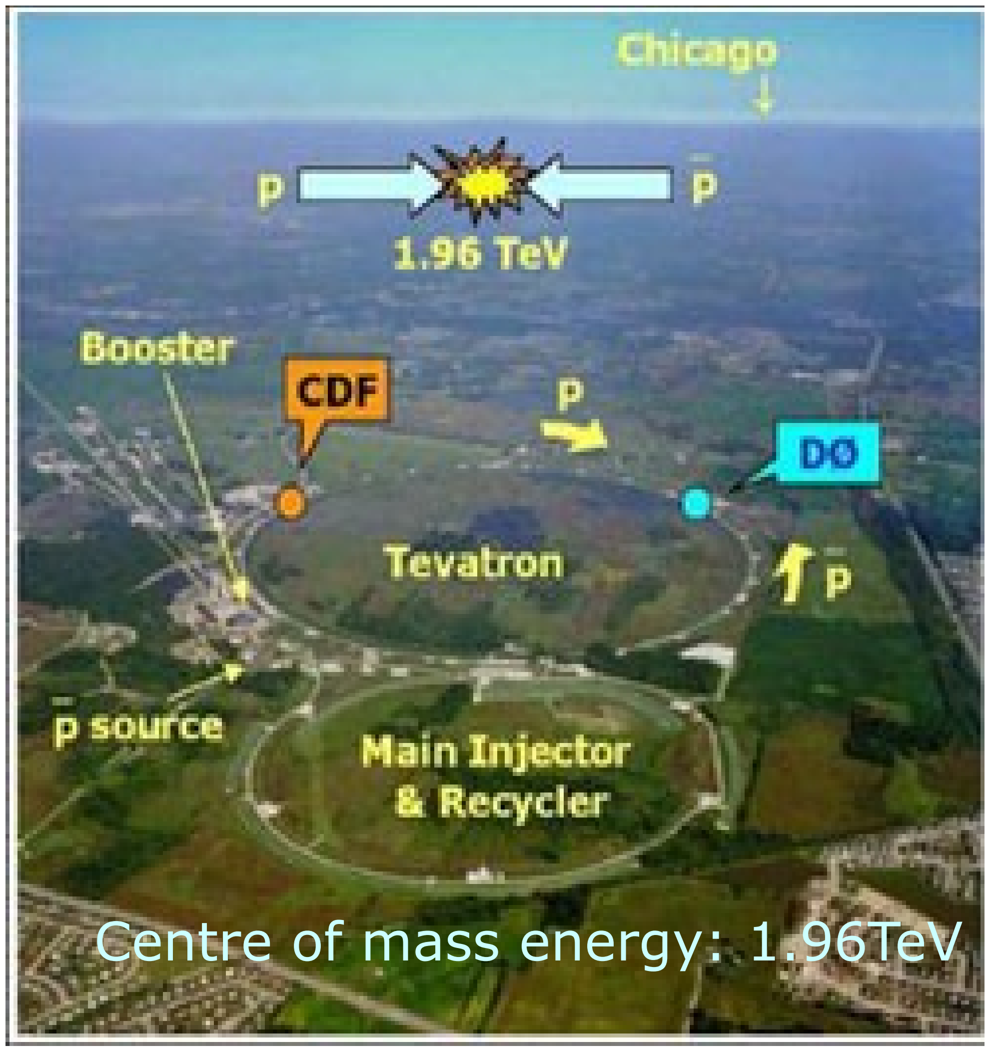
1995: top is discovered!

$\sqrt{s} = 1.8$ TeV

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

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

p$\bar{p}$ collisions



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

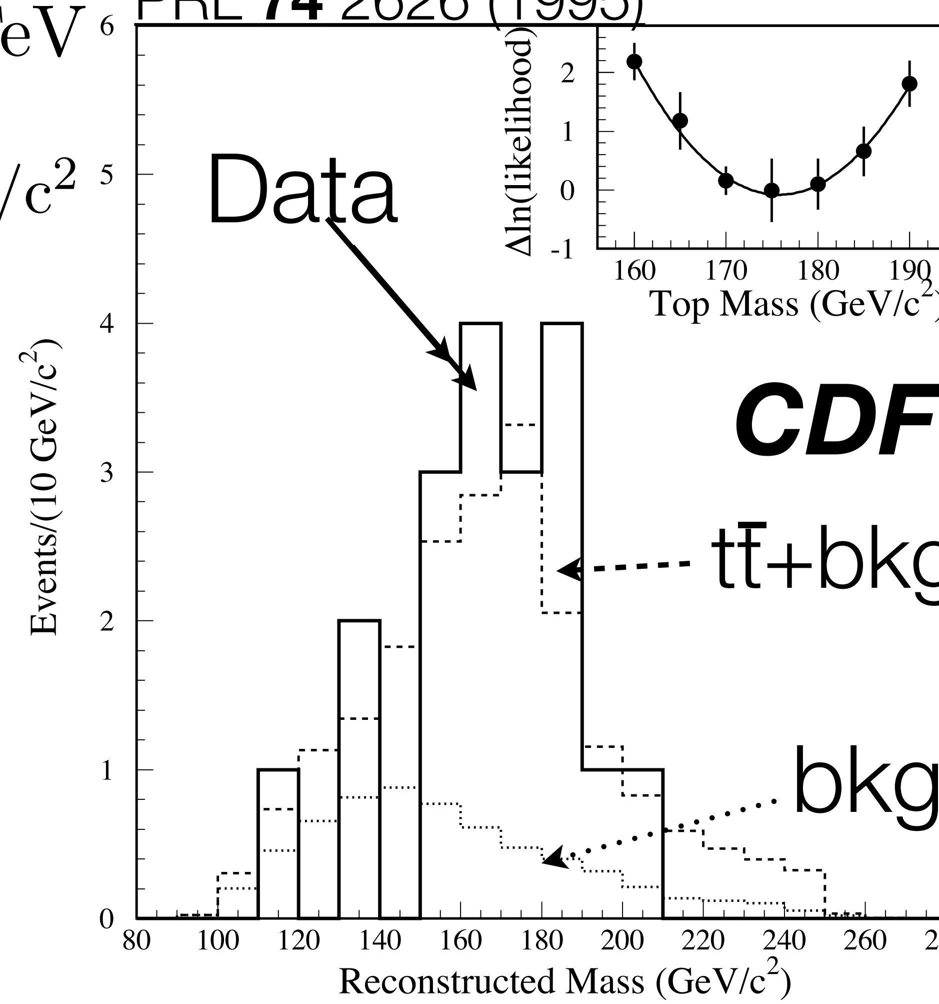
mass from likelihood fit to shape

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

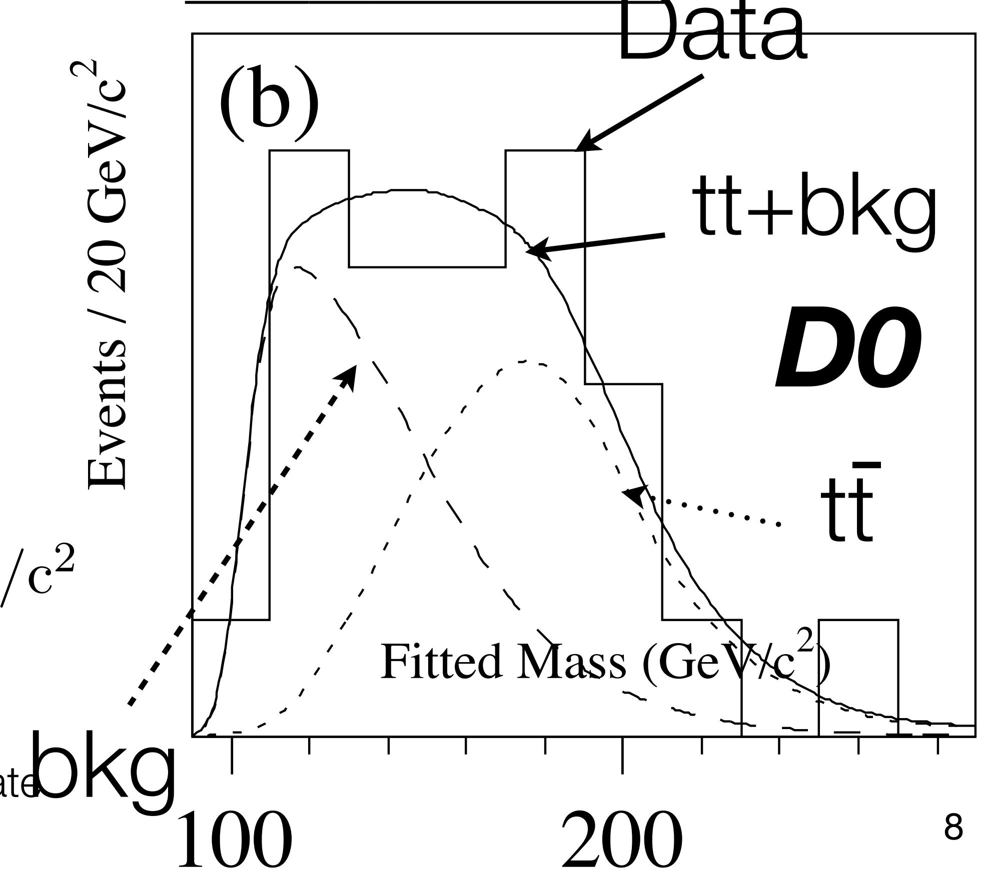
m$_{top}$ = 199^{+19}_{-21} (stat.) ± 22 (syst.) GeV/c^2

σ$_{t\bar{t}}$ = 6.4 ± 2.2 pb.

PRL **74** 2626 (1995)

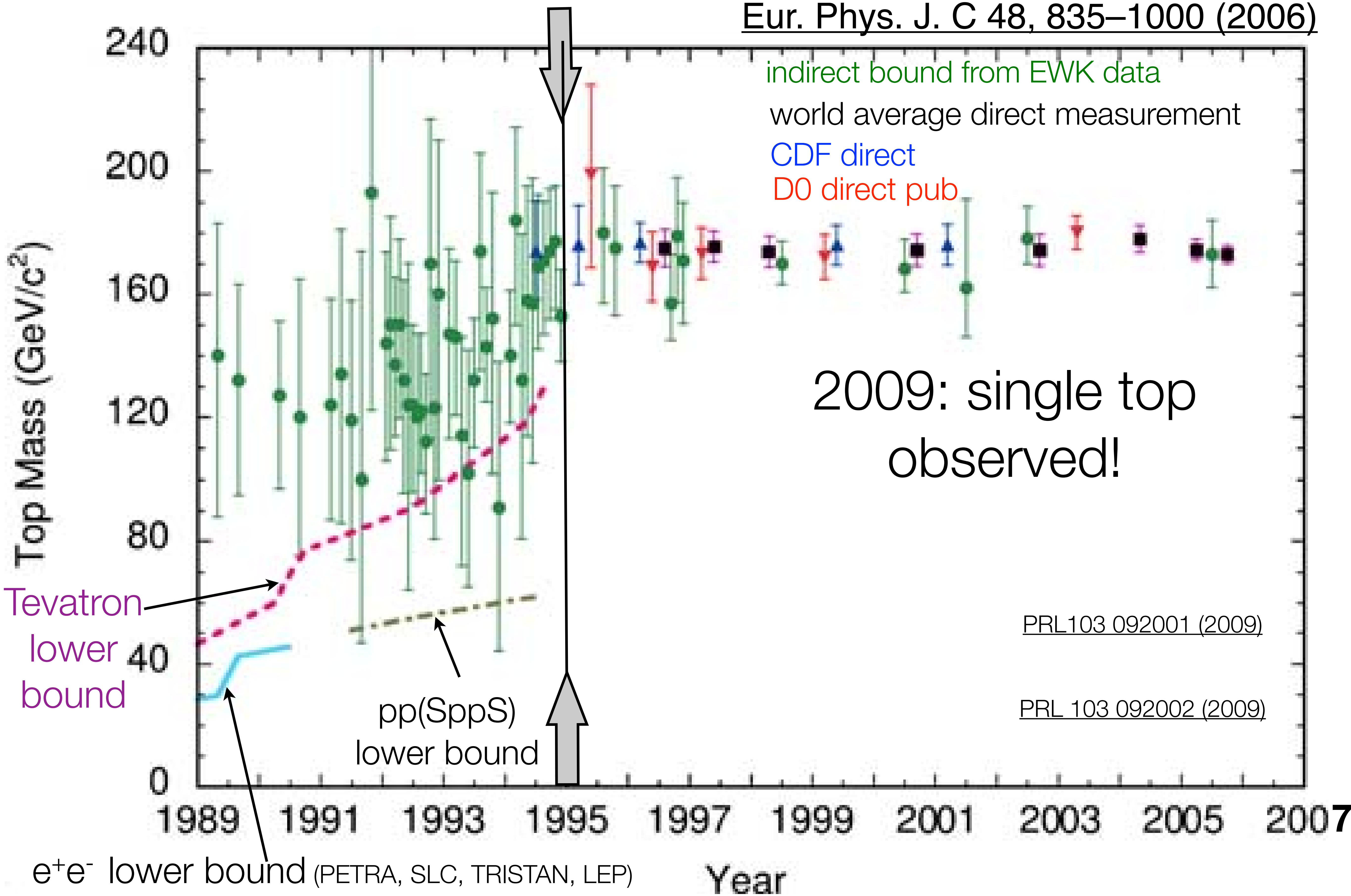


PRL **74** 2632 1995



From bottom to top: the global picture

A.Quadt
Eur. Phys. J. C 48, 835–1000 (2006)

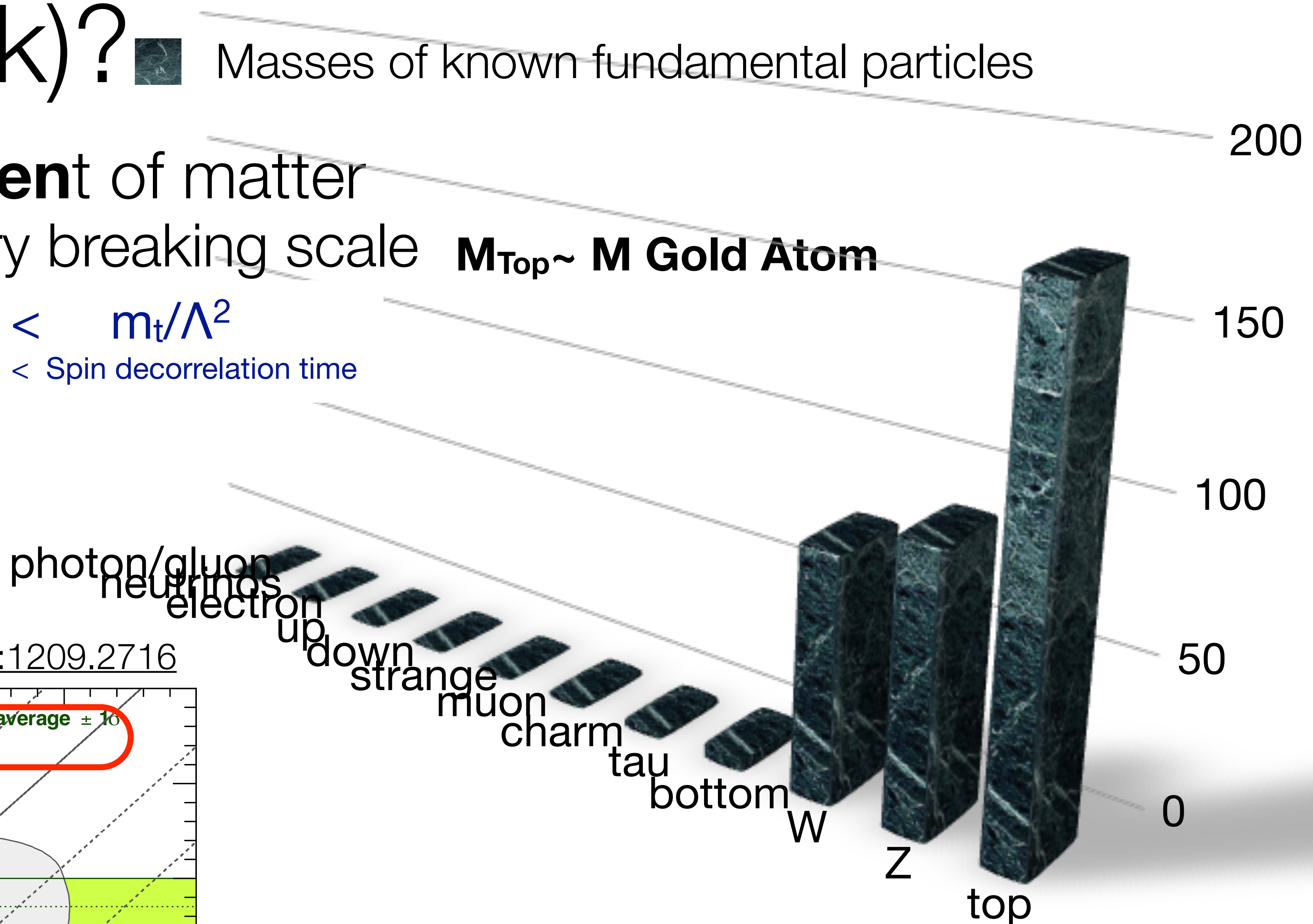


2009: single top observed!

PRL103 092001 (2009)

PRL 103 092002 (2009)

Why Top (quark)?



Most massive constituent of matter

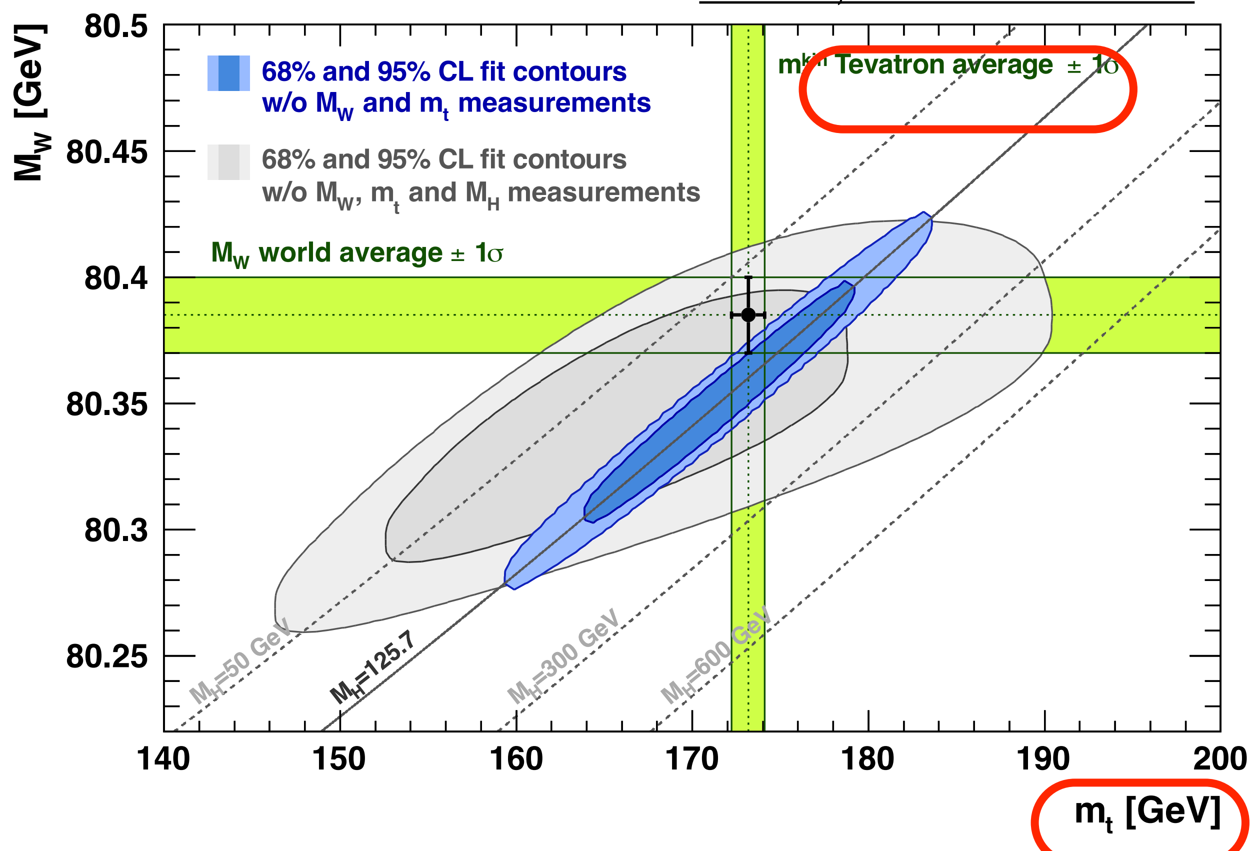
M_{top}~ electroweak symmetry breaking scale **M_{Top}~ M Gold Atom**

$1/m_t$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2

Production time < Lifetime < Hadronization time < Spin decorrelation time

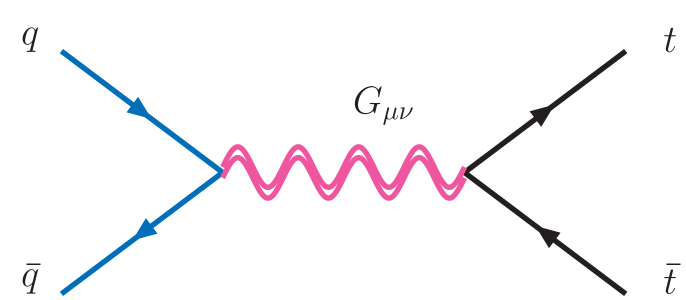
Decay and strong production rate are **tests of standard model**

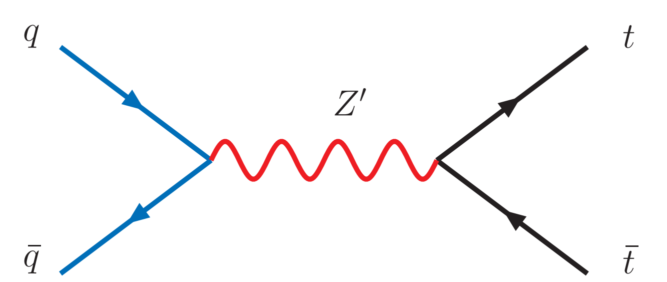
GFitter, arxiv:1209.2716



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

Various scenarios with **direct/indirect coupling to new physics:** from extra dimensions to new strong forces

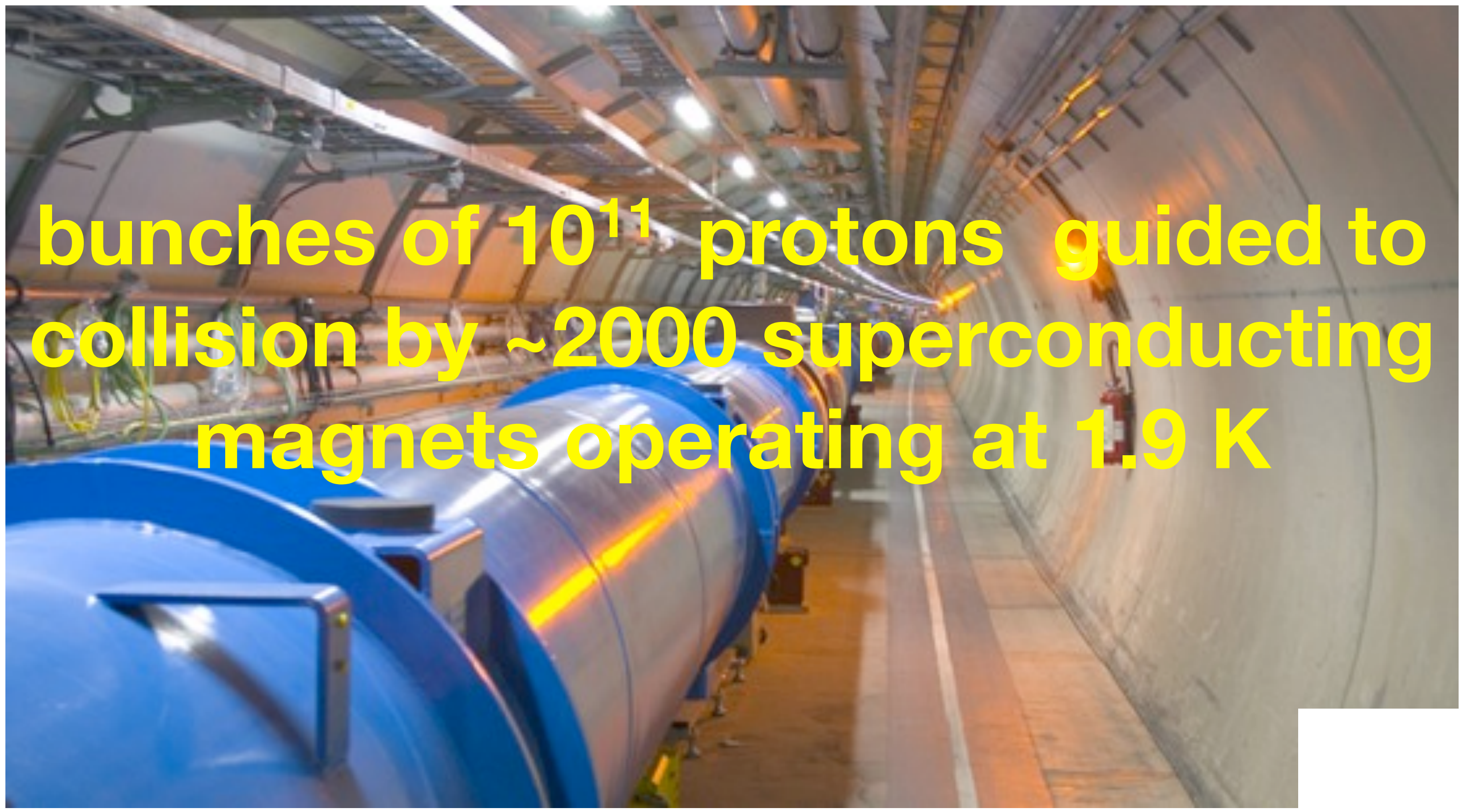


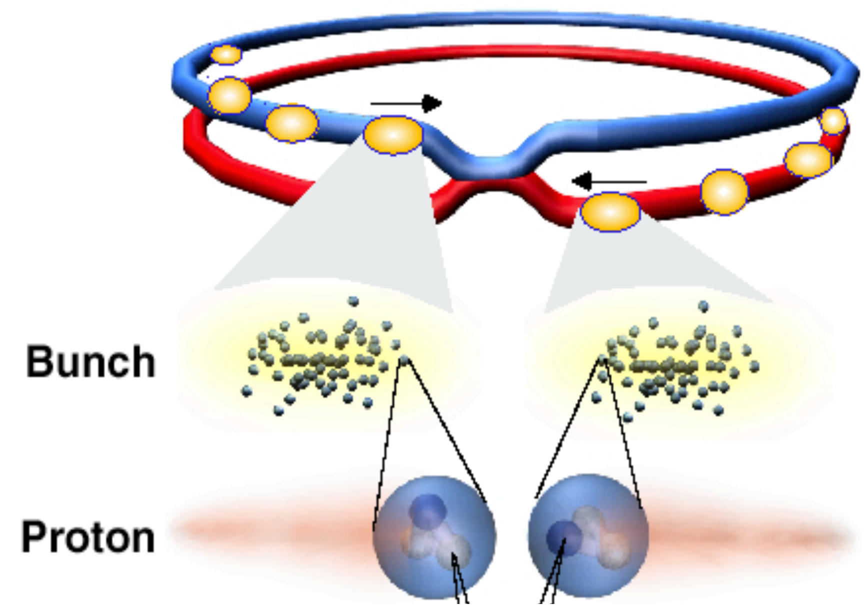


LHC : a *Top* producer

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

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

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

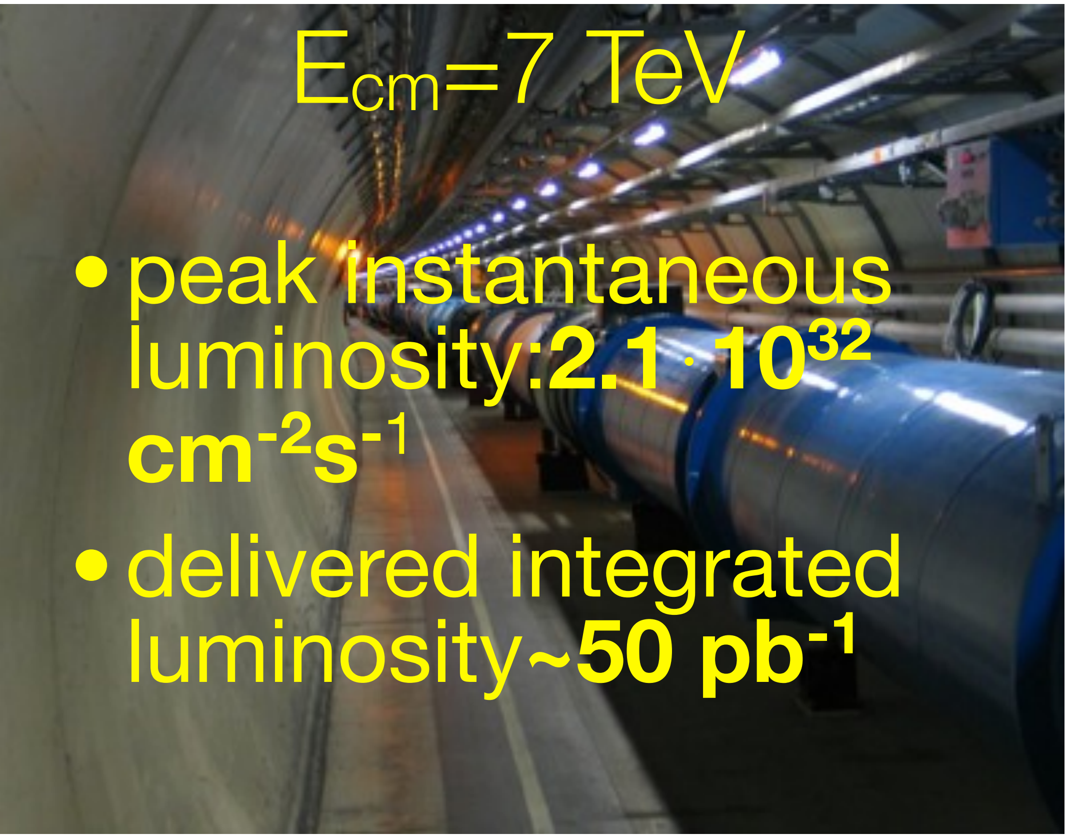
E_{cm}(Tevatron)= 1.96 TeV

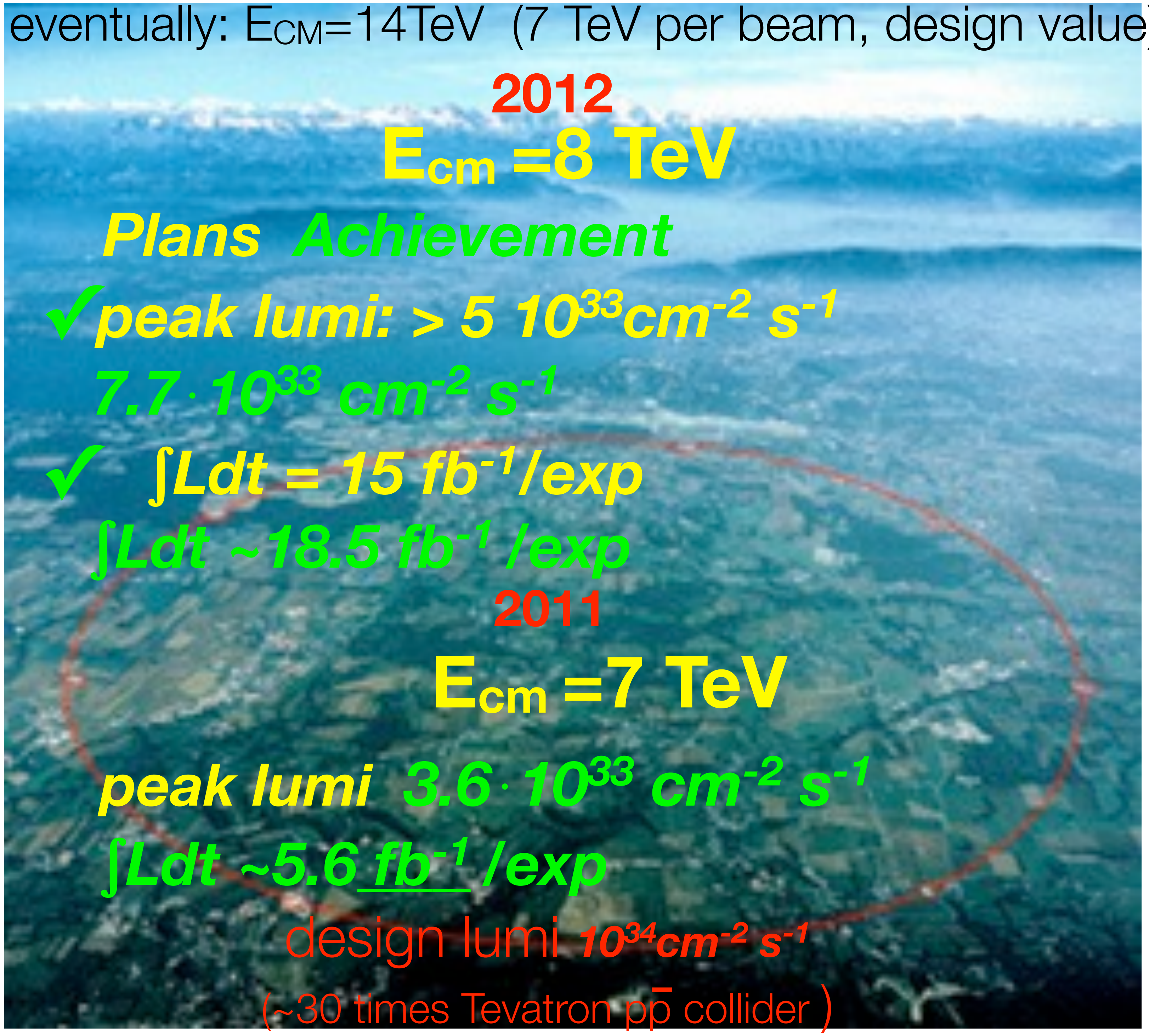
$$\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$$

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

Ad maiora..

2010

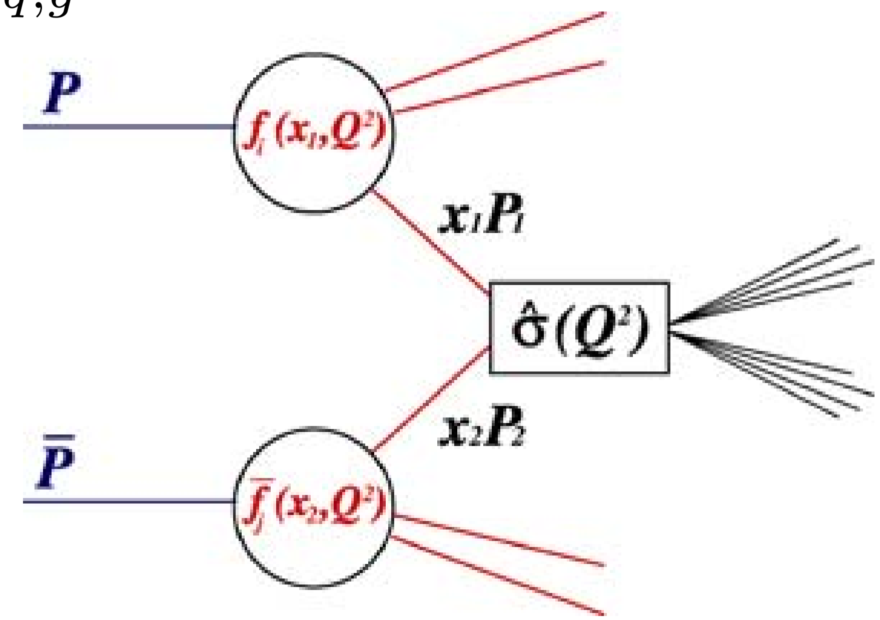




$N_{events}(\Delta t)$= $\int Ldt$ * cross section

Top quark @ LHC: production(I)

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



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

To produce $t\bar{t}$

~massless partons

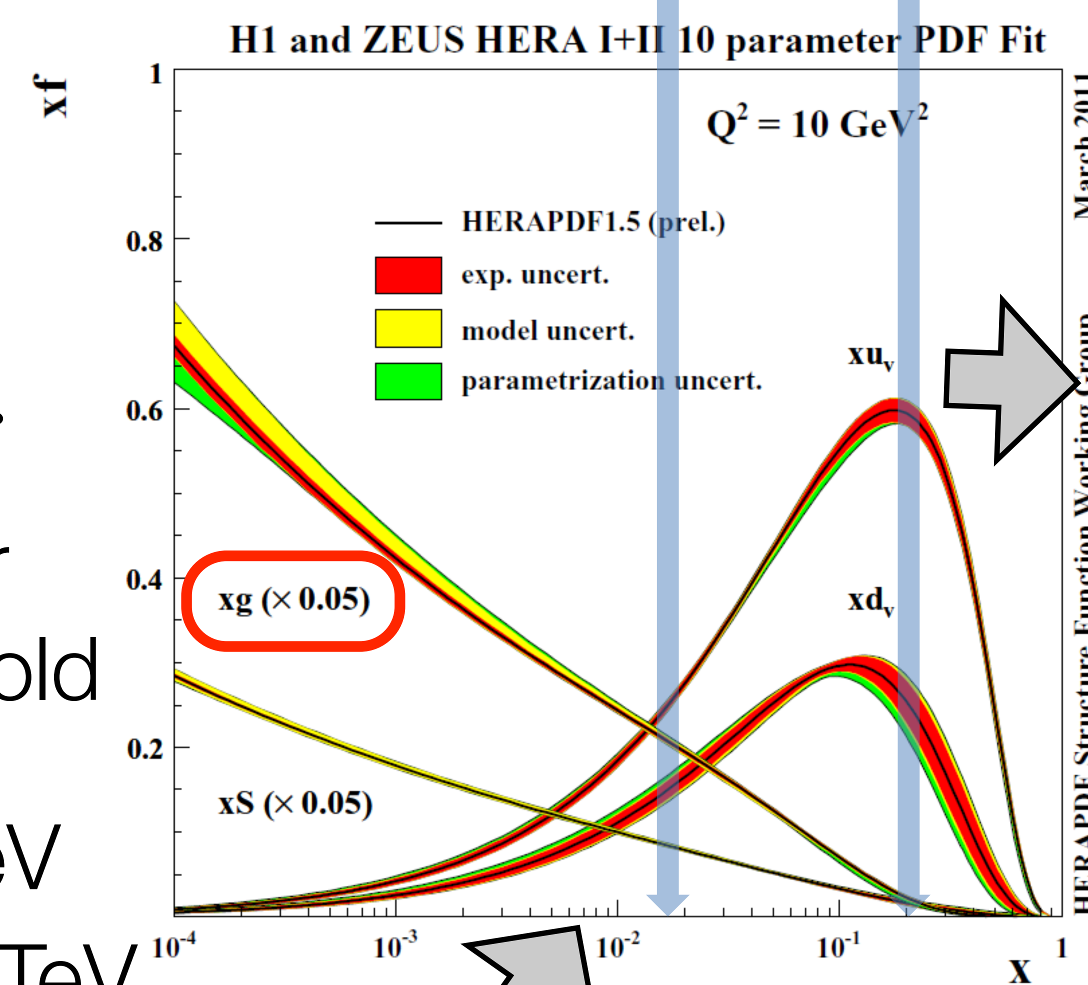
$\hat{s} \geq 4m_t^2$ ⇒ $x_i x_j = \hat{s}/s \geq 4m_t^2/s.$

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

⇒ $x \approx \dfrac{2m_t}{\sqrt{s}} =$ 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

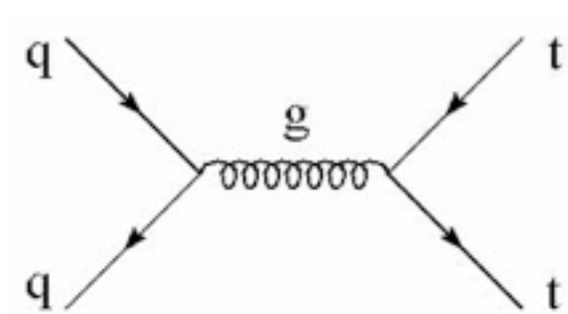


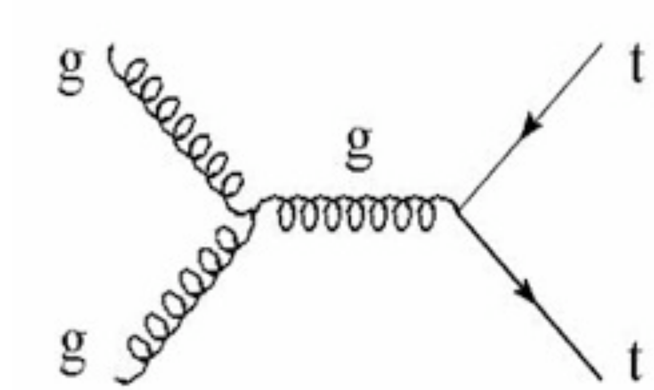
Top quark @ LHC: production

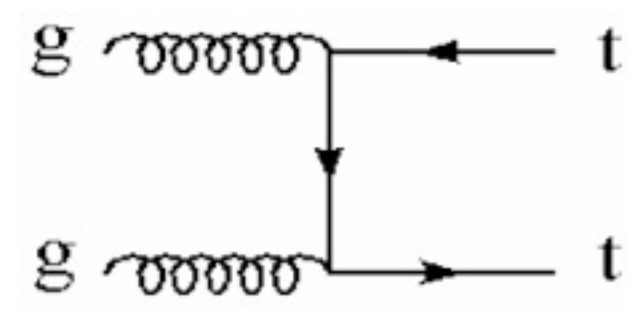
probe low x in pdfs → (abundant) gluon fusion dominated

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

top pairs: strong







Cacciari,Czakon,Mangano,Mitov, Nason 2011

$$\sigma_{7TeV} = 159\,^{+12}_{-13}\,^{+4}_{-4}\ \text{pb}$$

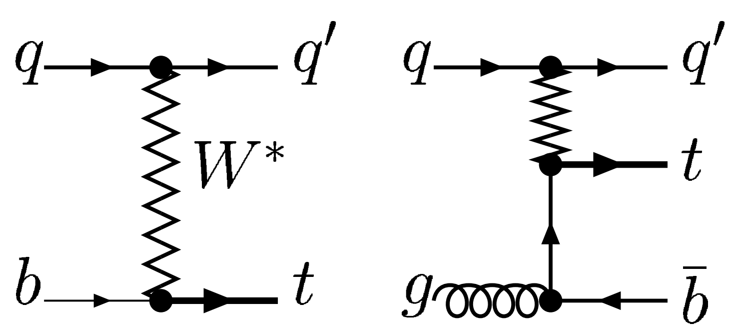
$$\sigma_{8TeV} = 227\,^{+18}_{-19}\,^{+6}_{-6}\ \text{pb}$$

scales *PDF*

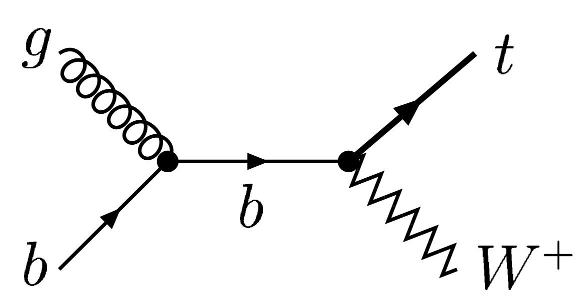
PDF=MSTW2008nnlo68cl for m_{top}= 173.3

single top: electroweak

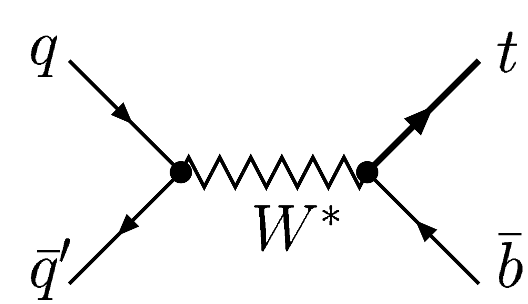
t chan



Wt chan



s chan



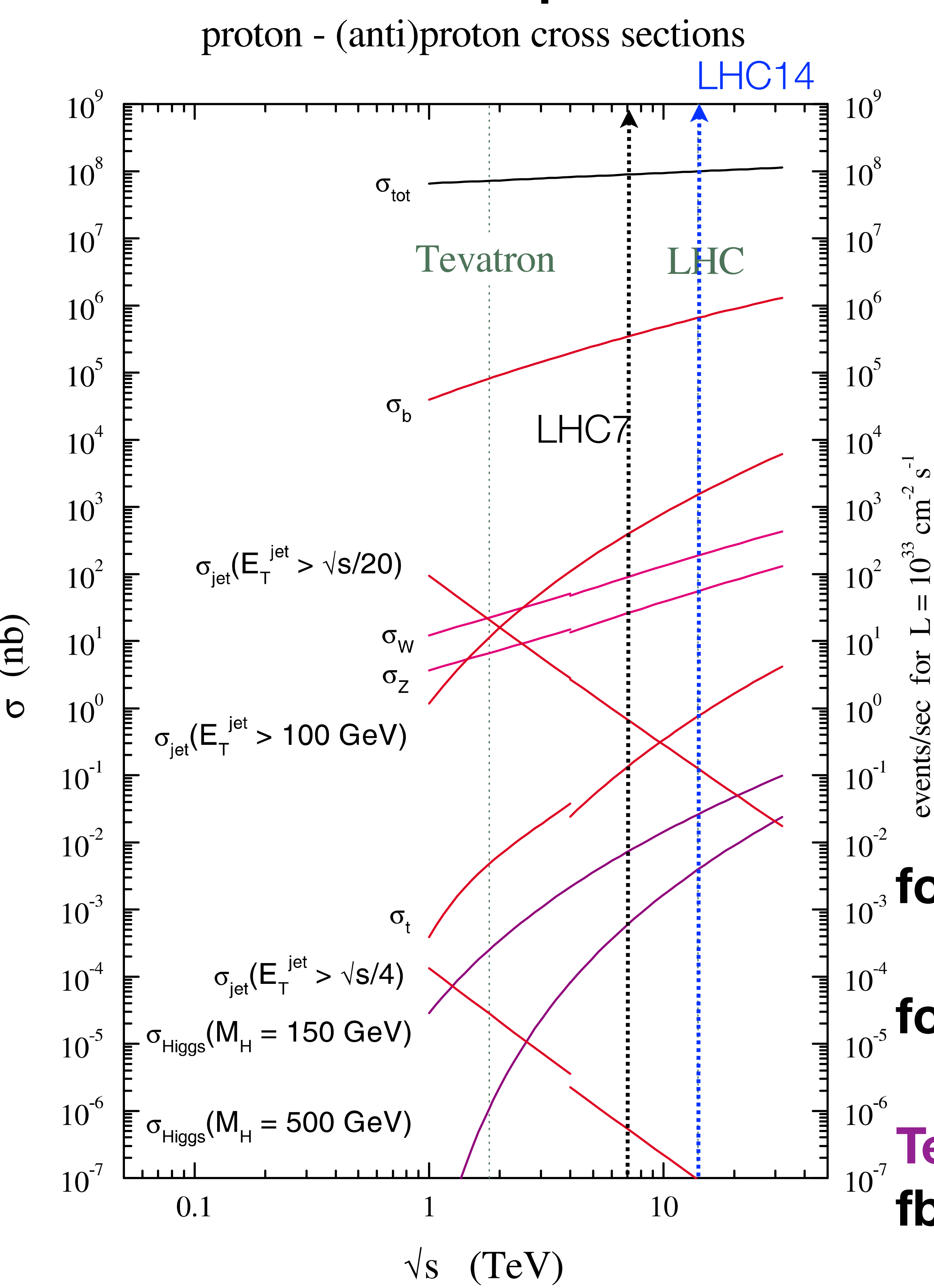
Kidonakis 2010,2011

$\sigma_{7TeV} = 64^{+3}_{-3}$ pb
$\sigma_{8TeV} \sim 86$ pb

$\sigma_{7TeV} = 15.7^{+1.3}_{-1.4}$ pb
$\sigma_{8TeV} \sim 22$ pb

$\sigma_{7TeV} = 4.6 \pm 0.3$ pb
$\sigma_{8TeV} \sim 5.6$ pb

Top @ LHC: in the context



$t\bar{t}$ cross section

$\sqrt{s}$(TeV)	xsec (pb)	Rate at L= 10^{33}cm^{-2} s^{-1}
1.96 ($p\bar{p}$)	~7	
7 (pp)	~165	0.16Hz
8(pp)	~230	0.23Hz
14 (pp)	~900	0.9Hz

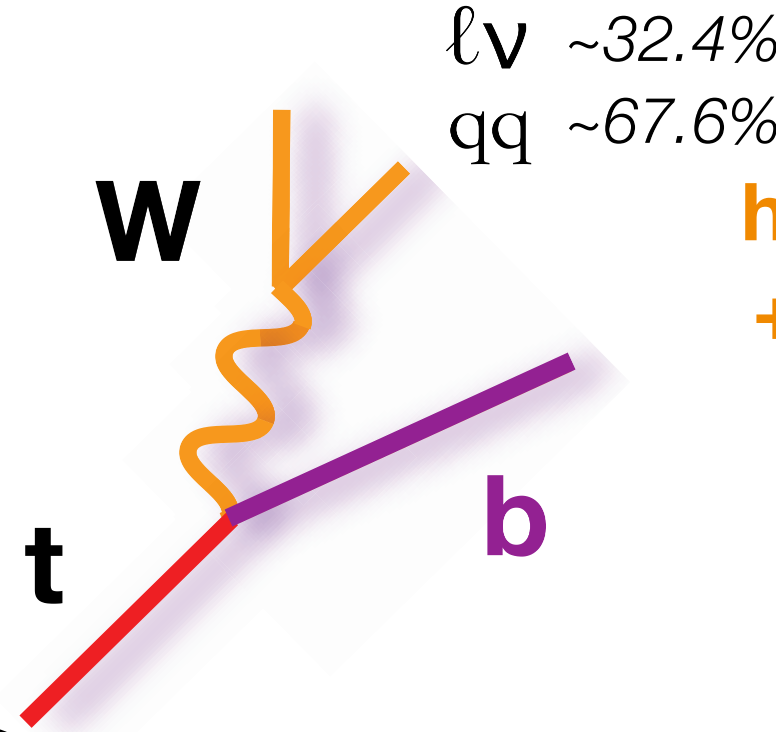
for $\int Ldt$ = 5 fb^{-1} @7TeV, expect ~$8 \cdot 10^5$ events

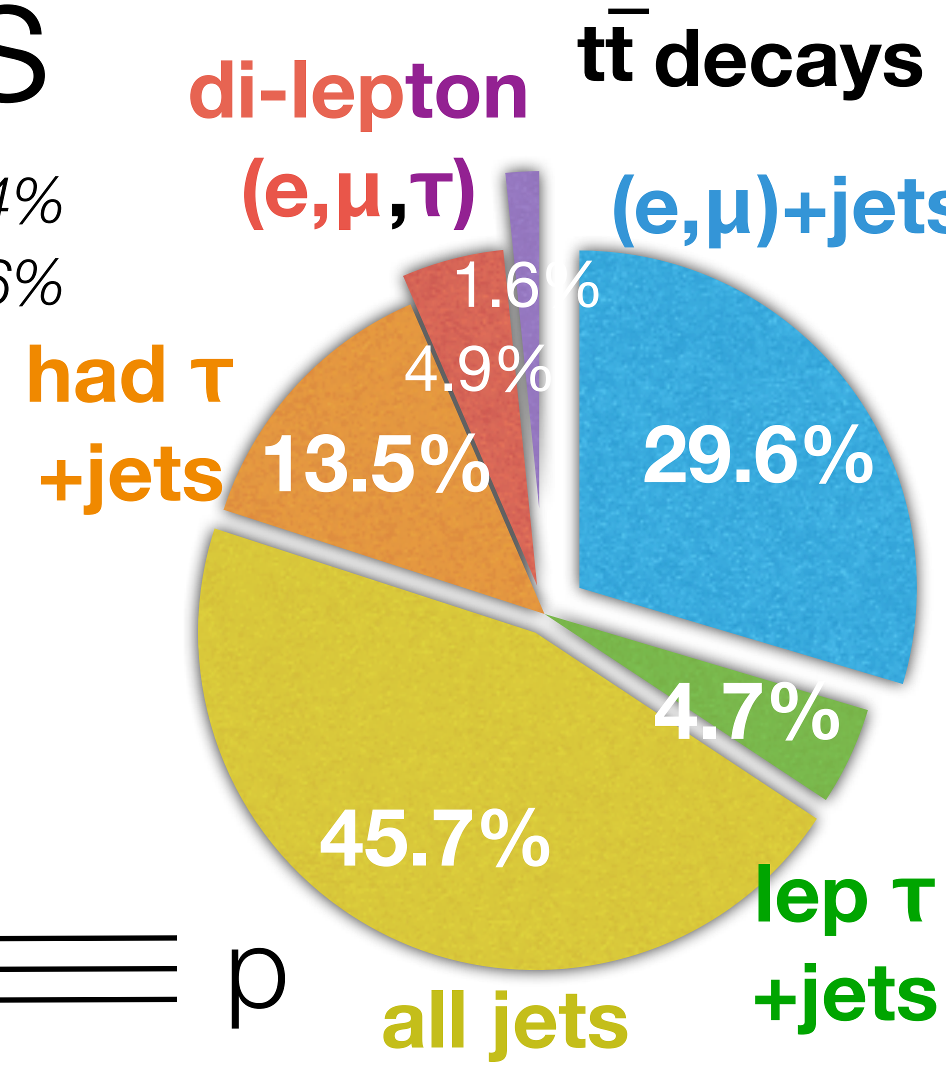
for $\int Ldt$ =18fb^{-1}@8TeV, expect ~4.1 10^6 events

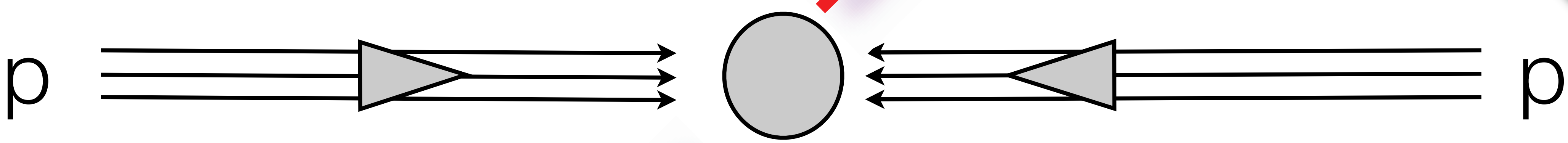
Tevatron (lower energy collider): $\int Ldt$ =9.4 fb^{-1} on tape, expect ~ $6.6 \cdot 10^4$ events

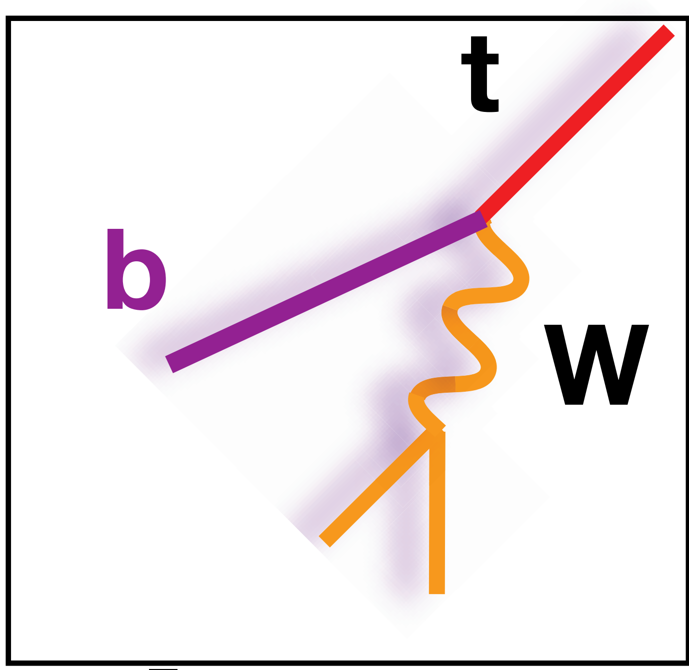
Top signatures

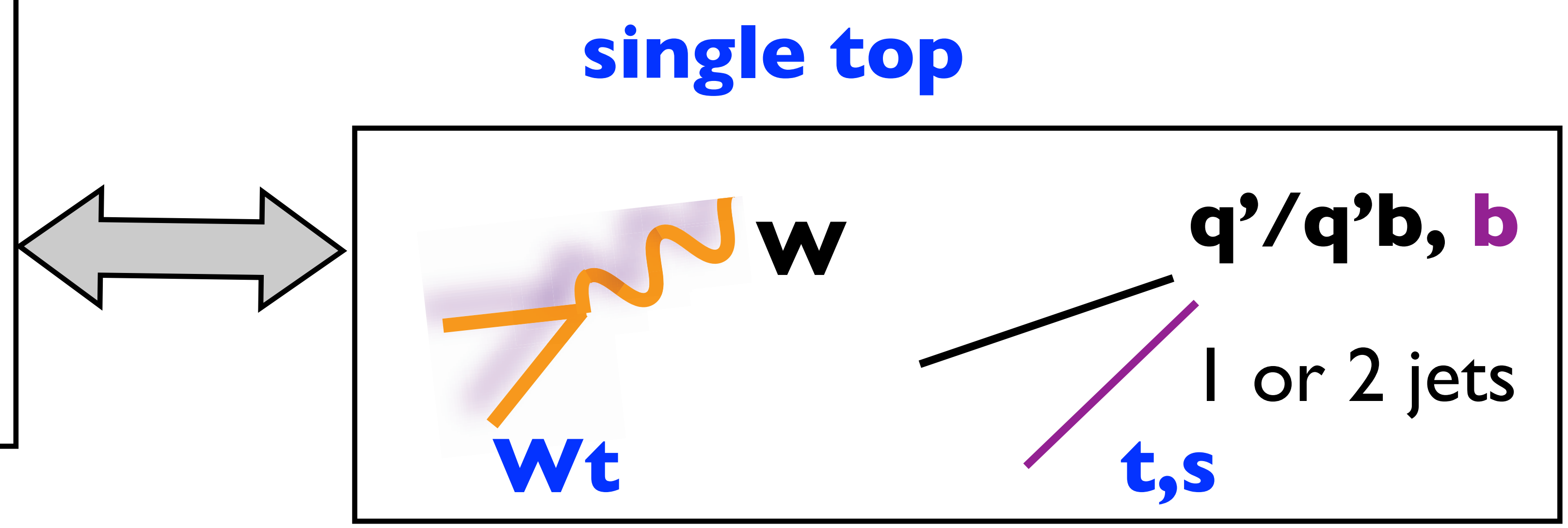
- **High P_T jets**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**









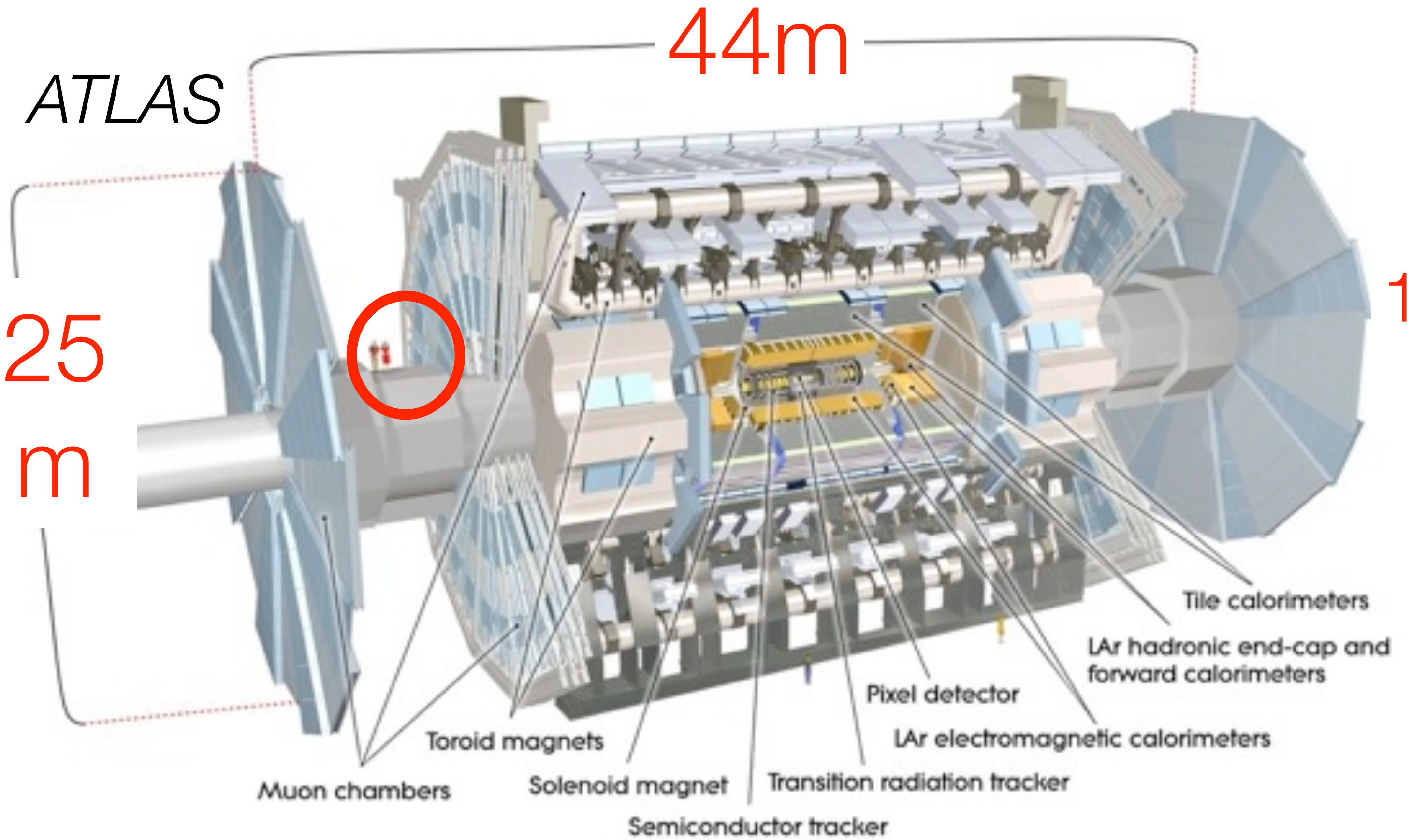


bkgs_tt: W/Z(+jets), single top, QCD, Di-bosons

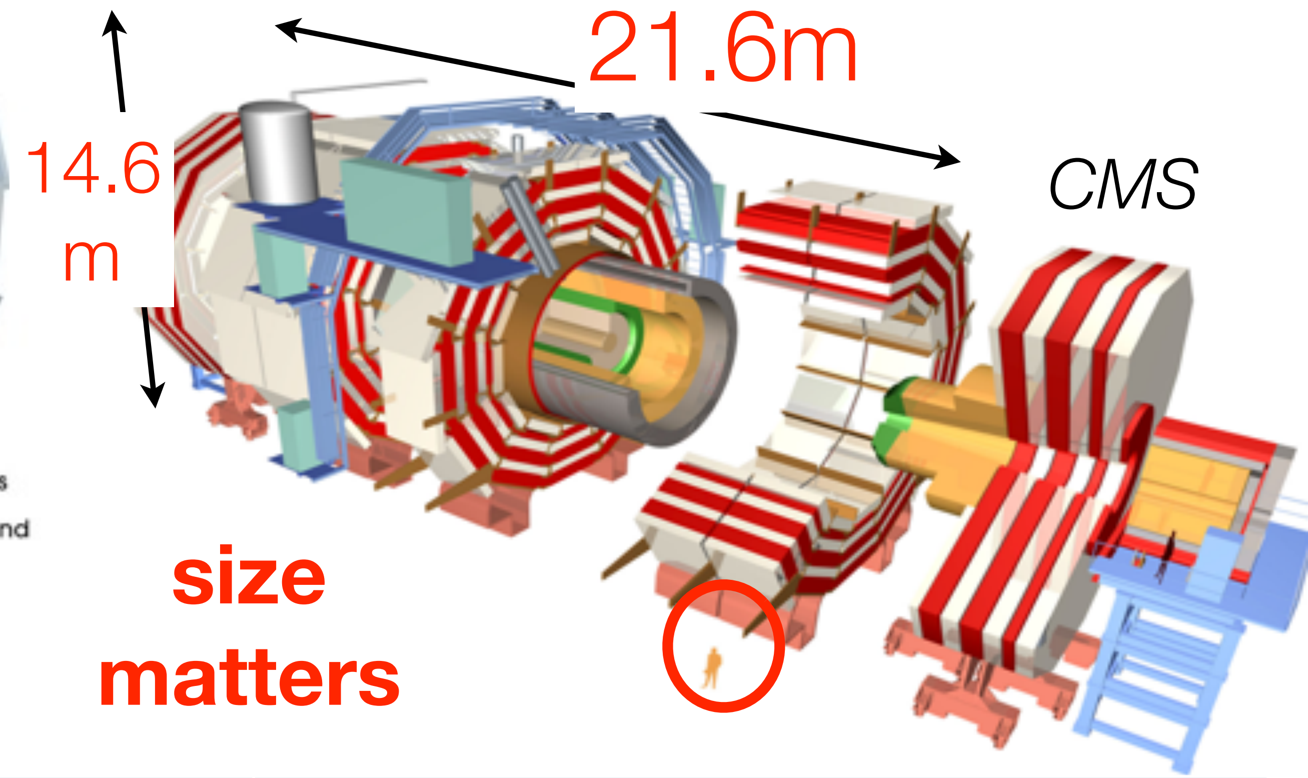
bkgs_single_t: tt +some bkgs_tt

***ATLAS* & *CMS*:** *Top* observers

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

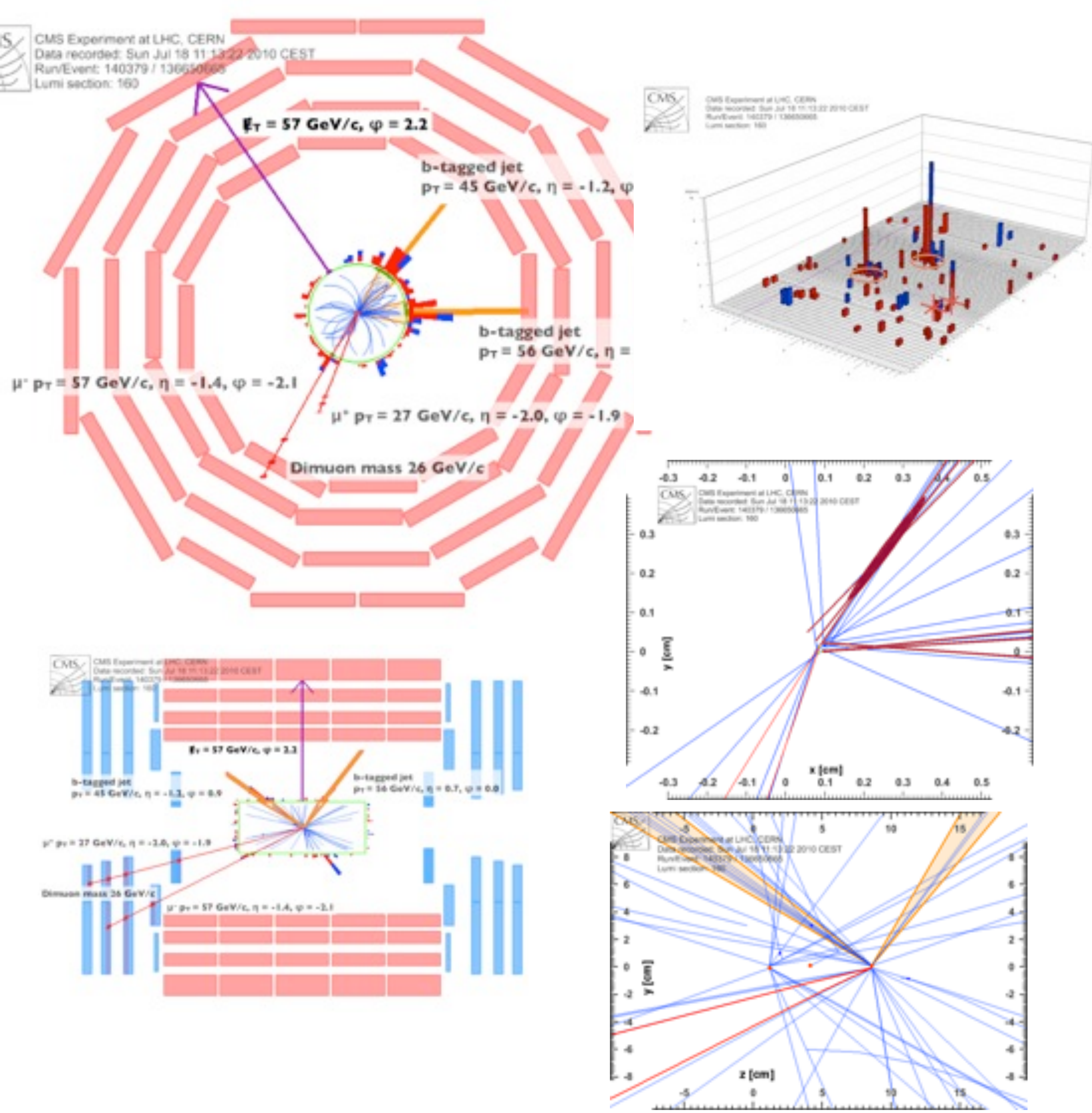


size matters



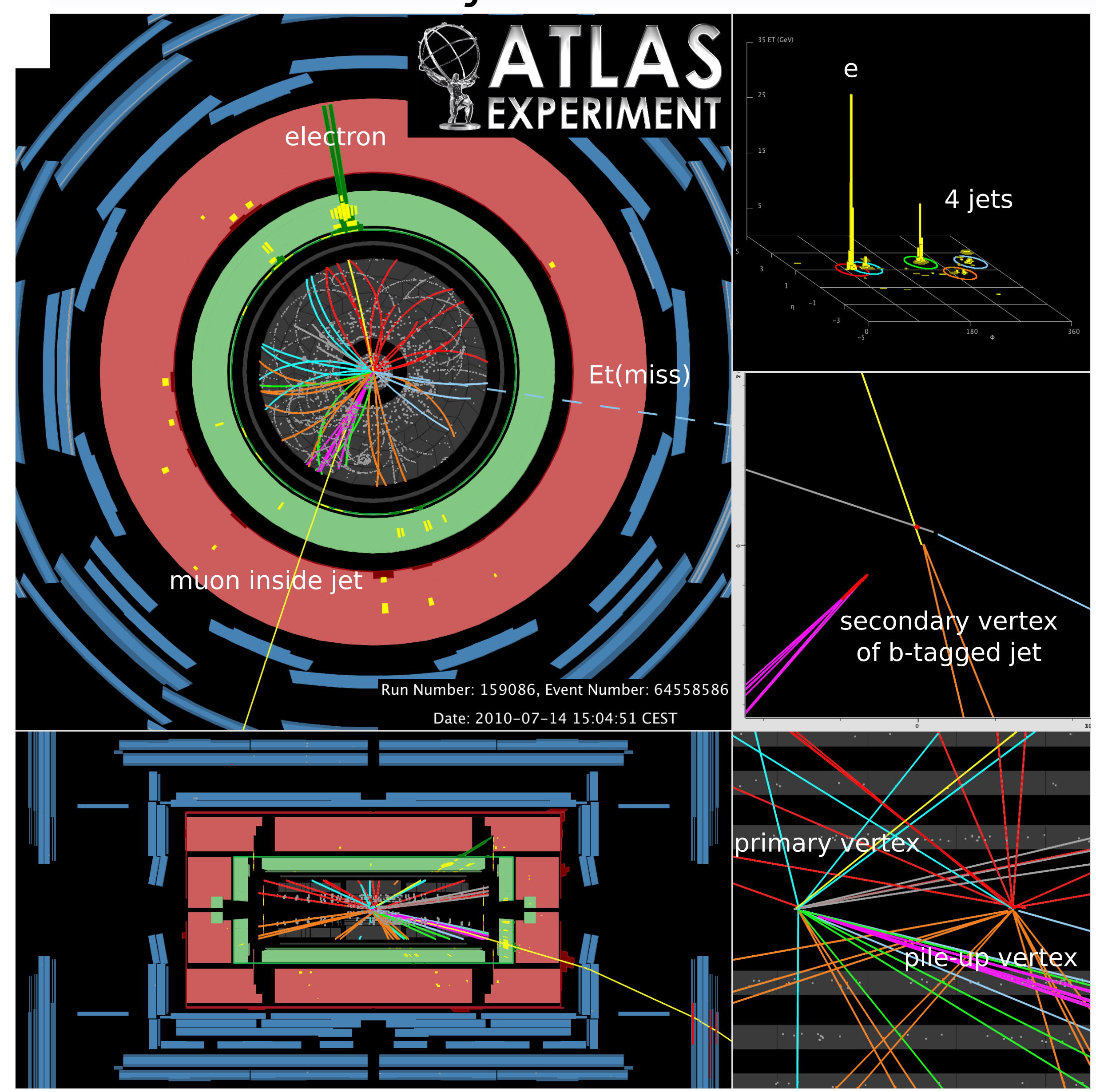
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	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 events are real commissioning tool: full detector at play!!

e+jets candidate

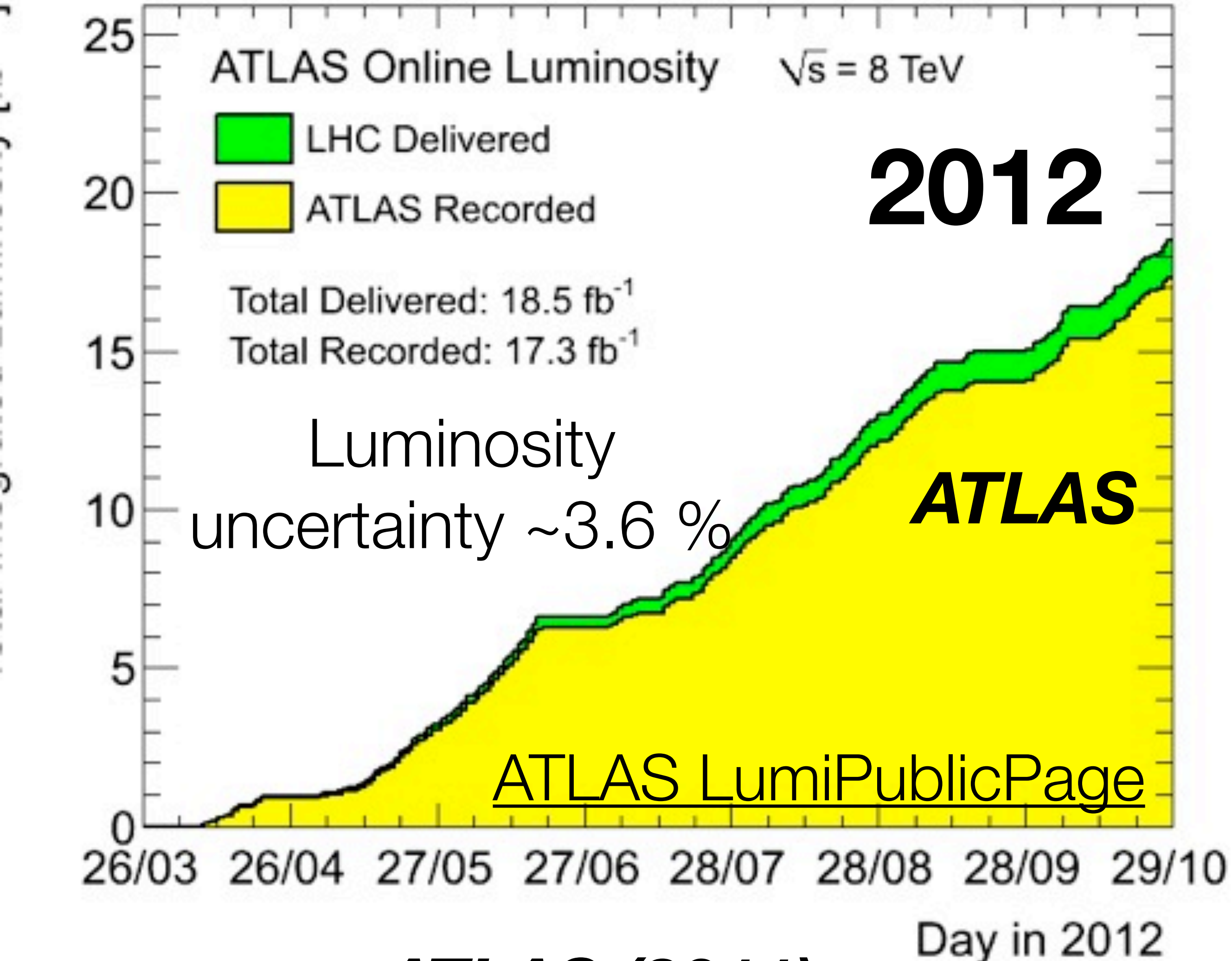


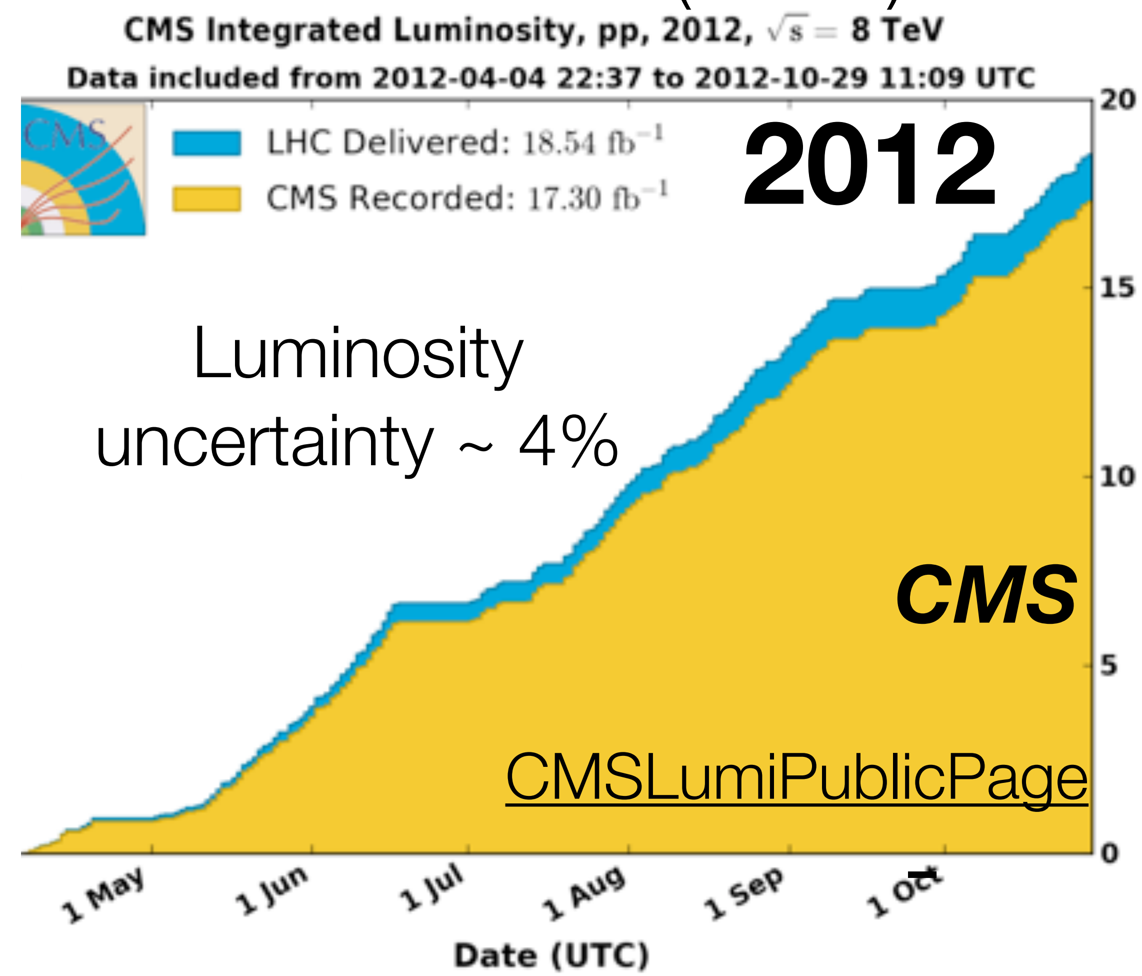
di-lepton (μμ+jets) candidate

...with excellent data taking performance

Analyses use 1. to 4.6 fb^{-1} (2011)

an ~5.6 fb^{-1} (2012)





ATLAS (2011)

tal Recorded (Delivered) Lumi: **5.61 (5.25) fb^{-1}**

Luminosity uncertainty ~3.7 to 4.5% (prel)%

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:

5.73 (5.22) Fb^{-1}

Lumi uncertainty~4.6%

CMS (2010)

Total Recorded (Delivered) Lumi:

47.03 (43.17) pb^{-1}

Lumi uncertainty~4%

...In a harsh environment

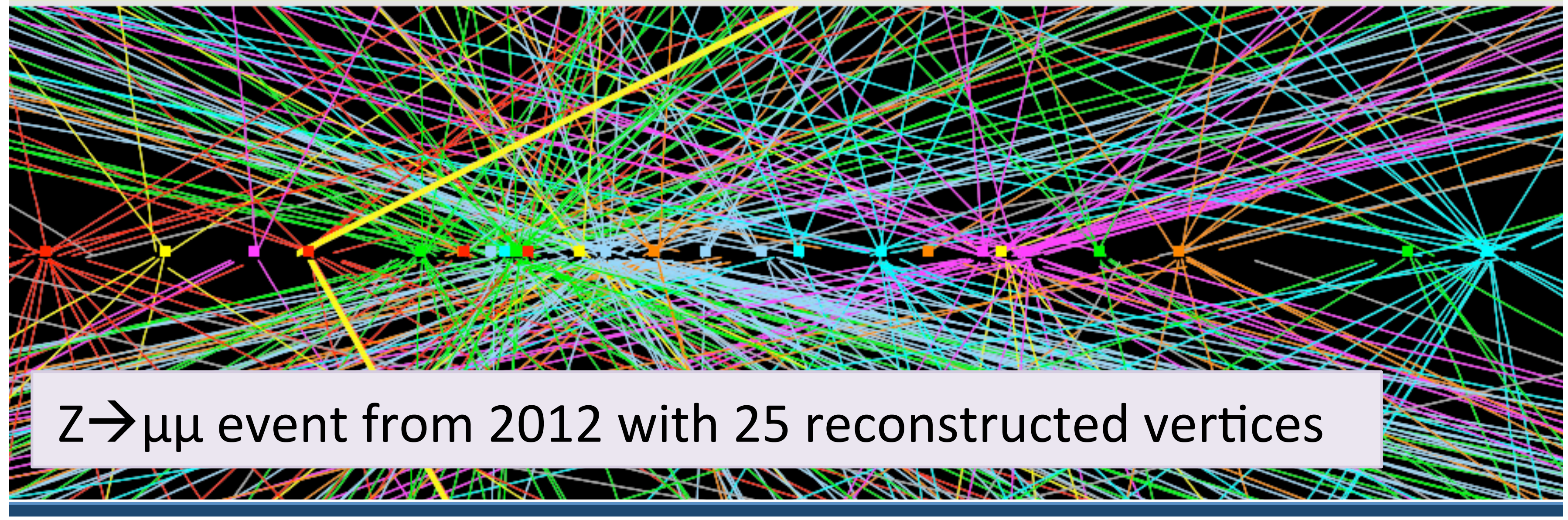
- ***Number of Interactions per Crossing***

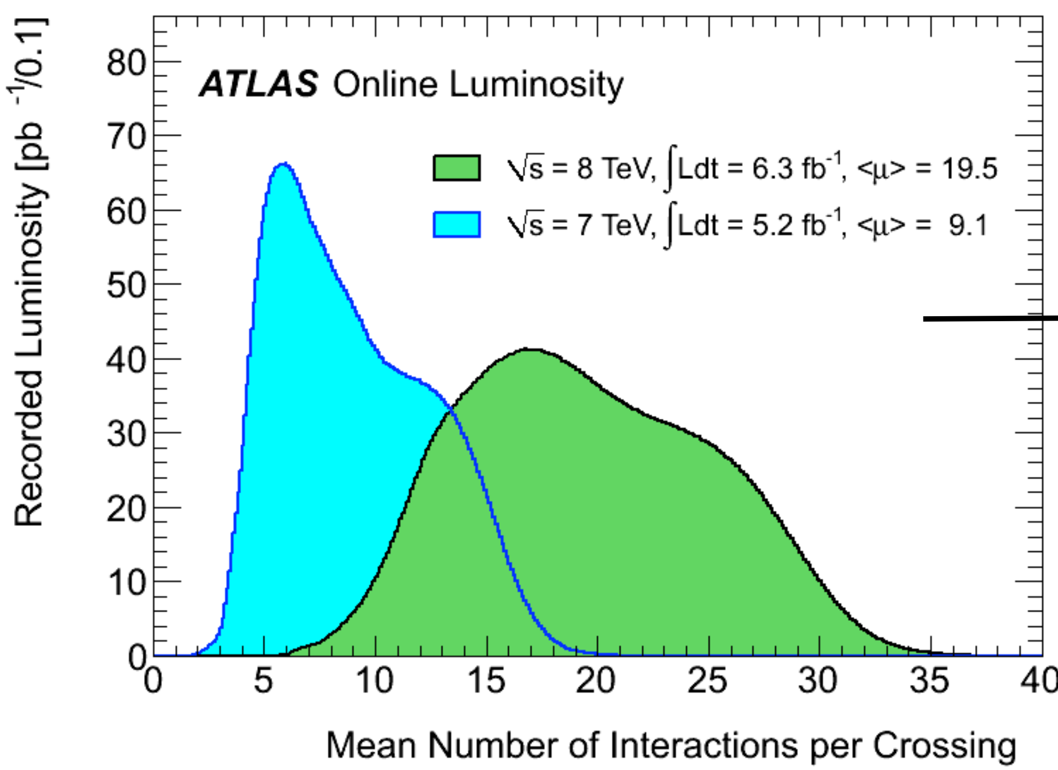
*Shown is the **luminosity-weighted distribution of the mean number of interactions** per crossing for 2012 taken upto June 18th. The integrated luminosities and the mean mu values are given in the figure. The mean number of interactions per crossing corresponds the mean of the poisson distribution on the number of interactions per crossing 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 73 mb, 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.*

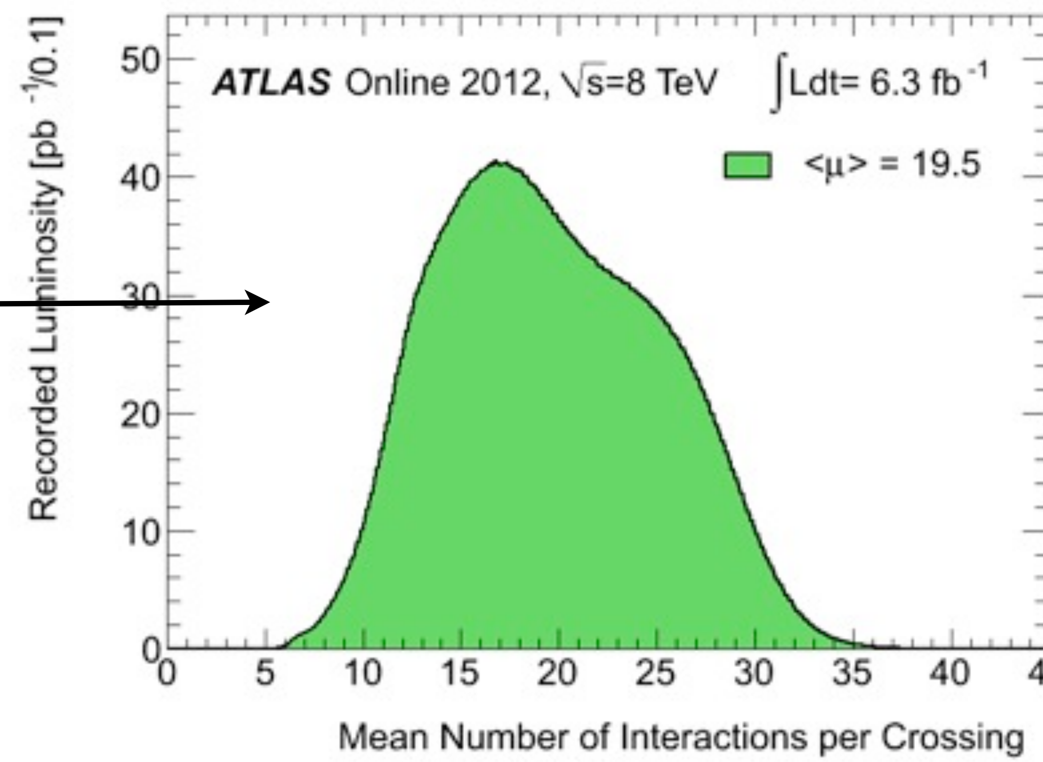
ATLAS LumiPublicPage

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…

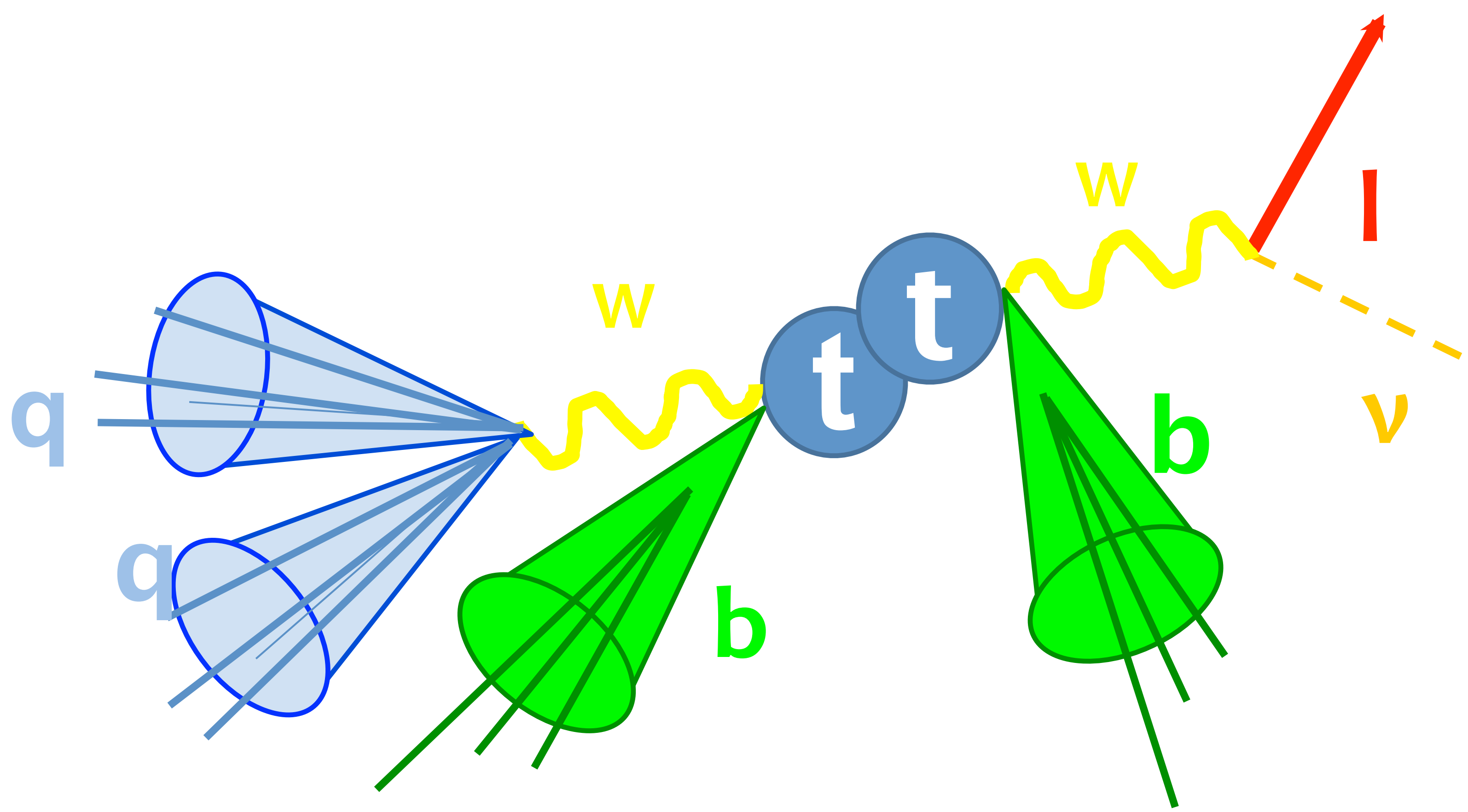






Selection/Ingredients for top quark pairs/single-top

ATLAS (CMS is similar)



Selection/Ingredients for top quark pairs/single-top

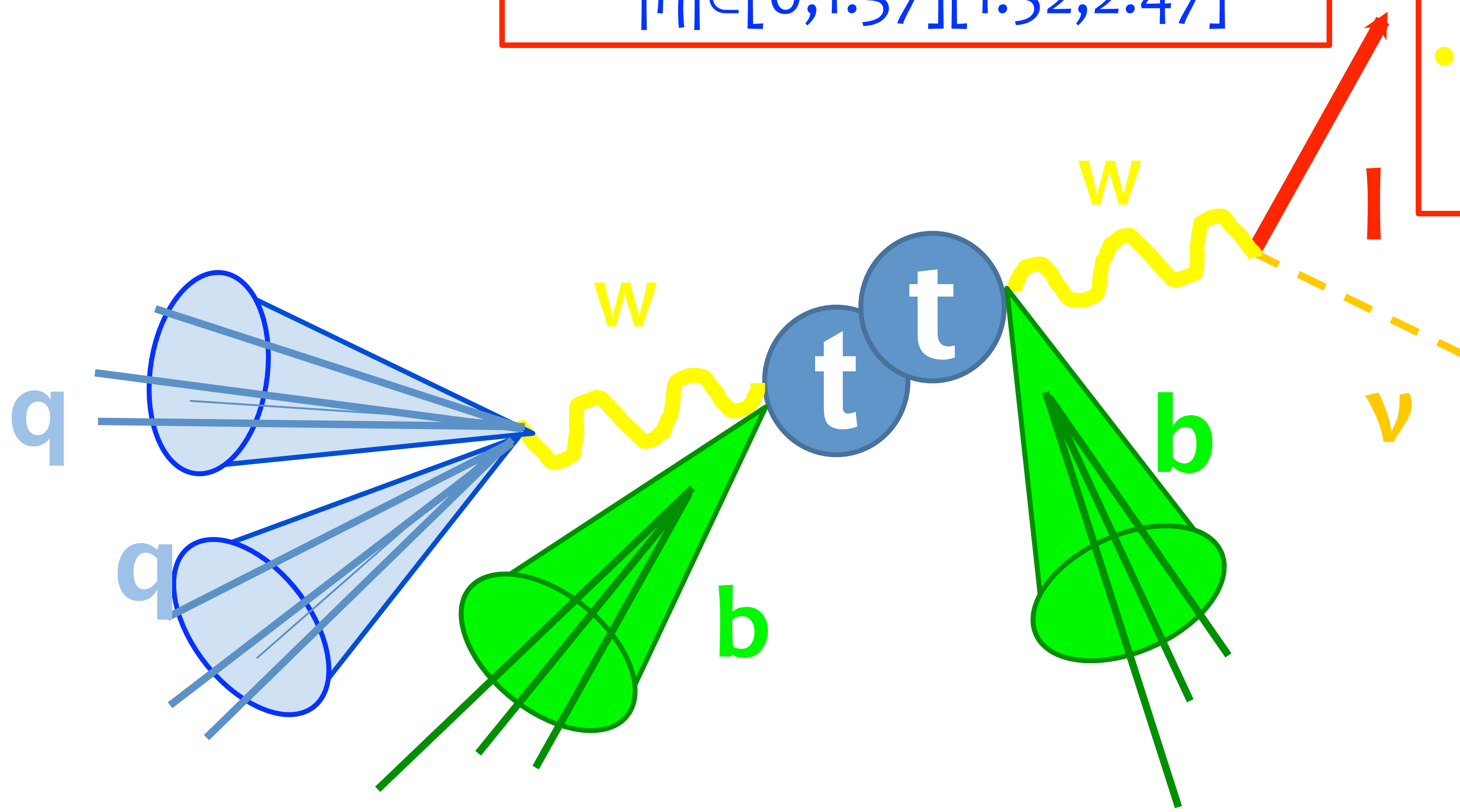
ATLAS (CMS is similar)

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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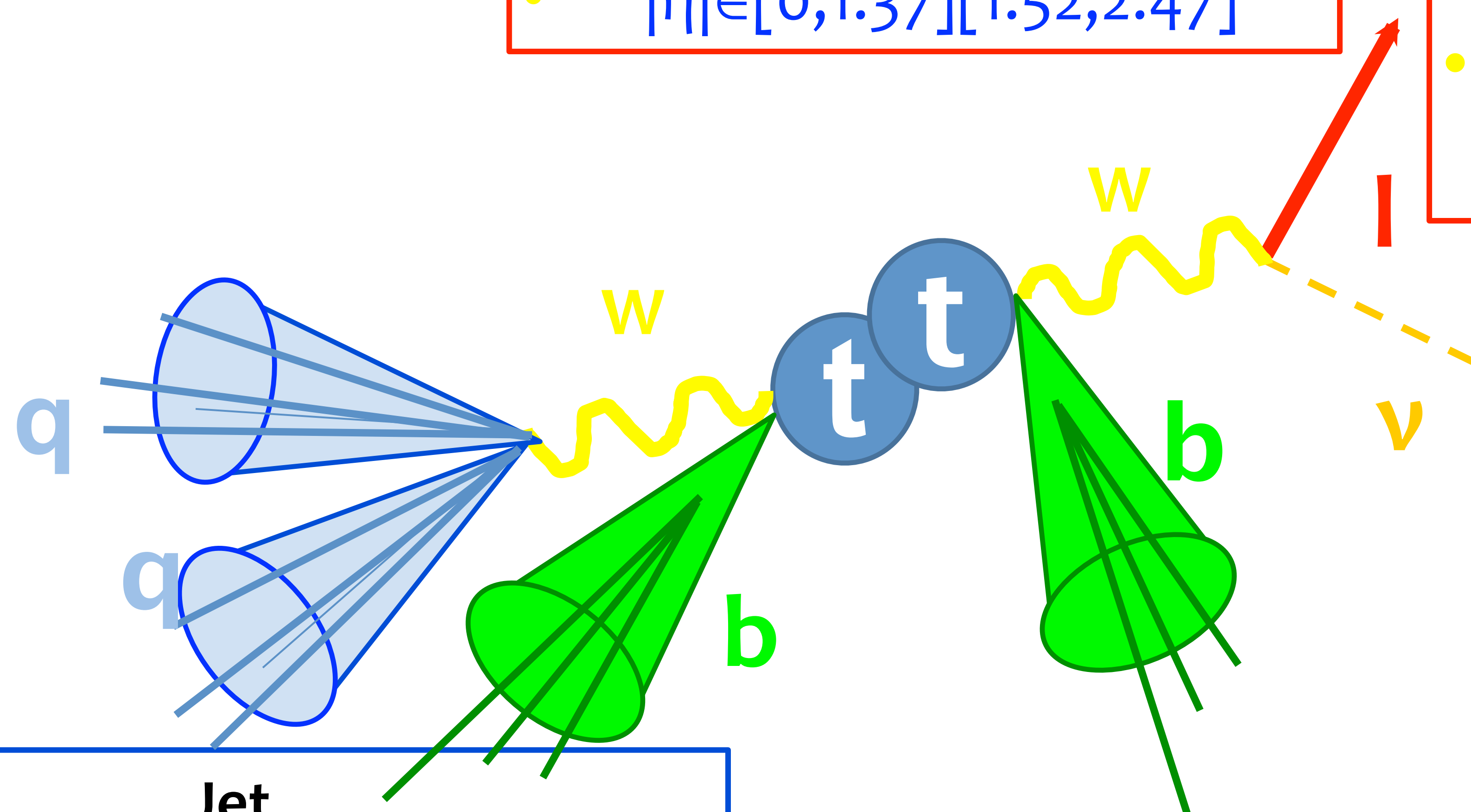

Jet

- 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 verted)

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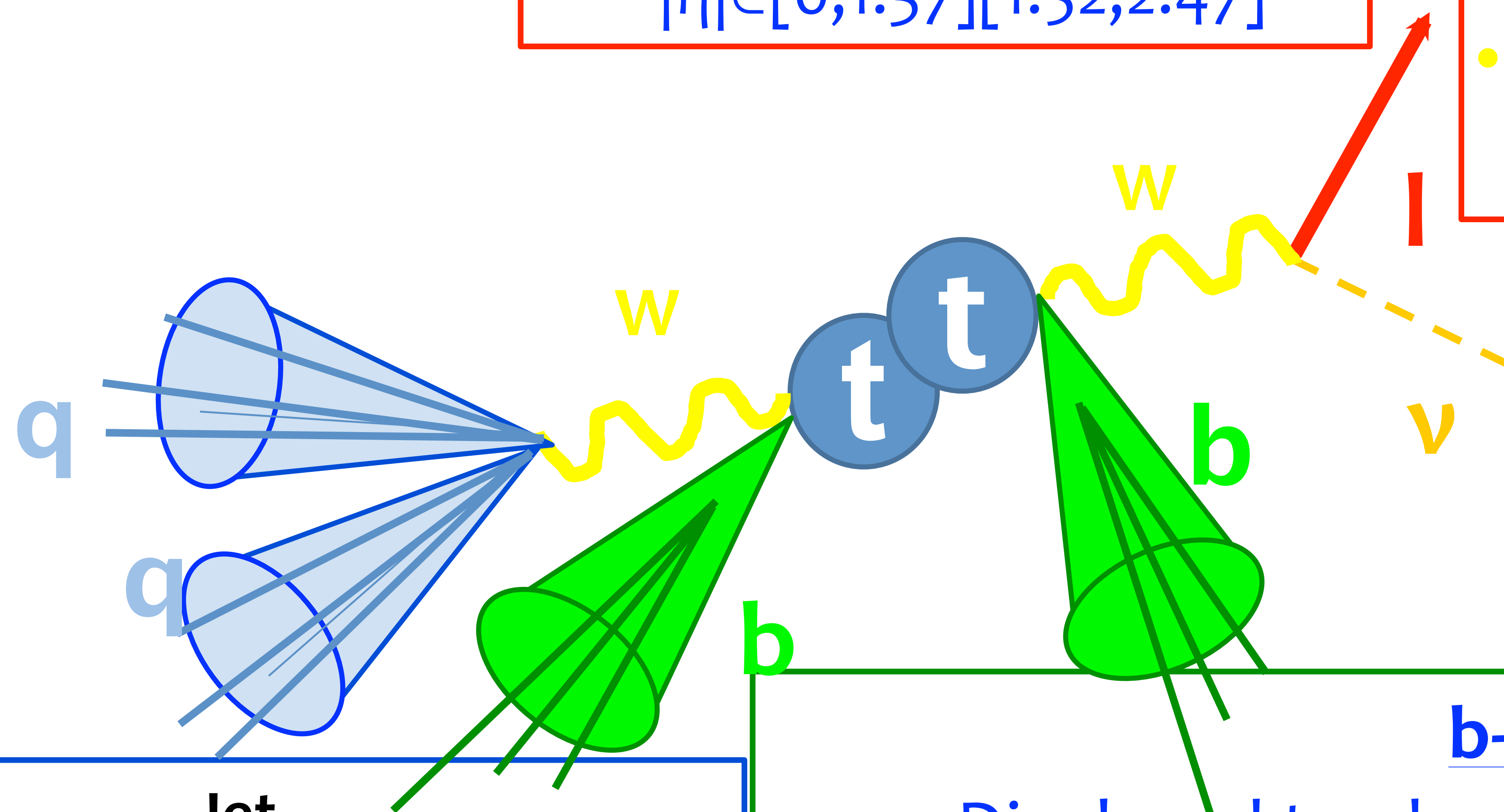

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b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with prim. vertex
- IP3D+SV1 +/or JetFitter: advanced lkl/NN taggers

Selection/Ingredients for top quark pairs/single-top

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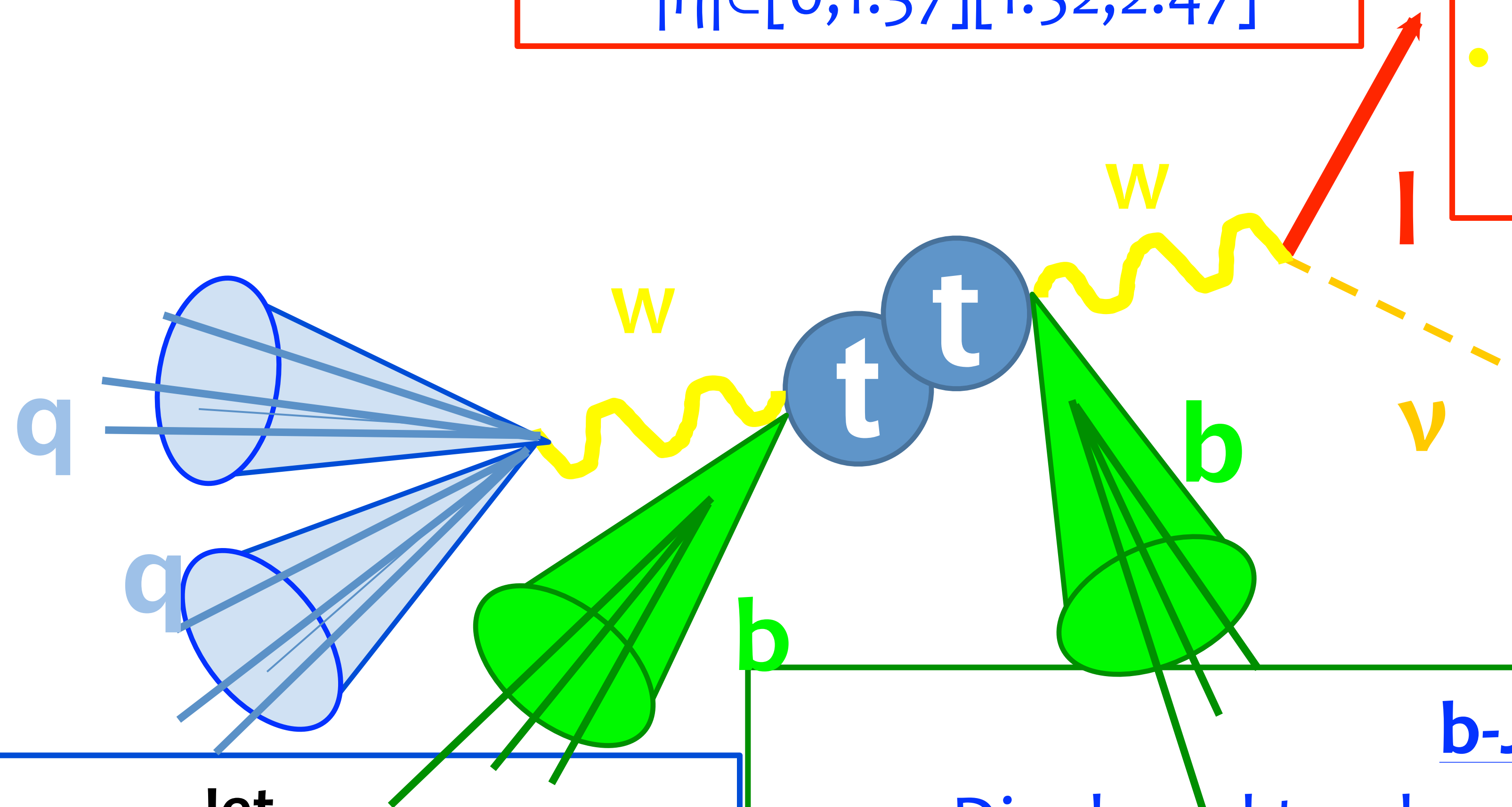

E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

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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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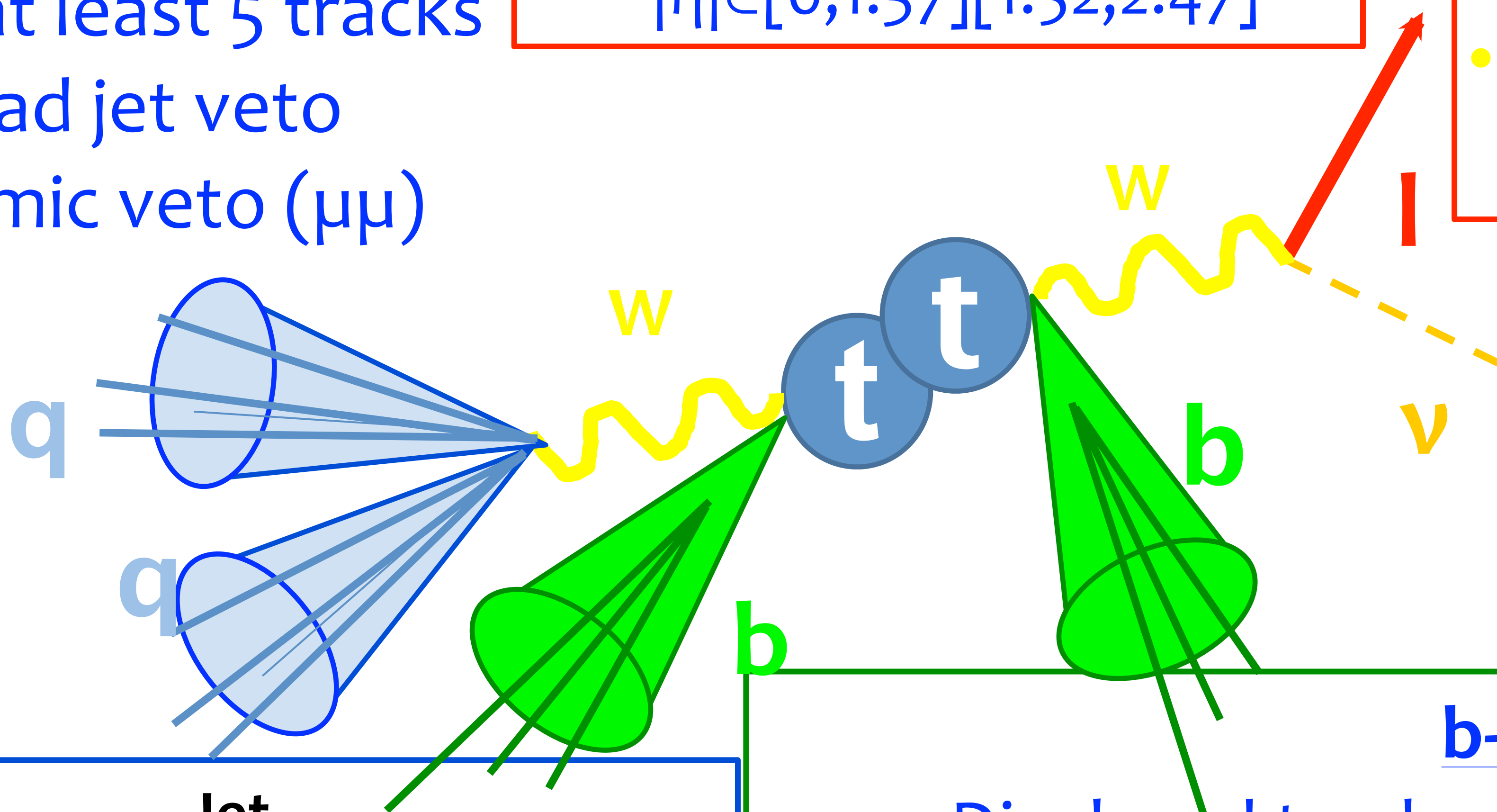

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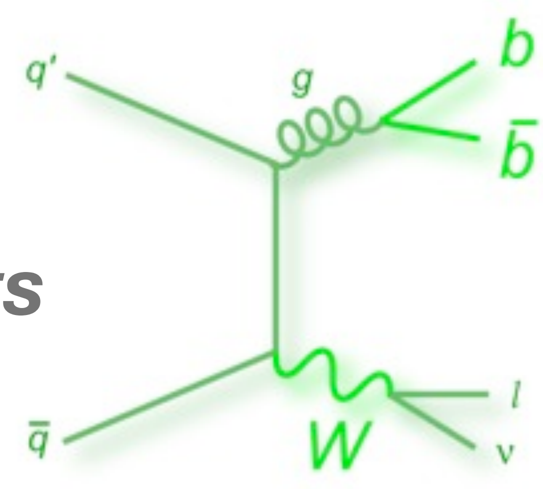
Backgrounds estimates (single lepton+jets)

- **W+jets**

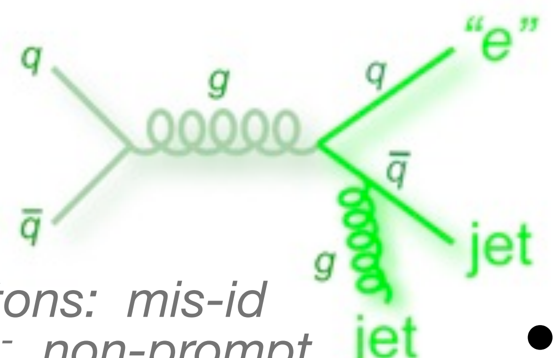


- *simulated shape*
- ***normalization: scale from charge asymmetry of W prod*** *before b-tag, MC extrapolation to b-tagged region*

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

MC data

- **QCD**



- *"Fake" leptons: mis-id jets,γ→e⁺e⁻, non-prompt leptons (b/c-decays), punch-through had*

- *Matrix method*

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

(J Boudreau Top2012)

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**

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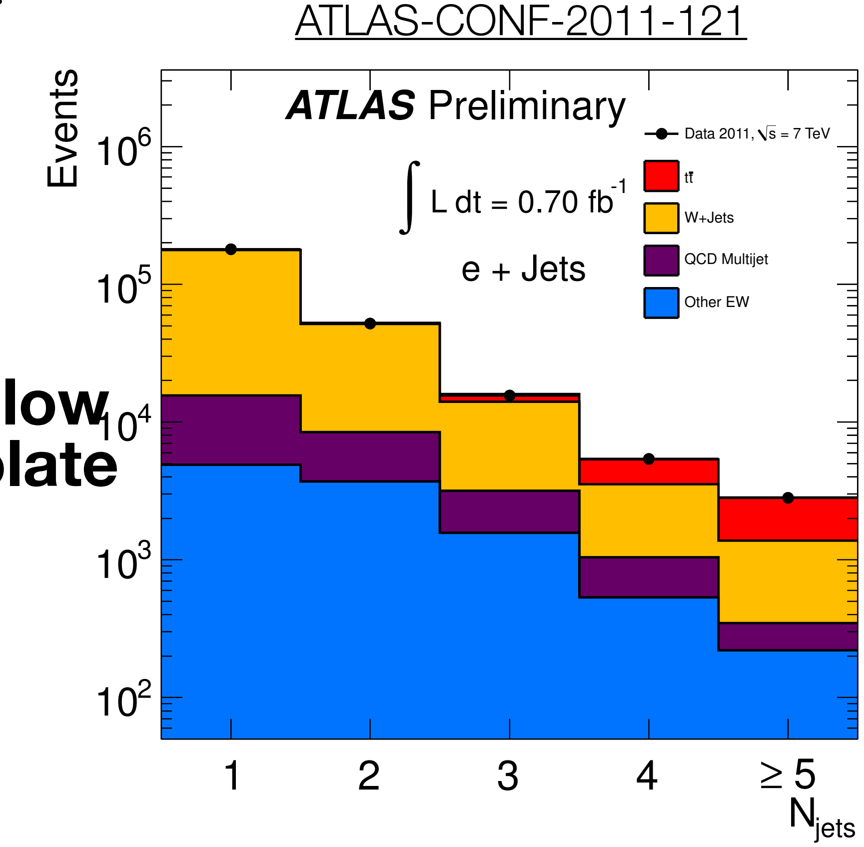
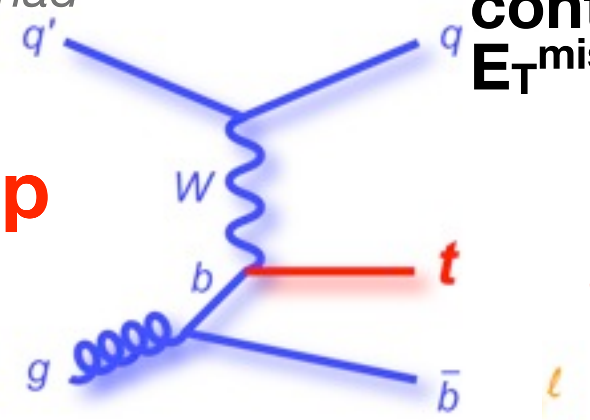


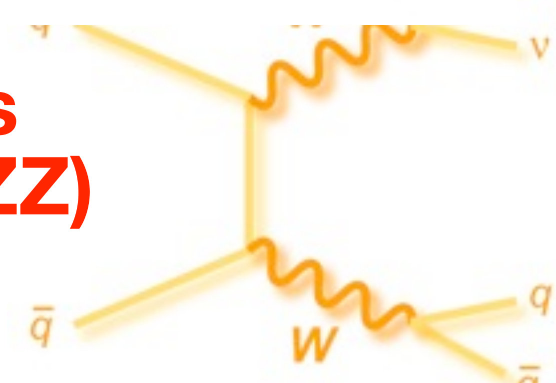
normalizations=fit parameters, estimates are starting points for fit

- **Single top**



Simulated shape+ rate set to SM

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



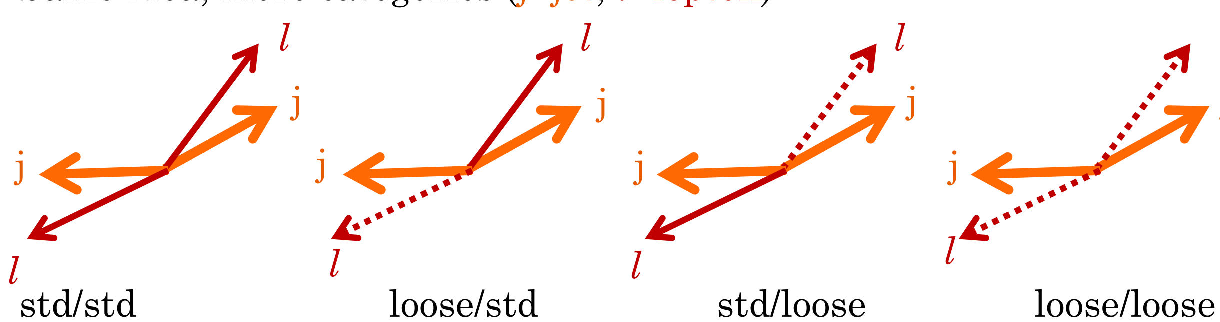
simulated shape+ rate from simul.

Backgrounds (di-lepton)

ATLAS-CONF-2011-100

- "Fake" leptons from data
  - 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**

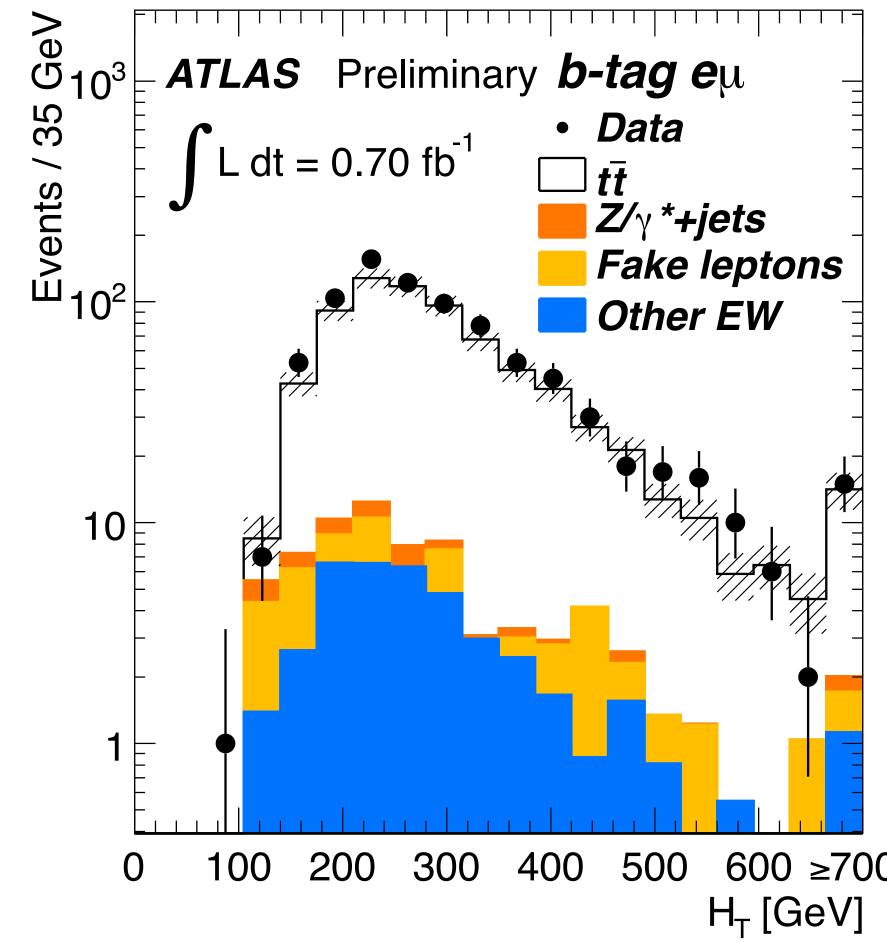
Same idea, more categories (j=jet, l=lepton)

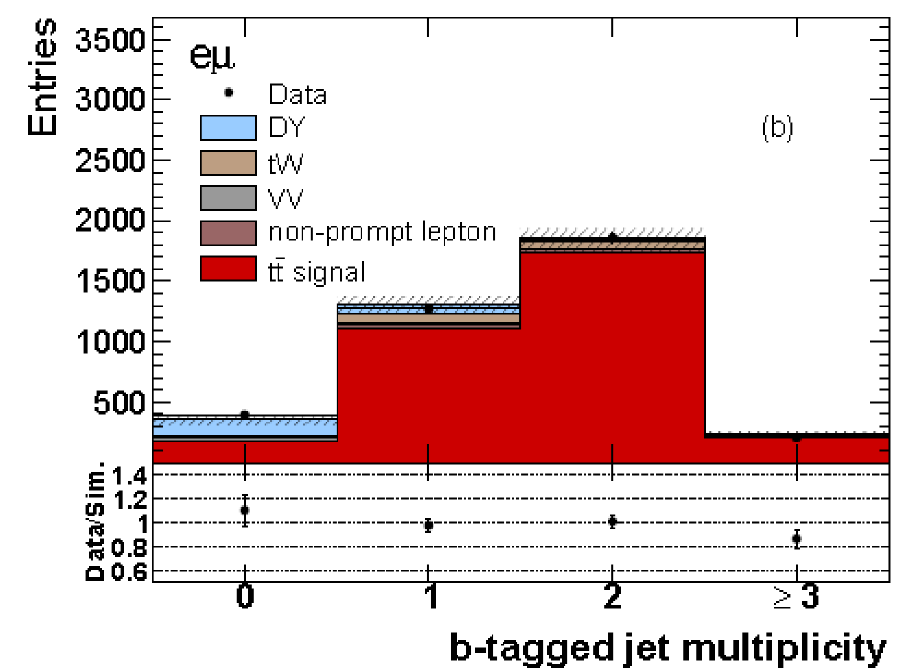


(J Boudreau Top2012)

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

- 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.**





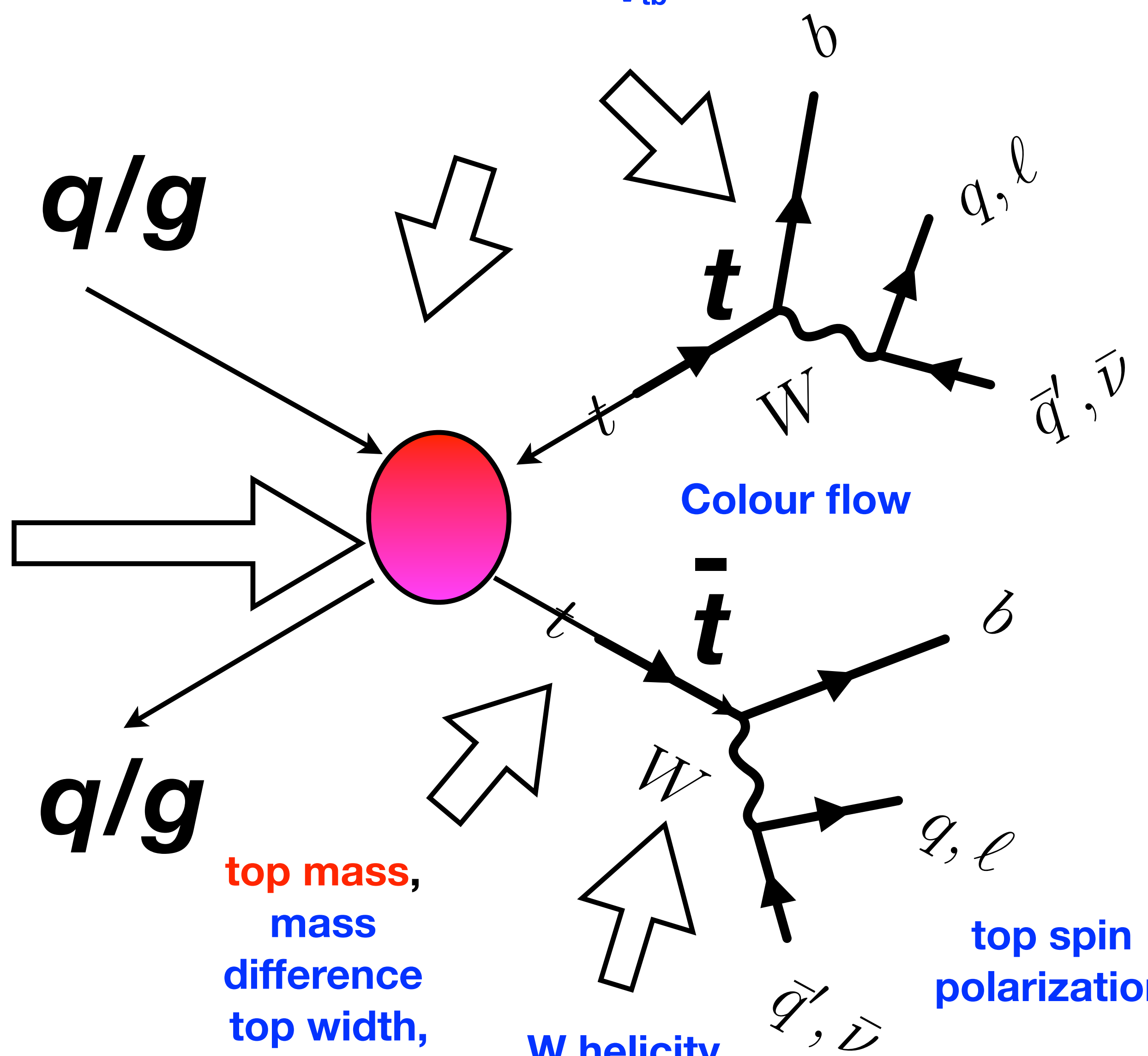
What we study about the top quark

inspired by figure
by D Chakraborty

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 mass,
mass
difference
top width,
spin,
charge
lifetime

W helicity
Wtb
coupling,V
(tb)

top spin
polarization

Typical analysis flow

- 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 systematc uncertainties on the measured quantity**

- Combine the results from different samples (if necessary)

- Compare with prediction(s)

Measurement of top cross sections: σ_{tt} and σ_t

or

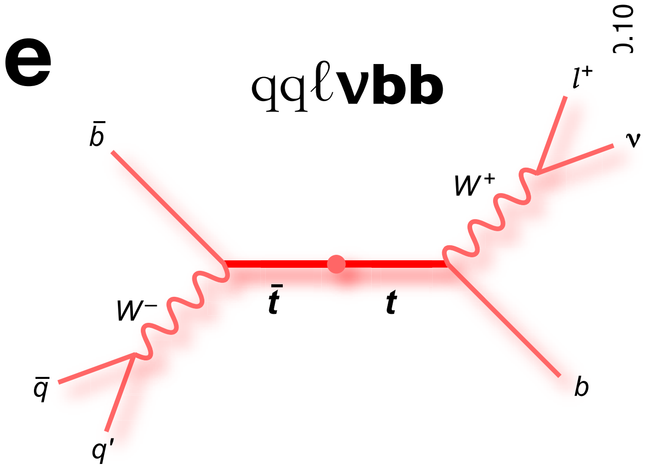
how many tops have we got?

Start to combine results at the LHC...

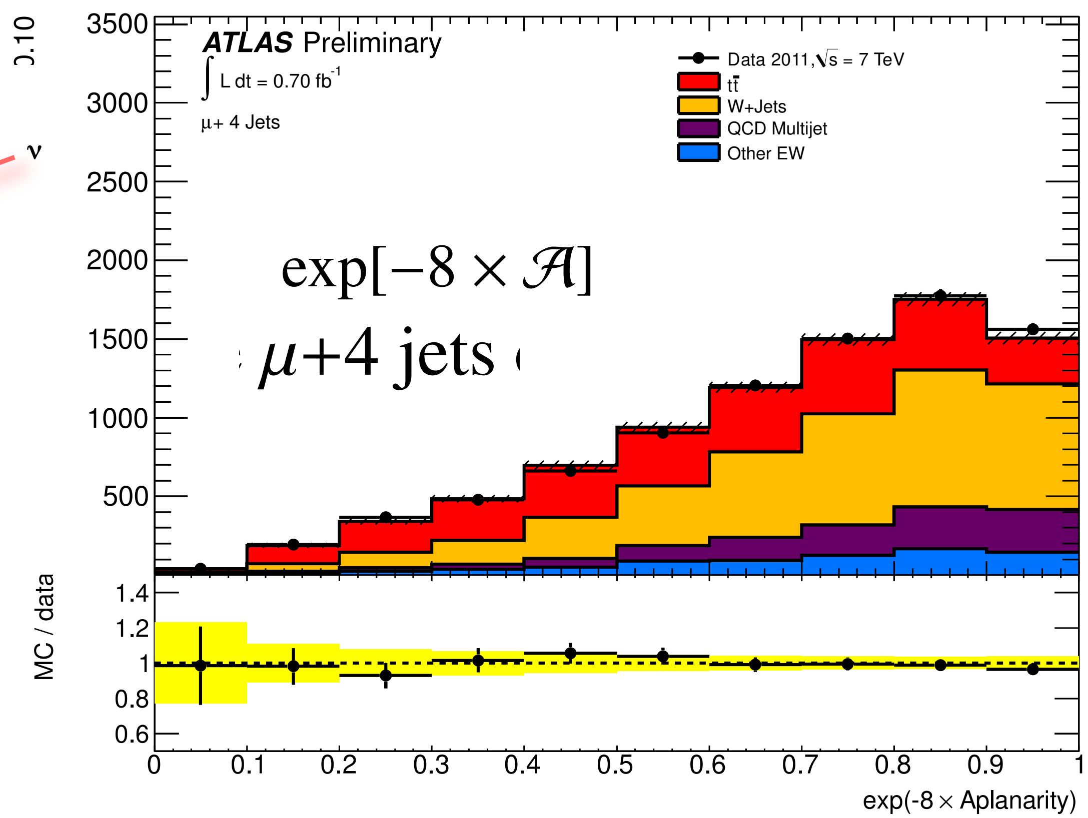
Measurement of $\sigma_{t\bar{t}}$ - single lepton

$\int L dt =$ **~0.7 fb^{-1}** *(2011)*

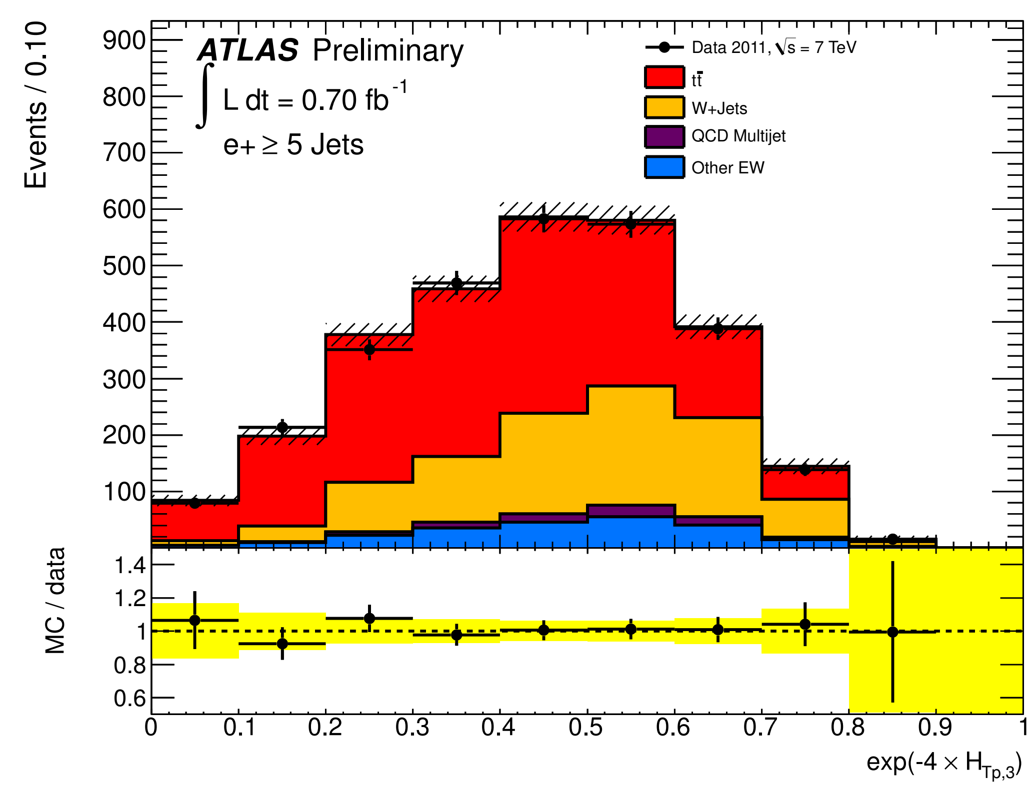
- **Trigger on** high p_T **single lepton (e,μ)**
- **1** high p_T **single lepton (e,μ), ≥4** high p_T **jets**
- **high E_T^{miss} and large transverse leptonic W mass** (M_T^W) *** to** reduce QCD bkg
  - *E_T^{miss} > 35 (25) GeV for e (μ) chan*
  - *M_T^W > 25 GeV (60GeV - E_T^{miss}) for e (μ) chan*



ATLAS-CONF-2011-121



ATLAS-CONF-2011-121



- Data-driven **QCD** (*matrix method*), **W+jets normalization** (*from W asymmetry meas.)*
- **Build discriminant from** signal+ bkg **templates of**
  - **lepton η, p_T of highest p_T jet, aplanarity** (←*top is more spherical*), **$H_{T,3p}$**, ratio of transverse to longitudinal activity (←*top is more transverse)*

$$^*M_T^W = \sqrt{2 p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$

Measurement of σ_{tt} - single lepton

$\int L dt =$ **~0.7 fb^{-1}** *(2011)*

ATLAS-CONF-2011-121

- **Extract σ_{tt}, σ_{bkg} by binned maximum likelihood fit of discriminant** to data **in** 3, 4 and **≥ 5**-jet bins

image by J Andrea (CNRS,strasbourg)

- Likelihood defined as :

σ_{tt}, backgrounds   Detector-related syst.

$$\mathcal{L}(\vec{\beta}, \vec{\delta}) = \prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k) \times \prod_j \mathcal{G}(\beta_j, \Delta_j) \times \prod_i \mathcal{G}(\delta_i, 1)$$

Interlude on Tools

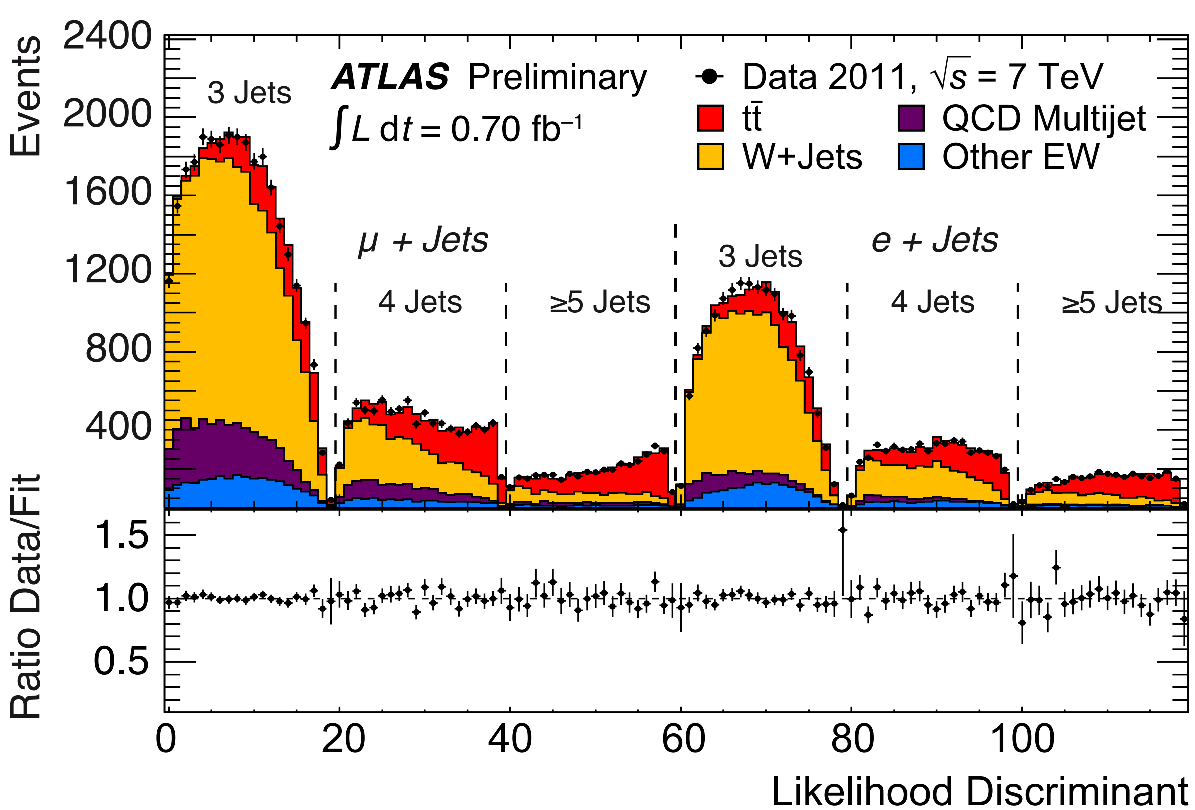
Background normalization constrained by the fit

parametrized lkl= Profile lkl

Poisson proba. density to observe n_k when μ_k is expected

Free parameters constrained by Gaussian distributions

Introduce sytematics as nuisance parameters



- **most syst uncertainties part of lkl fit** as Gaussian nuisance parameters→reduction in JES,ISR/FSR (20% to 70% of initial value)
- still syst-dominated: generator ~3% lepton scale~2%
- δσ/σ=6.6% (stat~0.5%, sys~5%)

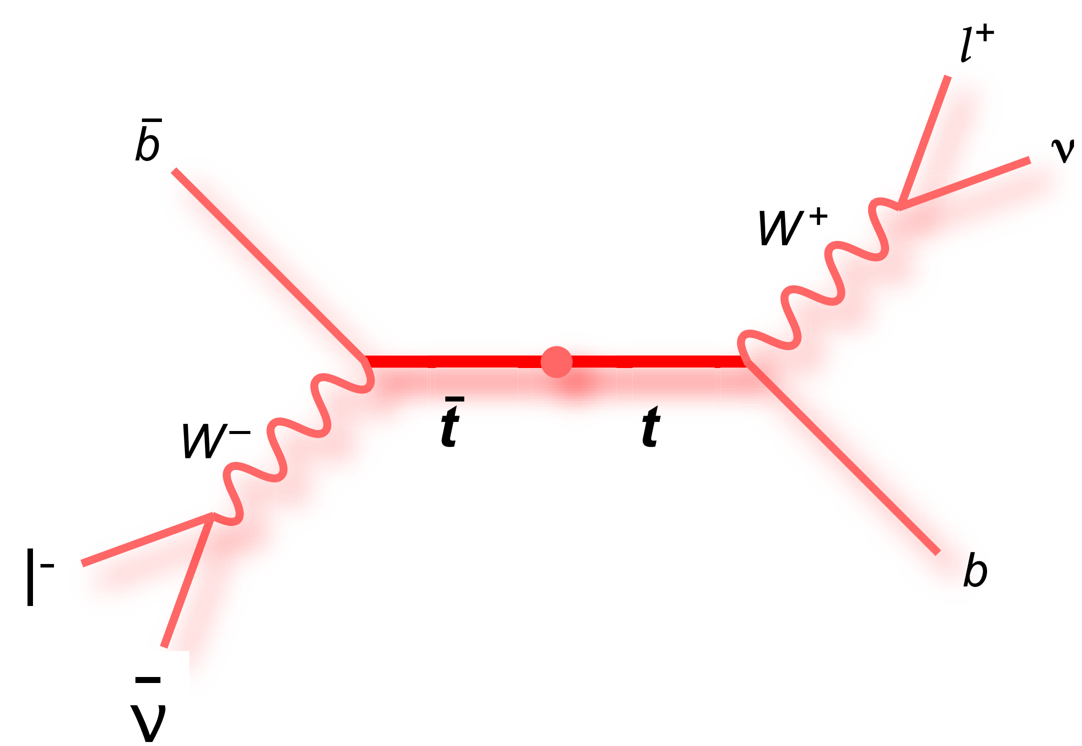
$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\ \text{pb}$$

Measurement of σ_{tt} @ 8 TeV - dilepton

$\int L dt$ = **~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.*

Measurement of σ_{tt} @ 8 TeV - *di-lepton channel*

- **Subtract background and get N_{tt}**

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

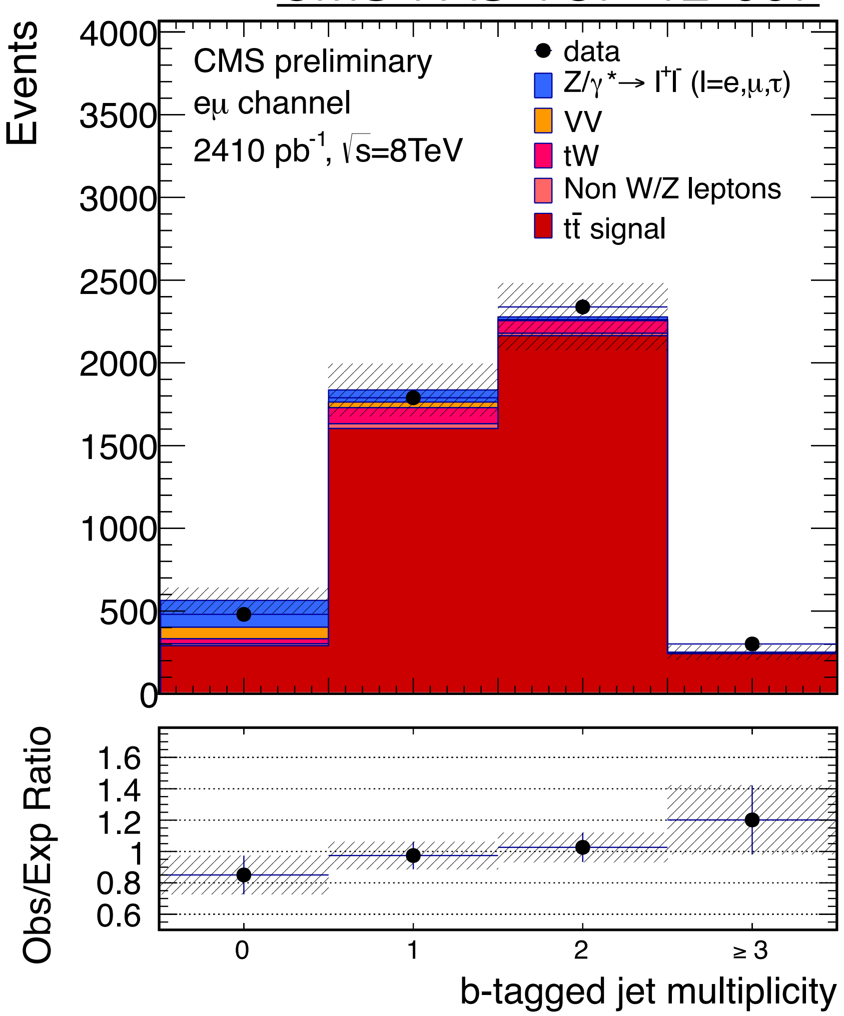
- **Extract cross section** combining channels with best linear unbiased estimator including correlations and systematics

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

$\delta\sigma/\sigma$~7%

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

CMS-PAS-TOP-12-007

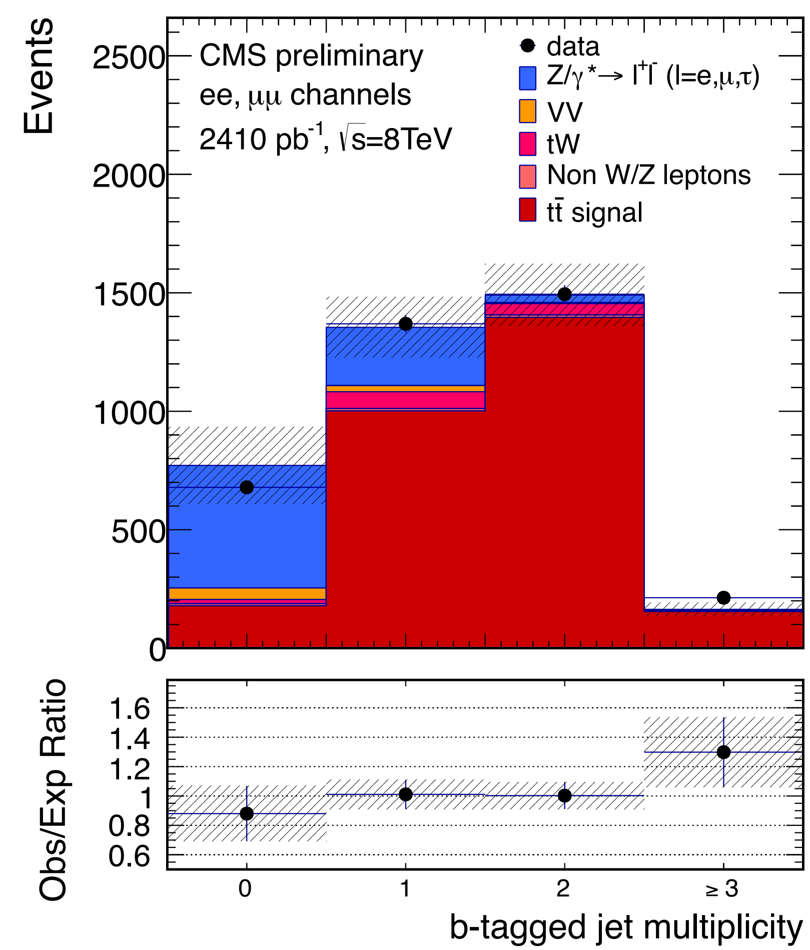


distributions
after all cuts,
except
Ntagged jets

syst
dominated!

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

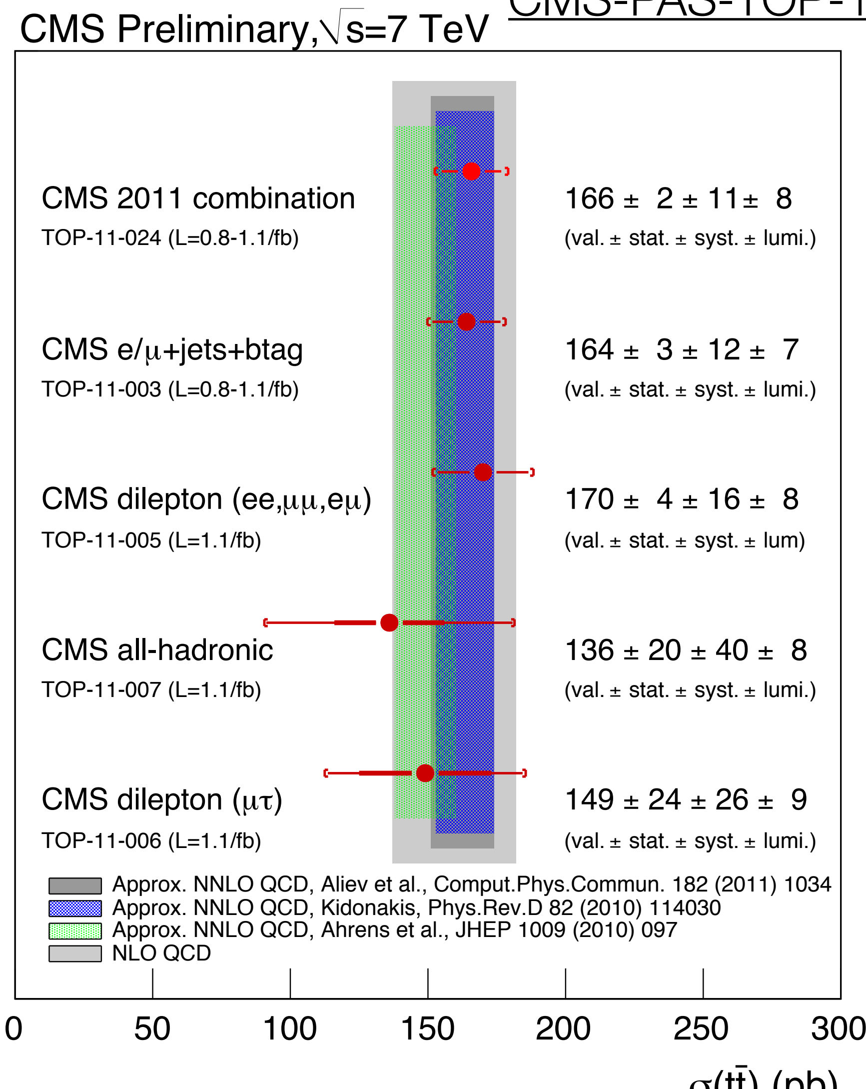
CMS-PAS-TOP-12-007



Measurement of σ_{tt} - Summary @ 7TeV

- CMS combination with 0.8-1.1/fb using **binned max lkl.** (see TOP-11-003)
- **Improvement by 21% (11%) in stat (syst) uncertainty** compared to l+jets channel

CMS-PAS-TOP-11-024

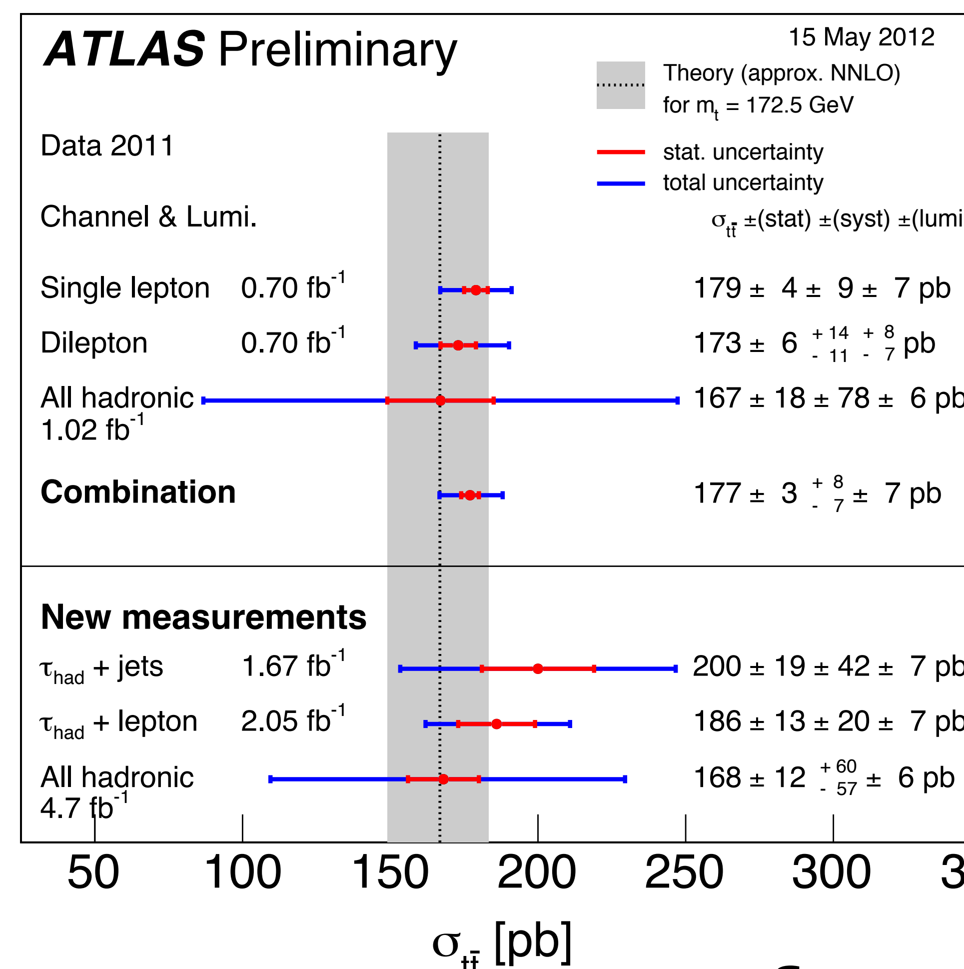


$\delta\sigma/\sigma$~8%

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb}$$

- ATLAS combination with 0.8-1.1/fb using **profile lkl ratio** method
- **Improvement by 25% (11%) in stat (syst) uncertainty** compared to l+jets channel

ATLAS-CONF-2012-024



$\delta\sigma/\sigma$~6.2%

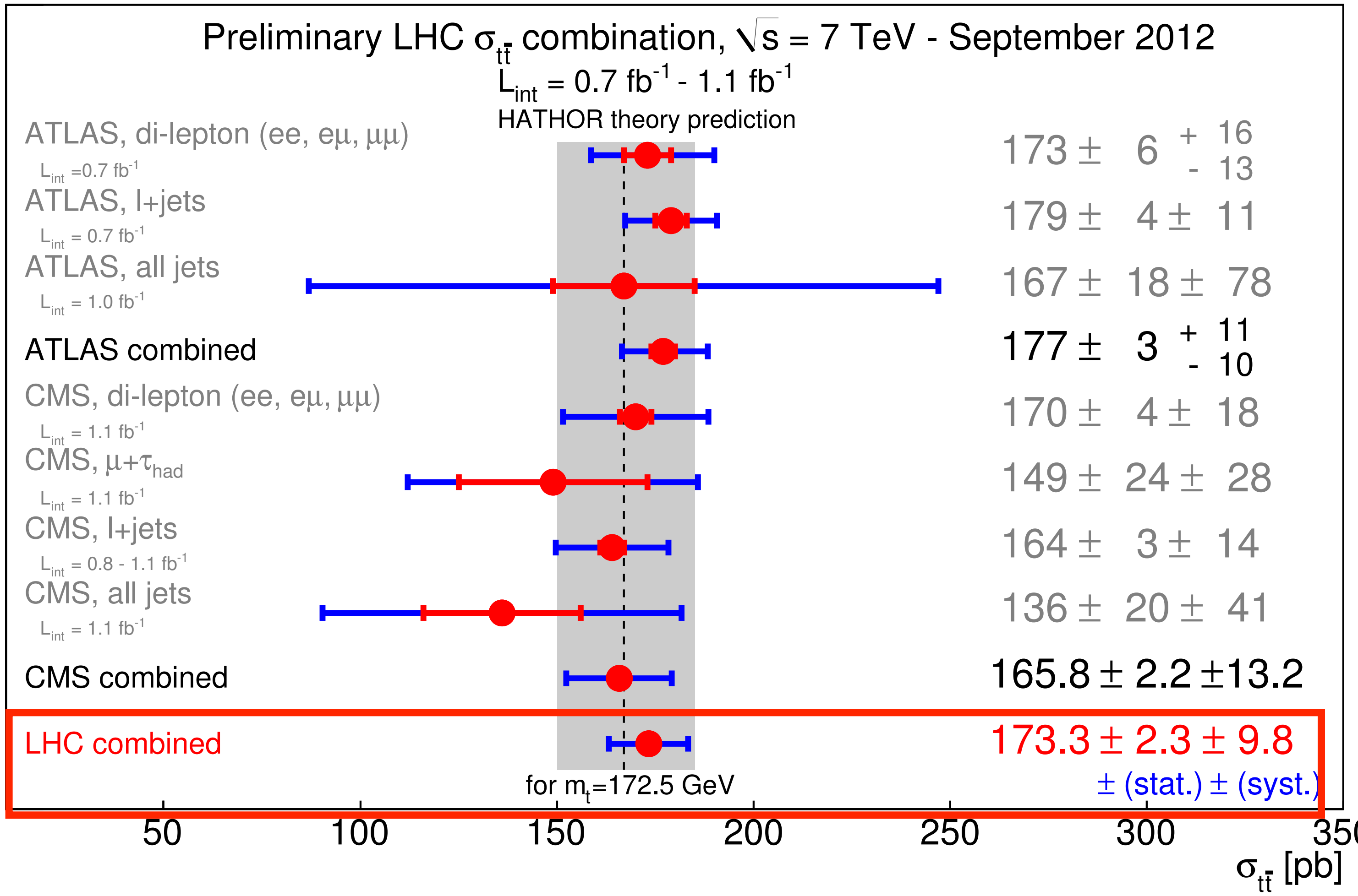
$$\hat{\sigma}_{t\bar{t}} = 177 \pm 3\ (\text{stat.})\ ^{+8}_{-7}\ (\text{syst.}) \pm 7\ (\text{lumi.})\ \text{pb}$$

Measurement of σ_{tt} - LHC Combination @ s = 7 TeV

	ATLAS	CMS	Correlation	LHC combination
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Enegy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1

- Combine with best linear unbiased estimator
- Total correlation~30%

ATLAS-CONF-2012-134 & CMS-PAS-TOP-12-003



- Improvement by 7% (11%) w.r,t most precise l+jets channel
- **Final δσ/σ~5.8% (10 pb)**

$$\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 9.8(\text{syst.})\ \text{pb}$$

Interlude on Tools

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

- 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

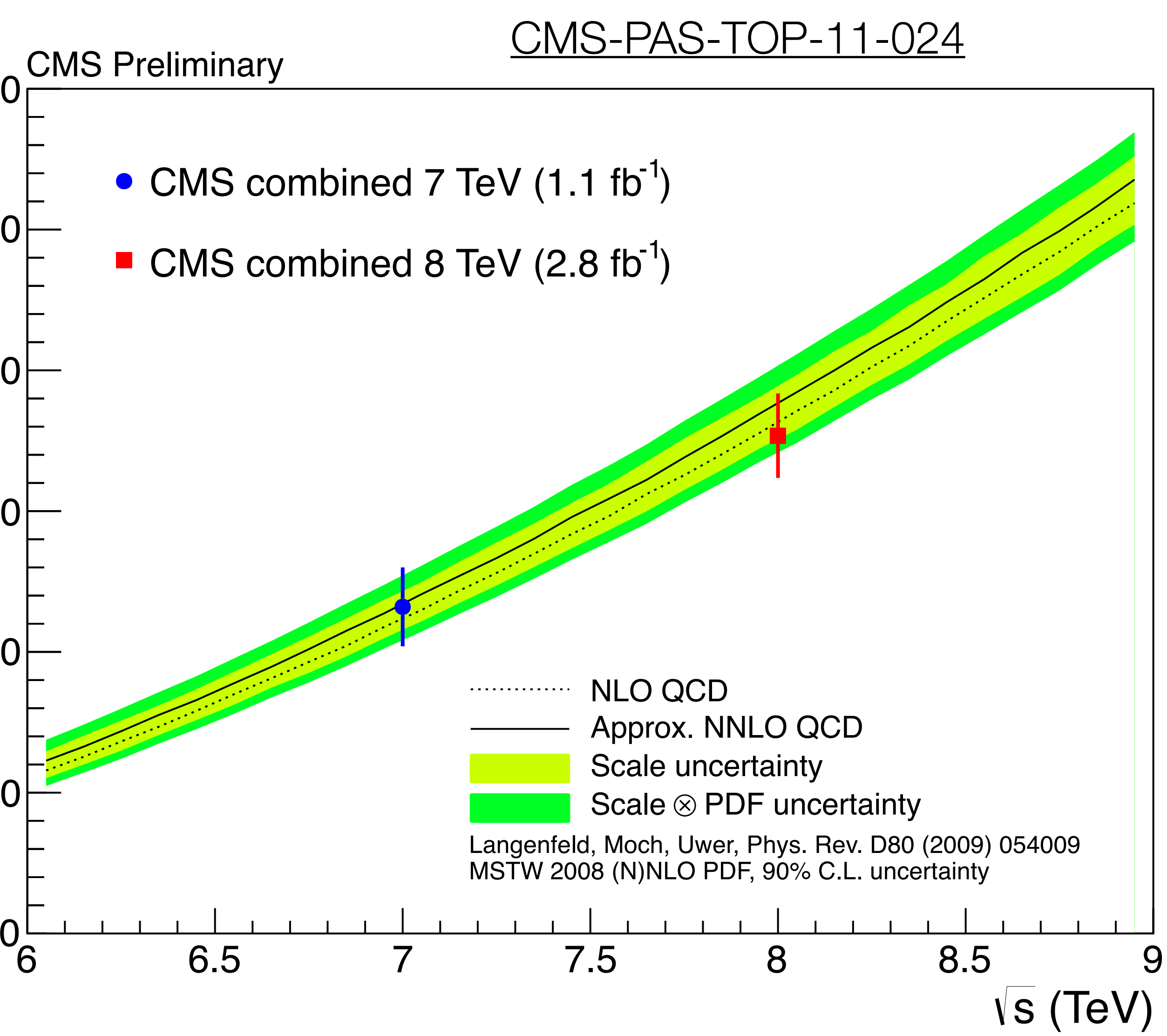
equivalent to χ^2 method

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

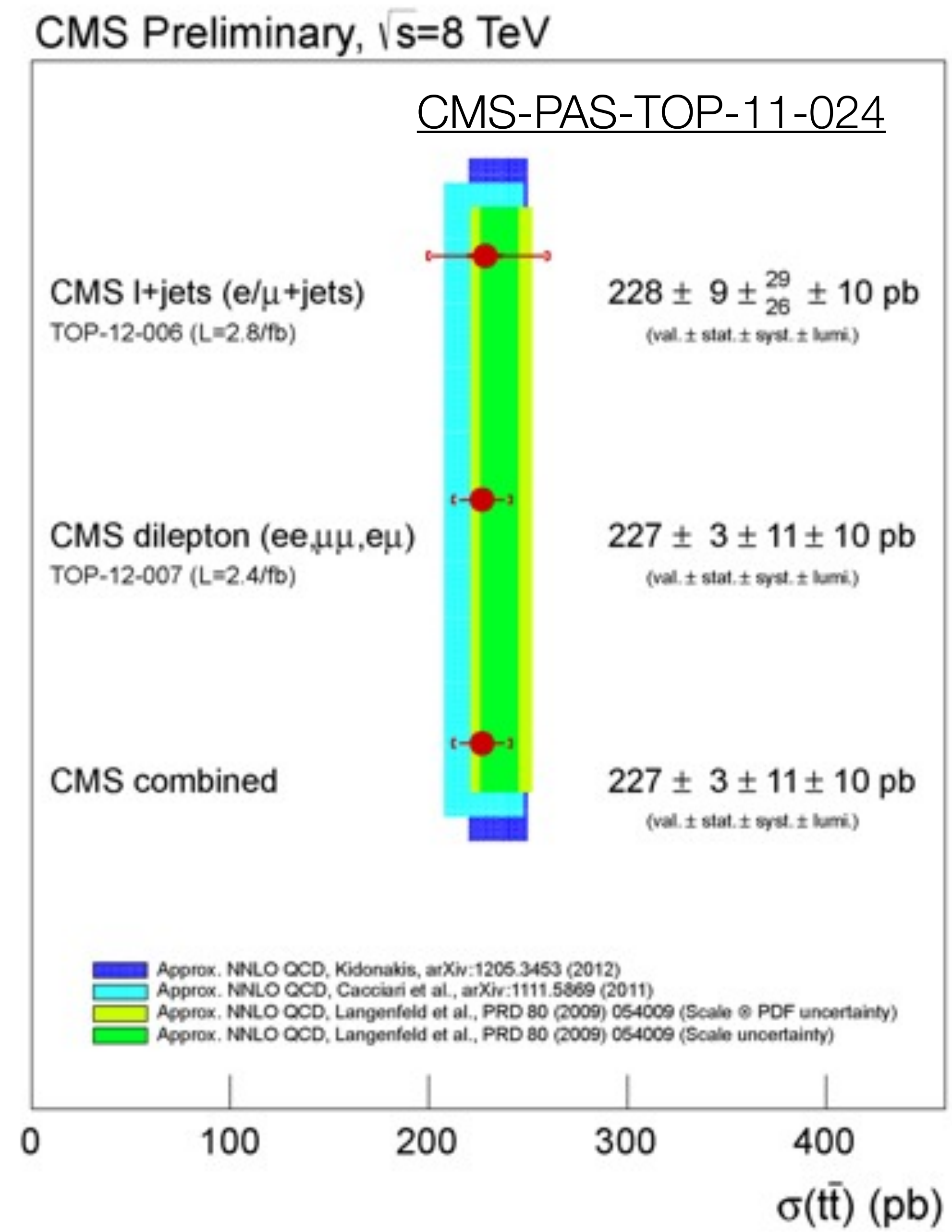
Measurement of σ_{tt} - CMS Combination @ s = 8 TeV

- Combination of 8 TeV measurements (CMS)with best linear estimator, dominated by dilepton measurement

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



$\delta\sigma/\sigma$~6.6%



- Ratio of 8 TeV to 7 TeV cross section is 1.41 0.10
  - partial cancellation of syst effects

Attention to systematic uncertainties!

- Harmonization in approach towards theoretical systematic uncertainties. Particularly about Monte Carlo generators and Initial/Final state radiation.

- ATLAS: takes difference between different generators

- CMS: varies parameters within a given generator

- Discussion still ongoing in TOP LHC Working group
  - test simulation of one exp in another's
  - use the same simulated set of events to compare performance/ correlations/analyses sensitivity to syst effects.

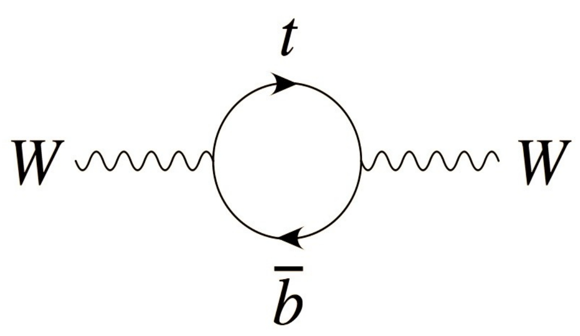
Measurement of top quark mass, m_t

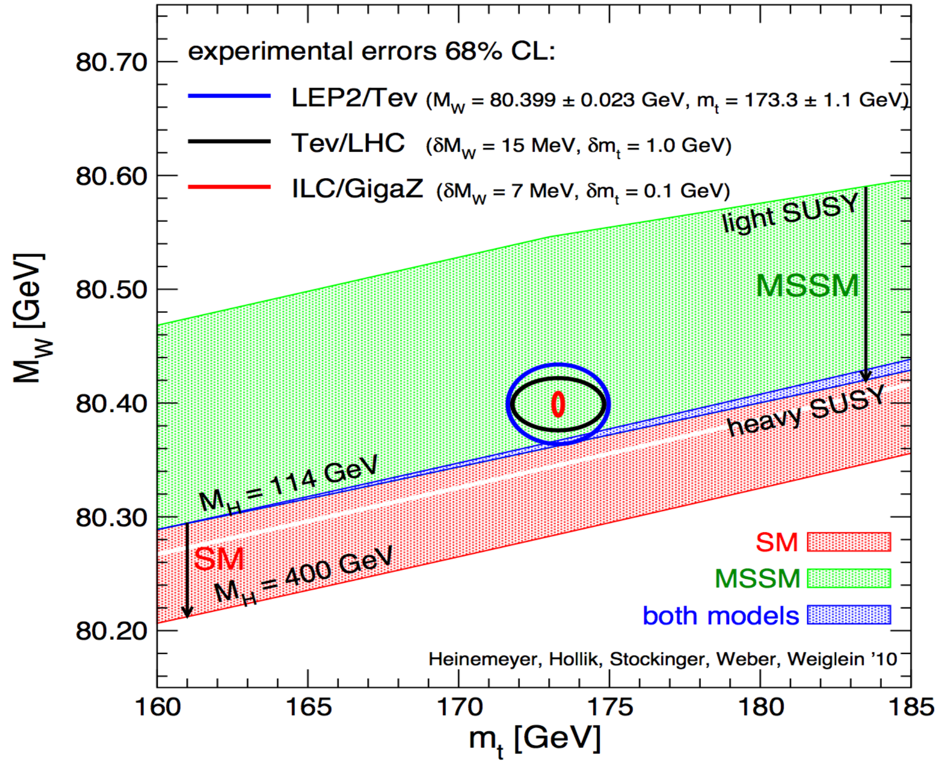
i.e.

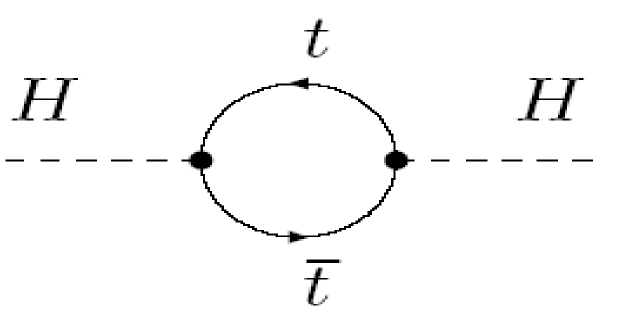
the defining property

Top Quark Mass

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass





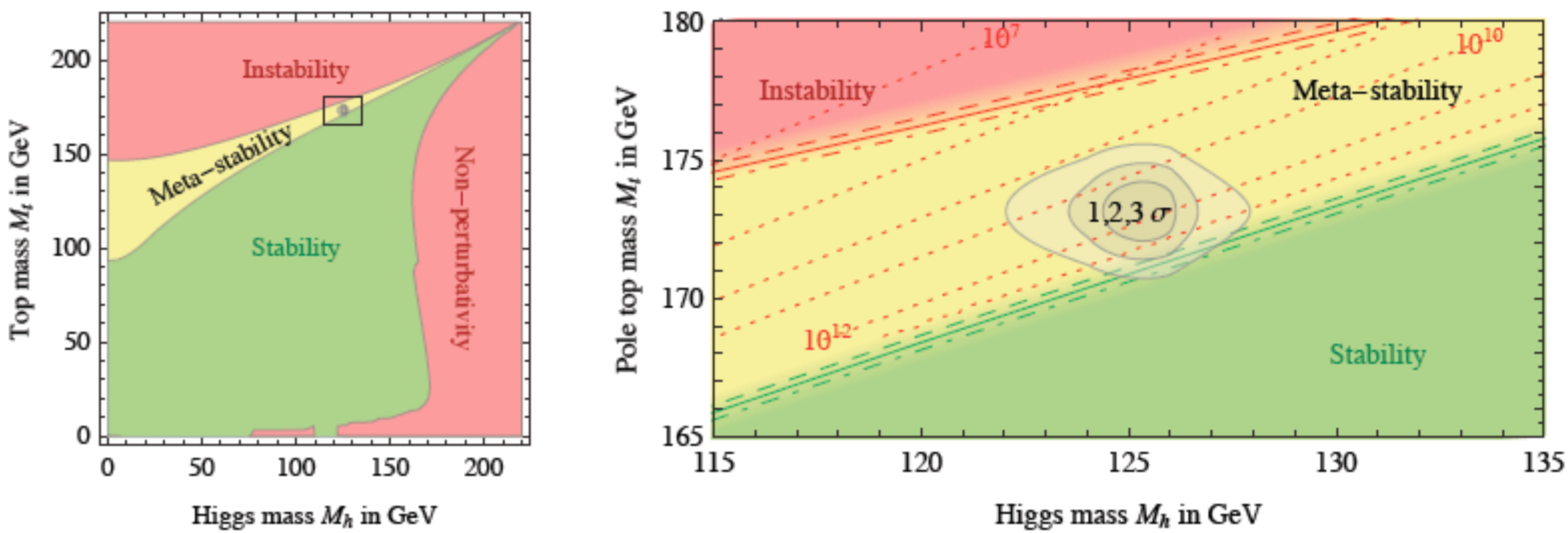


- Measurement done with several methods: Template method, ideogram, matrix element, etc.
  - Methods also used for other analyses, e. g. W helicity & spin correlations

Top quark and vacuum stability

- Knowledge of top quark mass and higgs boson mass is crucial for stability vacuum

* An up-to-date analysis indicates that we are in the stable/metastable region.



De Grassi et al, arXiv:1205.6497

(R.K. Ellis TOP2012)

CMS Lepton+Jets: Event Selection & Reconstruction

- Exactly 1 isolated muon/electron with $p_T > 30$ GeV, $|\eta| < 2.1$
- ≥ 4 jets with $p_T > 30$ GeV, $|\eta| < 2.4$, ≥ 2 with b-tag
- Assign b-tagged jets $\rightarrow$ b-quarks, untagged jets $\rightarrow$ light quarks

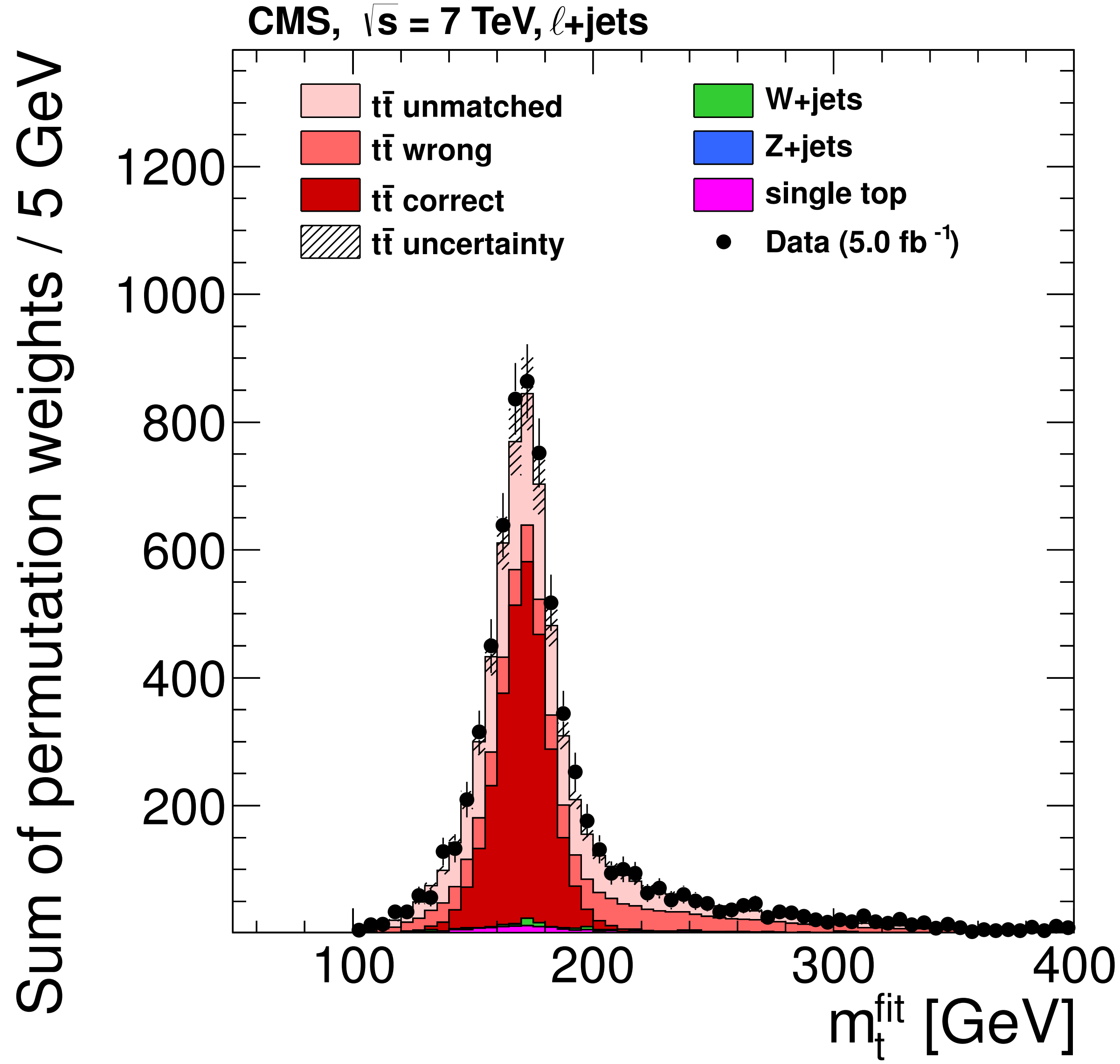
(M Seidel, TOP2012)

5.0 fb^{-1}, CMS-TOP-11-015, submitted to JHEP

Kinematic fit & final selection

- Use 4 leading jets, constraints: $m_W = 80.4$ GeV, $m_t = m_{\bar{t}}$
- Weight each permutation by $P_{\text{gof}}(\chi^2) = \exp\left(-\frac{1}{2}\chi^2\right)$, $P_{\text{gof}}(\chi^2) > 0.2$ required
- Selected sample contains 5194 events in 5 fb^{-1} data
- Estimated purity: 96% $t\bar{t}$ events

after kinematic fit: 44% of $t\bar{t}$ correct



CMS Lepton+Jets: 2D Ideogram Method

5.0 fb^{-1}, CMS-TOP-11-015, submitted to JHEP

- Likelihood for event with n permutations, j representing correct, wrong and unmatched permutation case

before kine fit (M Seidel, TOP2012)

$P_{gof} = P(\chi^2) = \exp(-\frac{1}{2}\chi^2)$

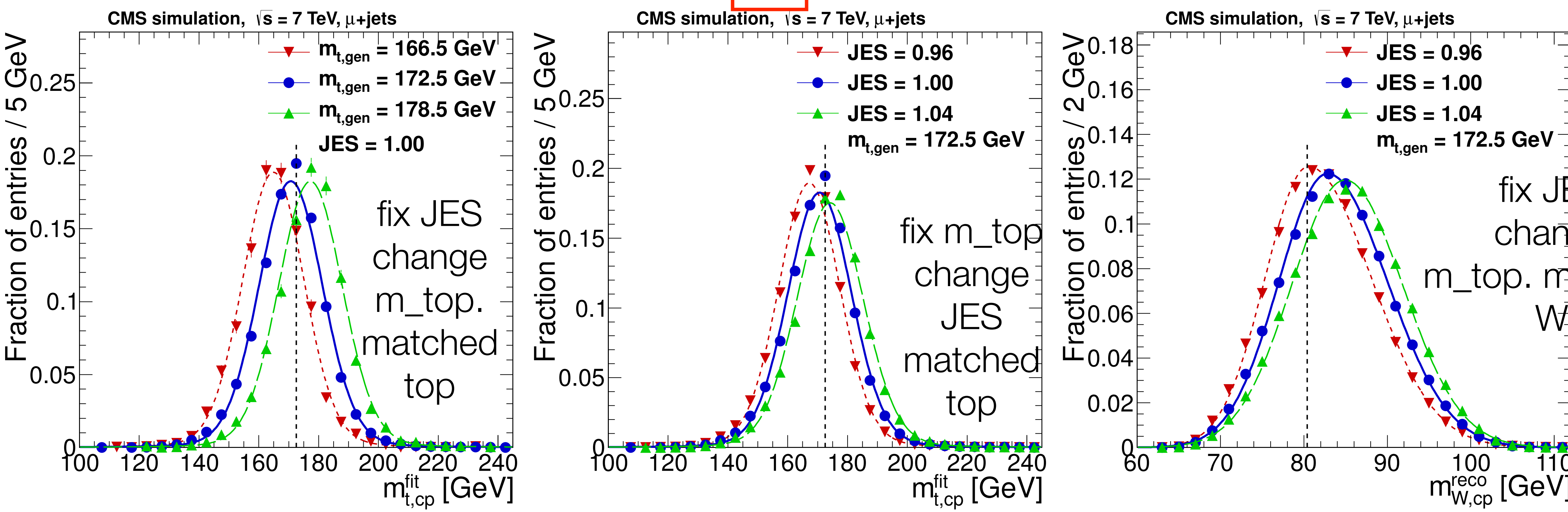
$$\mathcal{L}(\text{event}|m_t, \text{JES}) = \sum_{i=0}^{n} P_{gof}(i)\, P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right),$$

functions fitted from simulated events, pars depend on JES and m_top

BWigner conv with gauss *asymm Gauss*

$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_j f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

assume uncorrelated because of W mass constraint,



- Most likely m_t and JES given data sample (Maximum Likelihood)

(M Seidel, TOP2012)

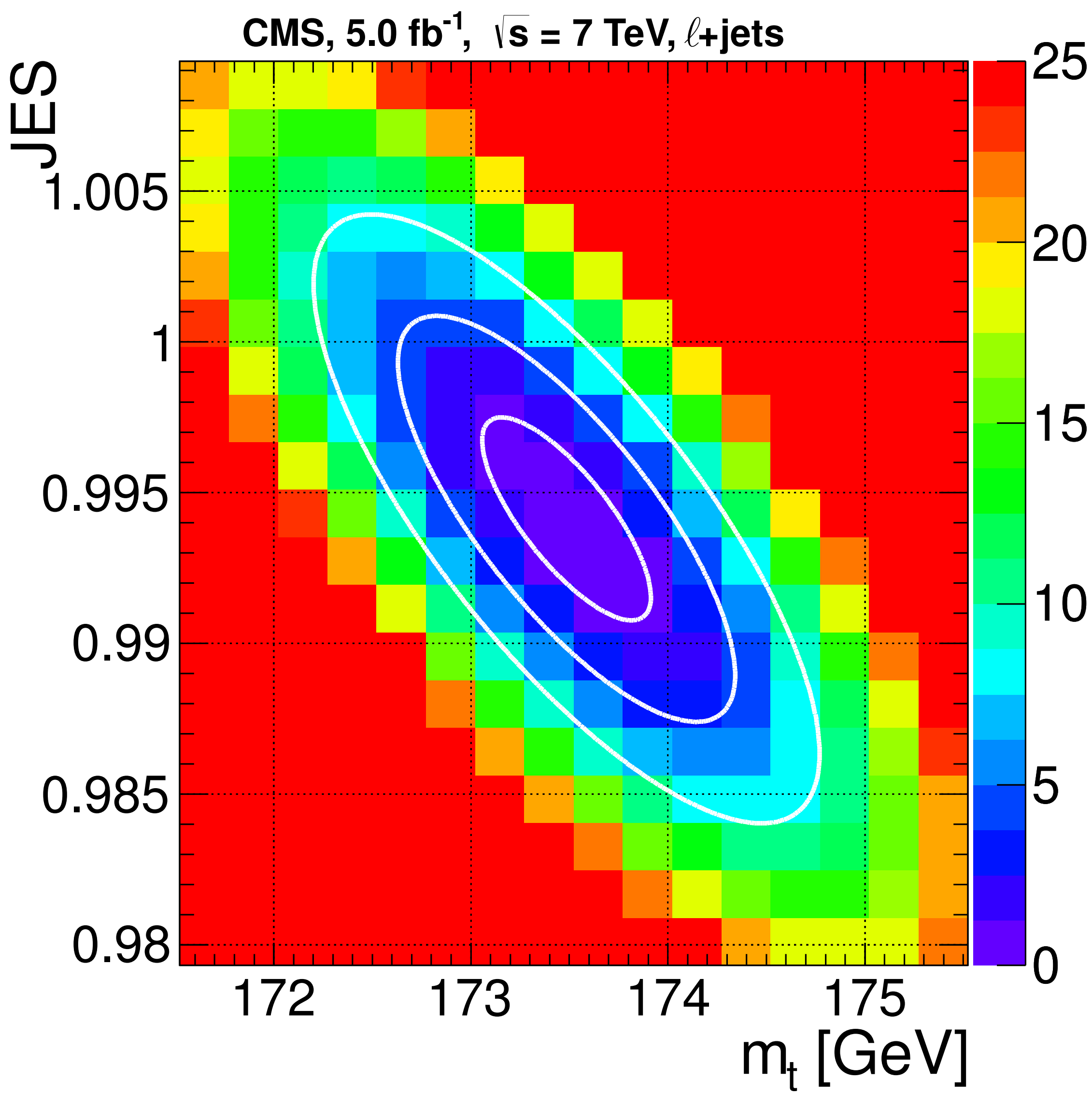
$$\mathcal{L}(m_t, \text{JES}|\text{sample}) \sim \prod_{\text{events}} \mathcal{L}(\text{event}|m_t, \text{JES})^{w_{\text{event}}}$$

CMS **Lepton+Jets: Uncertainties & Result**

$5.0\ \text{fb}^{-1}$, CMS-TOP-11-01
submitted to JHEP

- Calibration with pseudo-experiments, small corrections for m_t and JES

Systematic uncertainty	Δm_{top} [GeV]
Calibration	0.06
b-JES	0.61
p_T- and η-dependent JES	0.28
Lepton energy scale	0.02
Missing transverse energy	0.06
Jet energy resolution	0.23
b-tagging	0.12
Pile-up	0.07
Non-$t\bar{t}$ background	0.13
PDF	0.07
μ_R, μ_F	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnections	0.54
Total	**0.98**

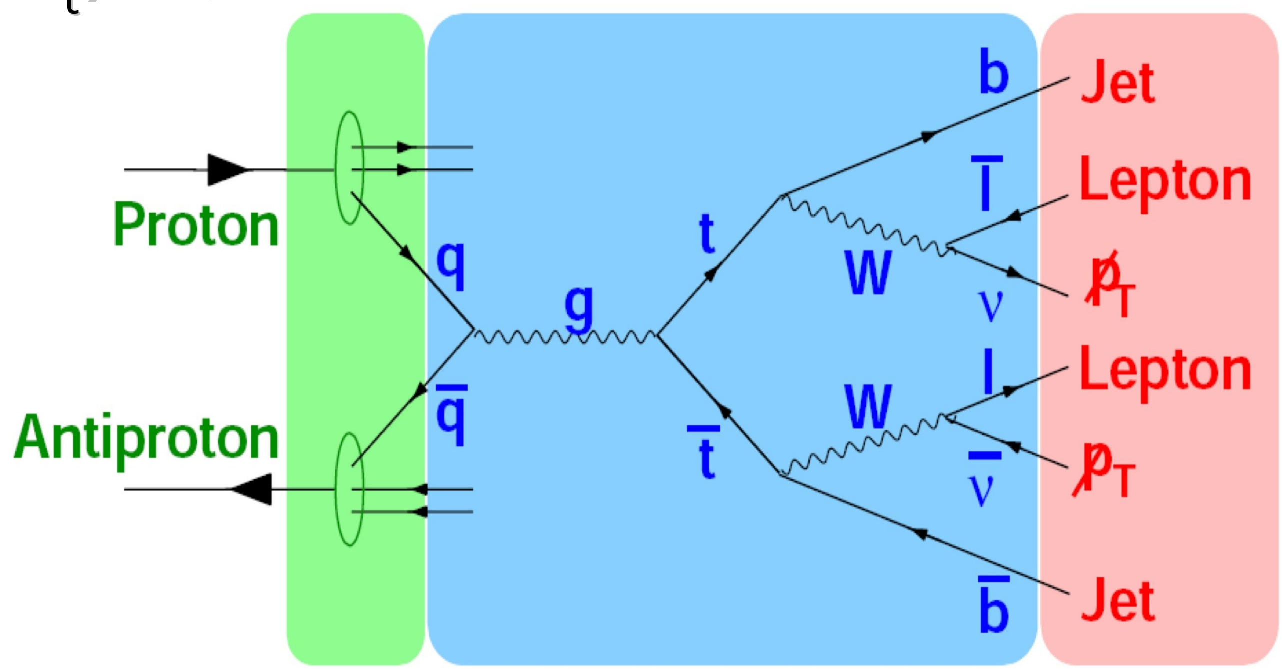


Result: $m_t = 173.49 \pm 0.43\ (\text{stat+JES}) \pm 0.98\ (\text{syst})\ \text{GeV}$ (M Seidel, TOP2012)

Top Quark Mass: Matrix Element Method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

$P_{sig}(x;m_t) \propto \int$ PDF x Matrix element x Transfer function

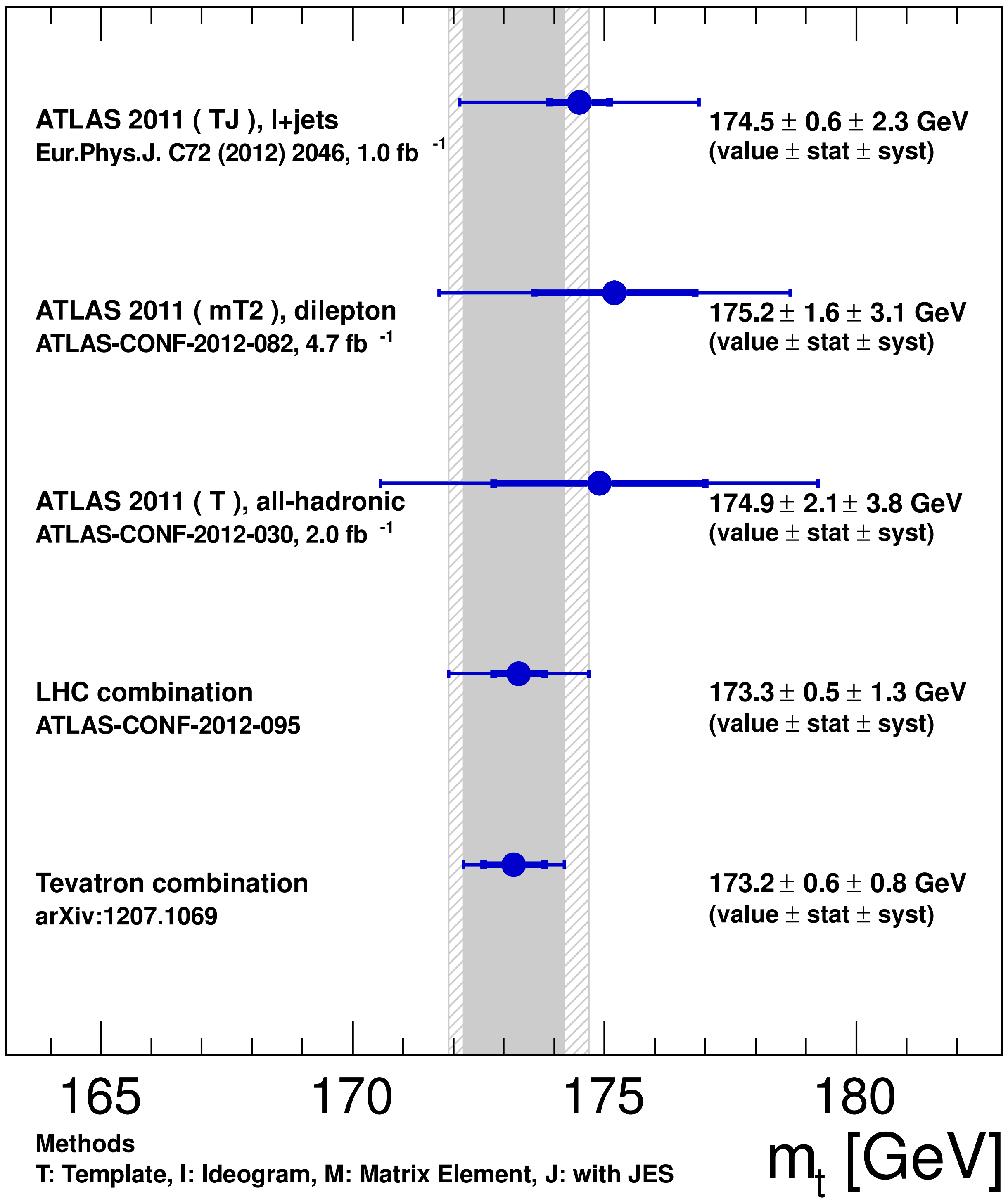


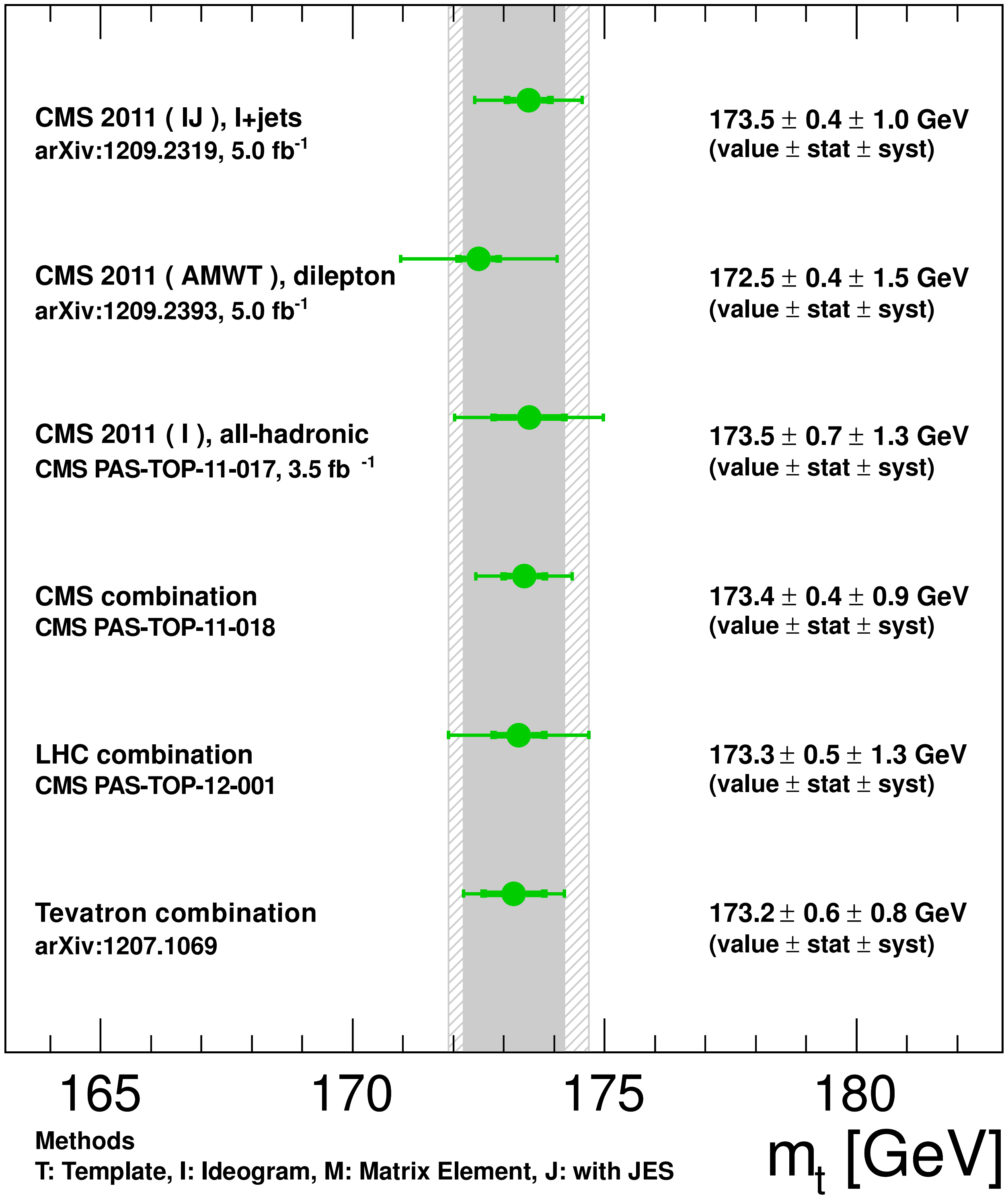
Y. Peters PIC2011

- Perform likelihood fit of event probabilities
- Probability depends on top mass (& JES for in-situ fit)
- Used in l+jets & dilepton final states

Overall Status of m_t - LHC+Tevatron

(M Seidel, TOP2012)



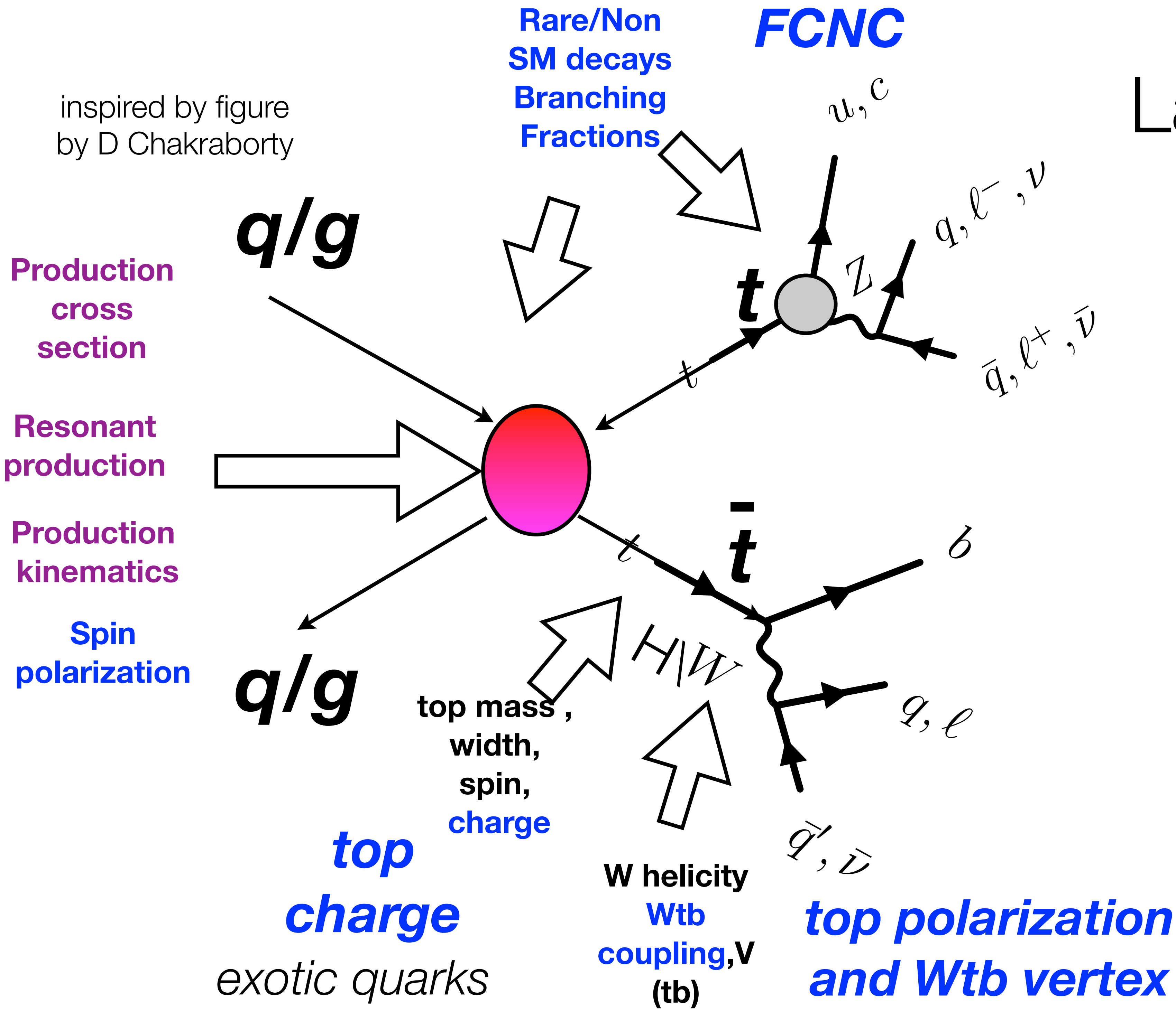


Top quark as a window on new physics

i.e.

Beyond the Standard model

Top quark as a window on new physics



Large $t\bar{t}$ and t sample

Go differential!

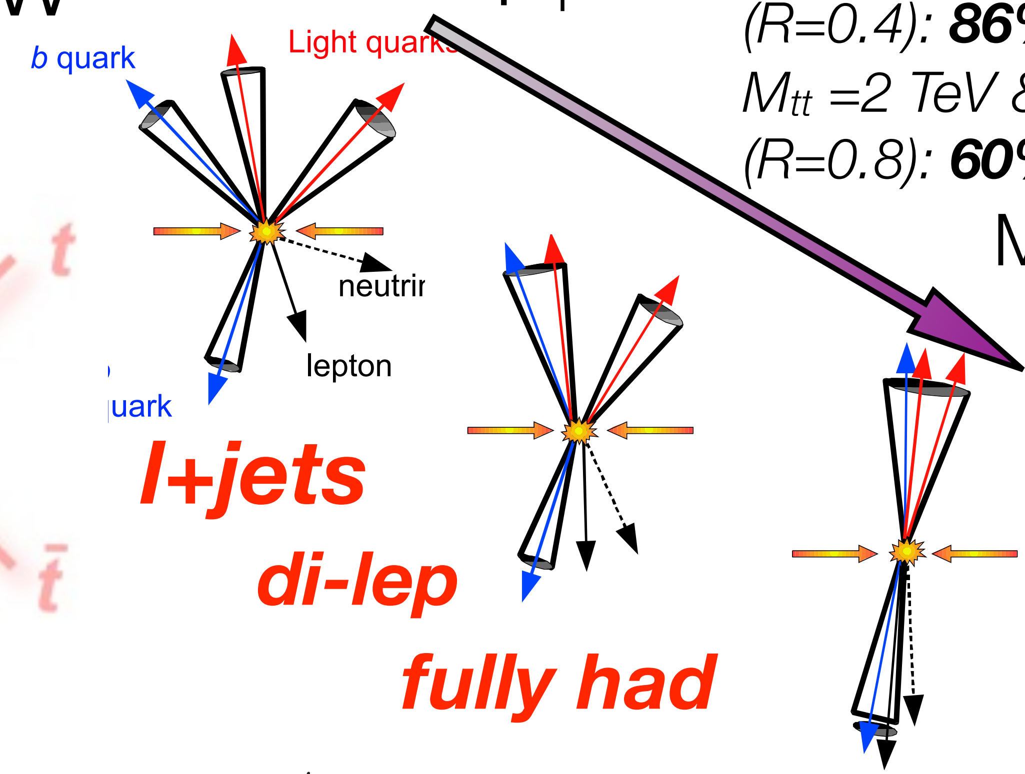
- Explore top quark production and decay as a function of kinematic variables to search for new physics

Example: heavy resonances decaying to top quark(s)

Measure property→ test SM assumption vs ANY new physics ⟺ **Searches** for effects of known new phys model

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

by no means exhaustive list of models!



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***

M_{tt}

l+jets

di-lep

fully had

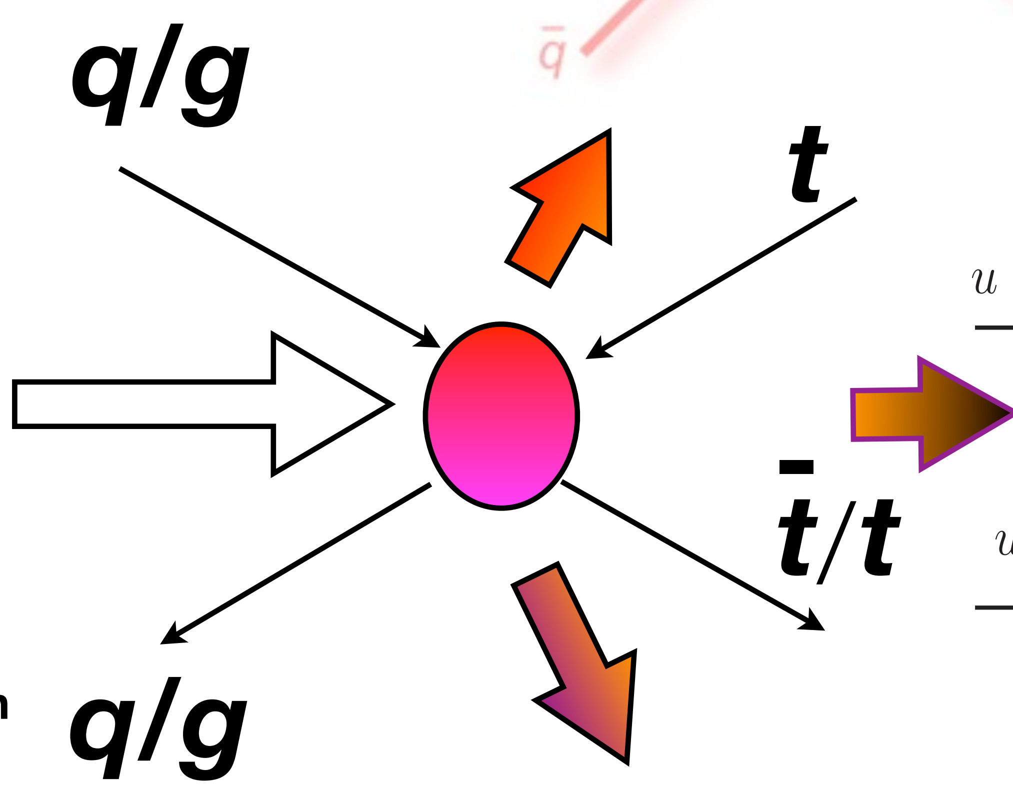
For ΔR=0.8, M_{tt} ~1.7 TeV, P_T ~600 GeV

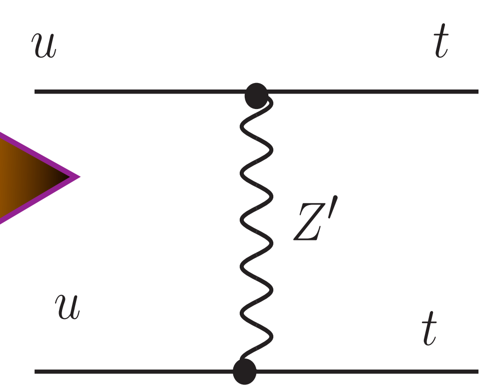
Production cross section

Resonant production

Production kinematics

Spin polarization



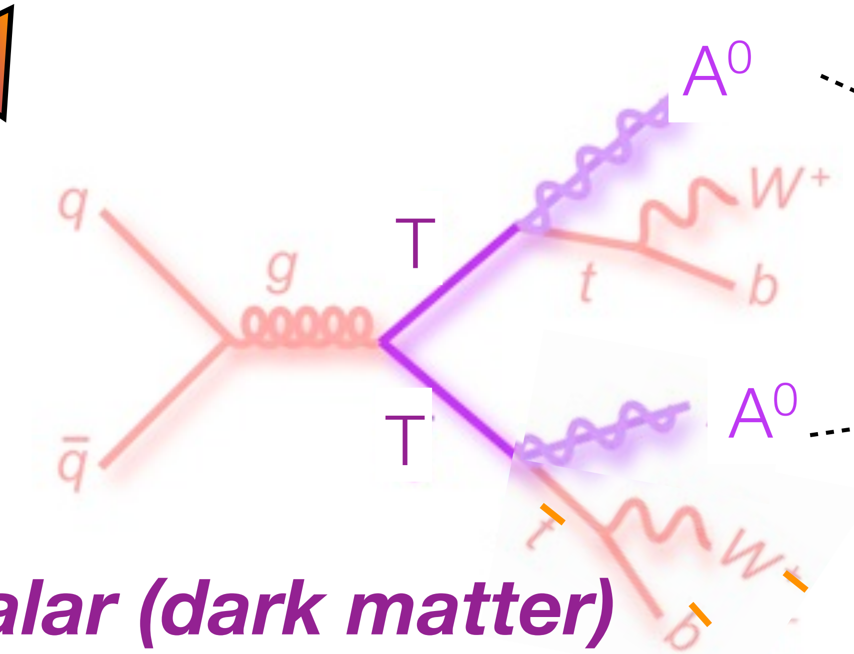


t/t̄ charge asymmetry

color octect vector, color singlet Z', color triplet scalars

Same sign top pair

4th gen, FCNC, left-right symmetric, higgs triplets, SUSY, UED, little higgs



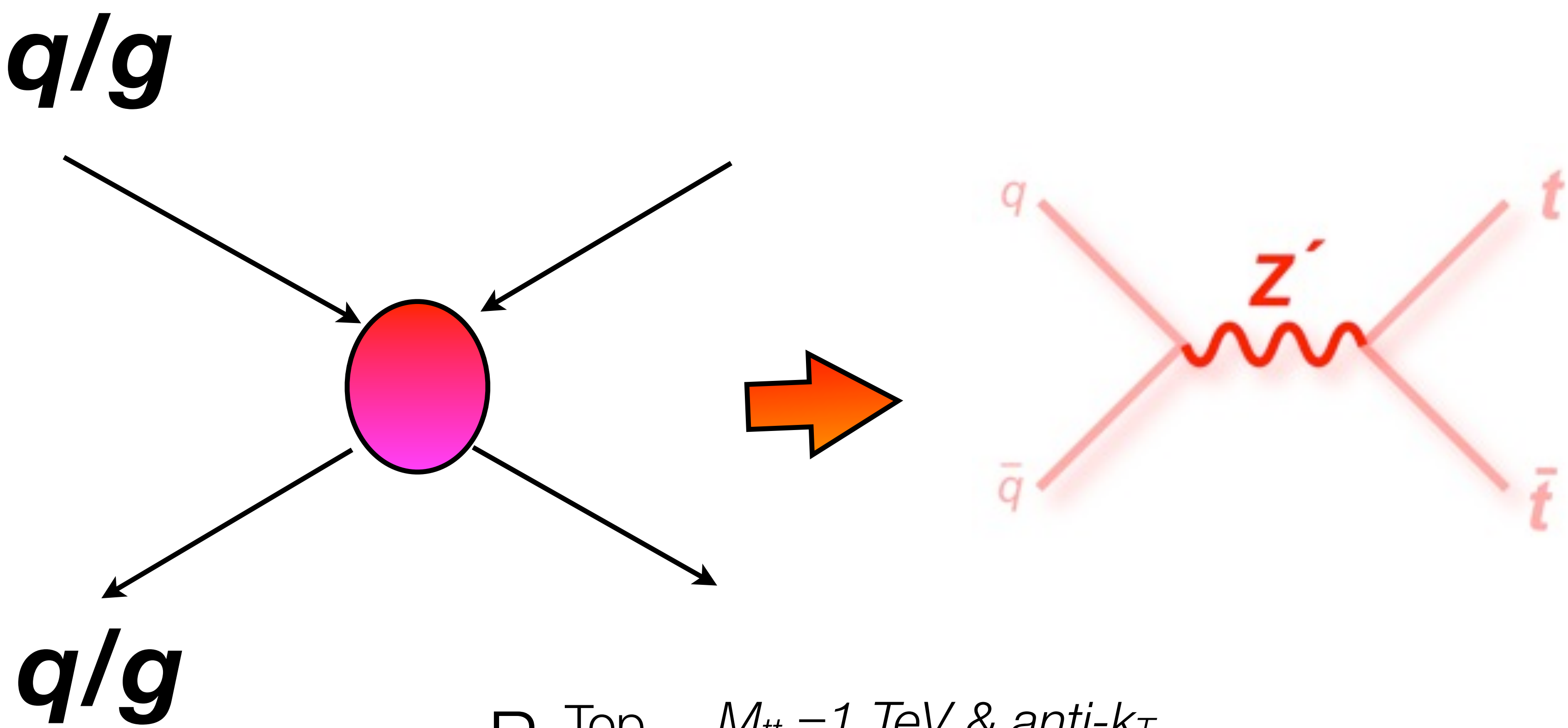
tt+E_T^{miss}

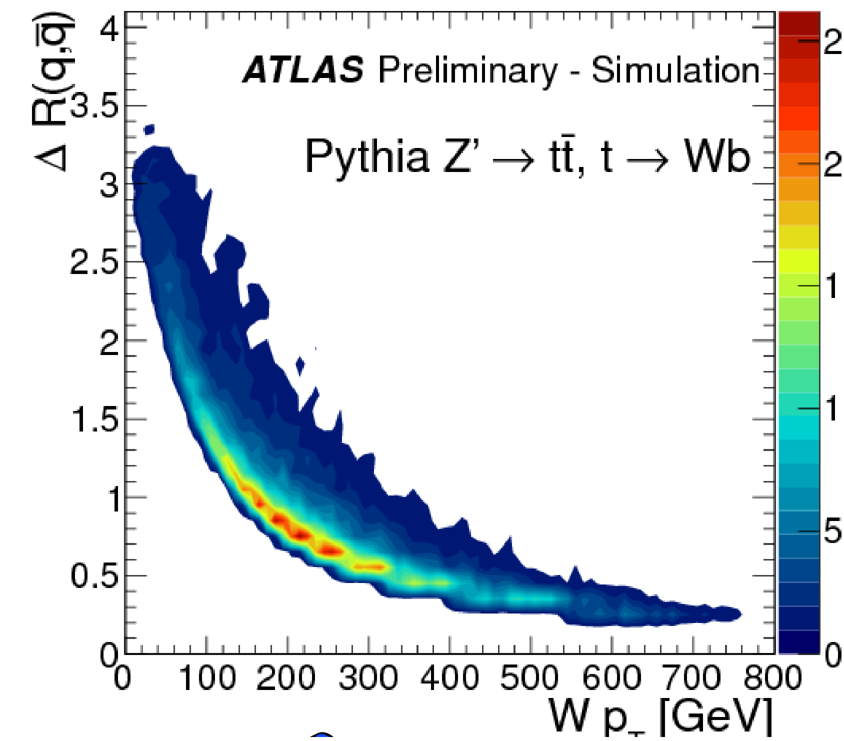
exotic 4th gen, leptoquarks, stop →top +neutralino, UED, little higgs,

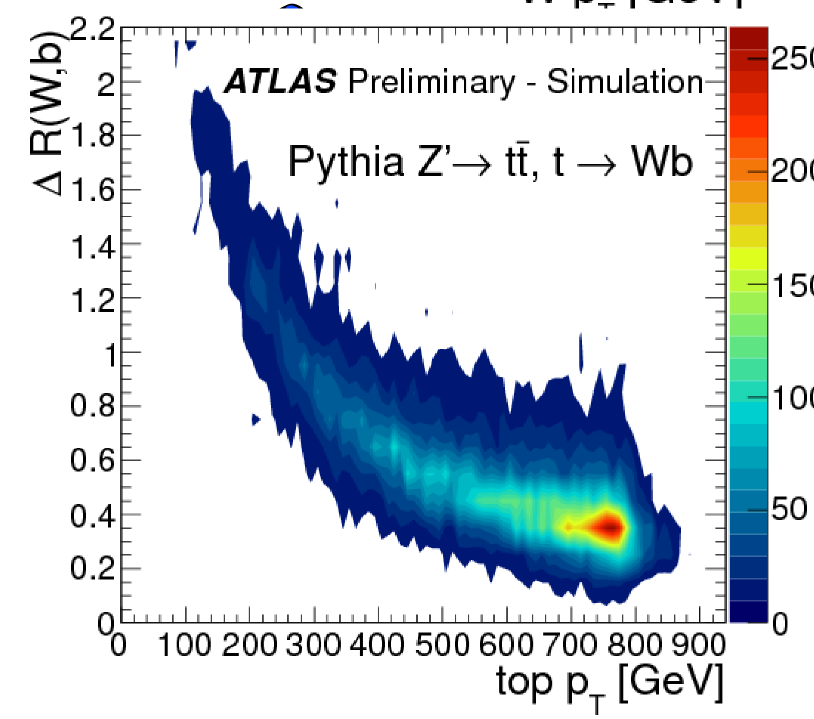
top partner + stable scalar (dark matter)

The emergence of boosted tops

ATLAS-CONF-2012-065

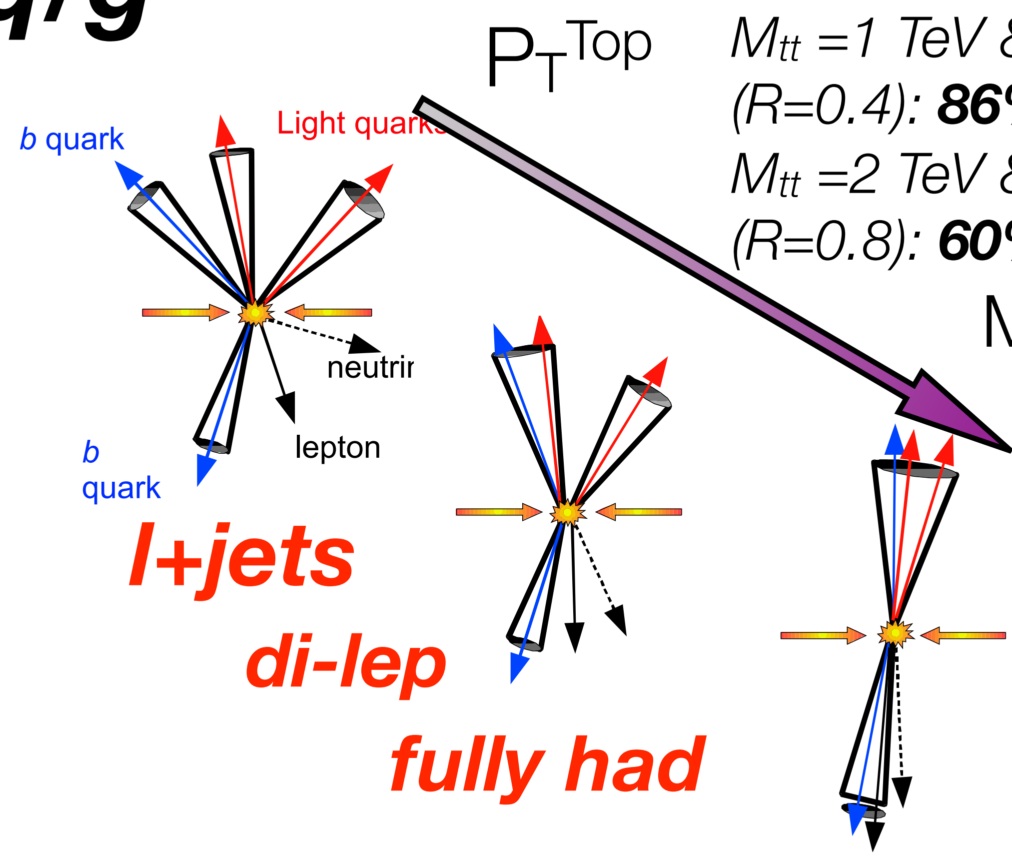






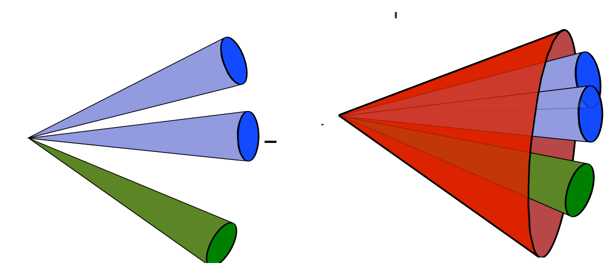
M_{tt} =1 TeV & anti-k_T (R=0.4): ***86% resolved***

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



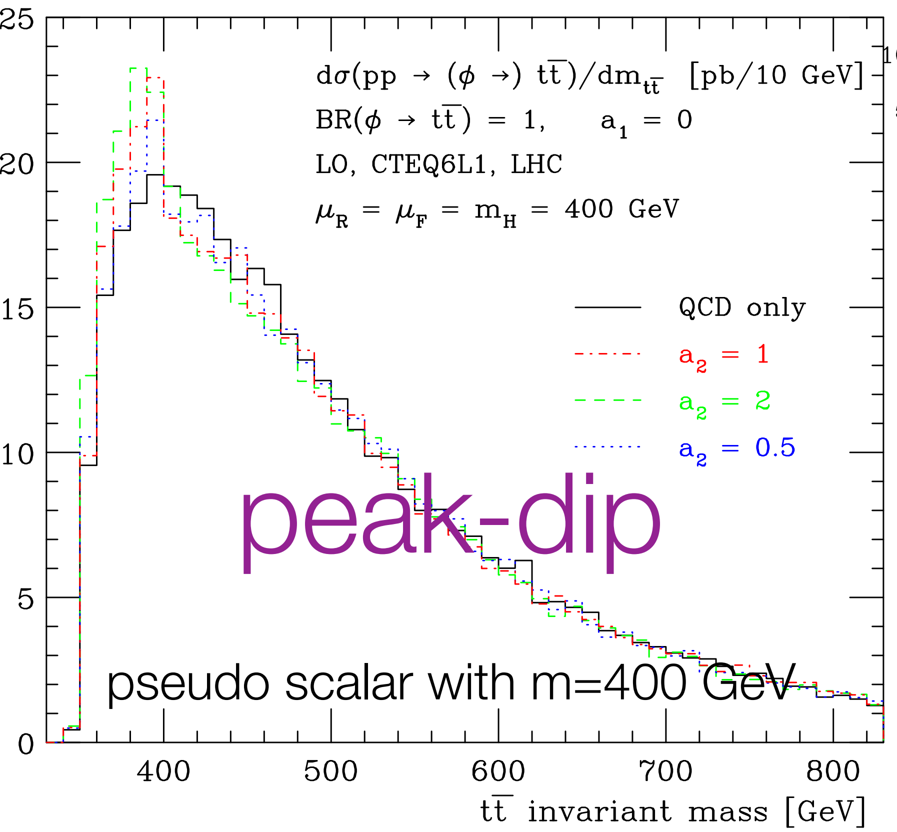
For ΔR=0.8, M_{tt} ~1.7 TeV, P_T ~600 GeV

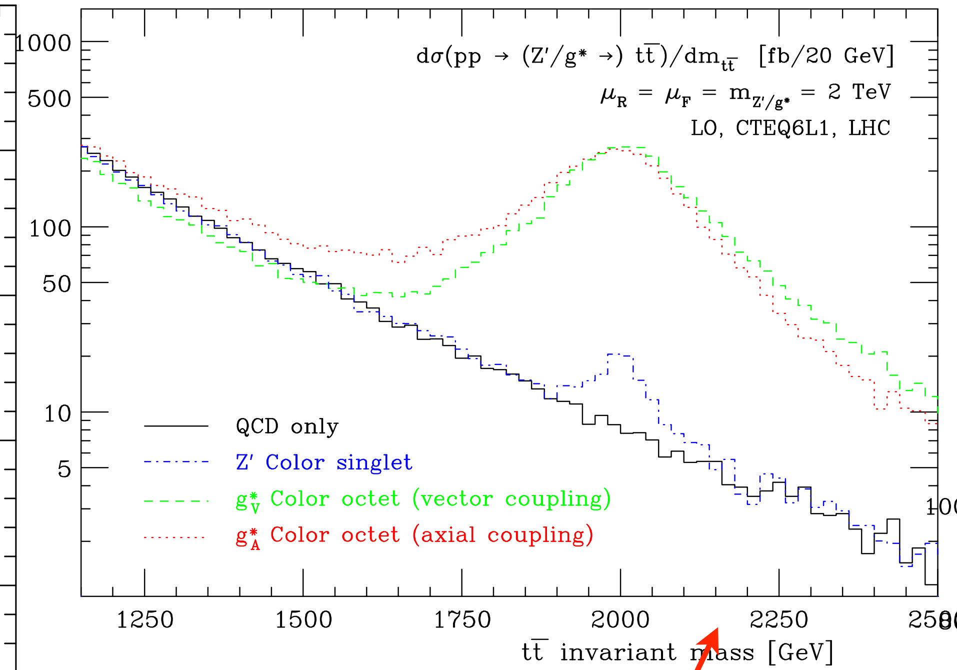
$\Delta R = 2m/p_T$



t/t̄ charge asymmetry

Example: new phys in ttbar mass



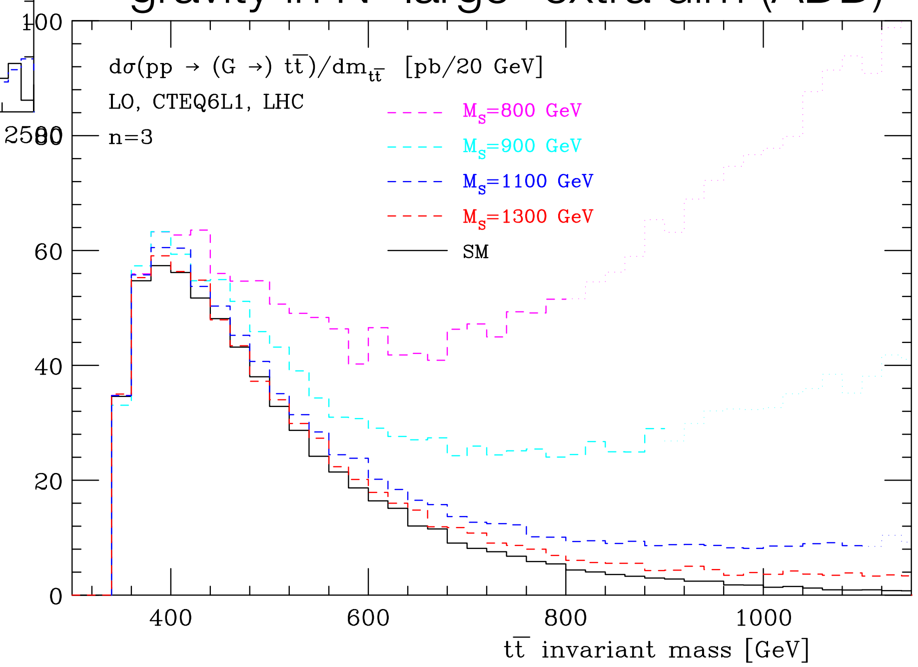


one peak

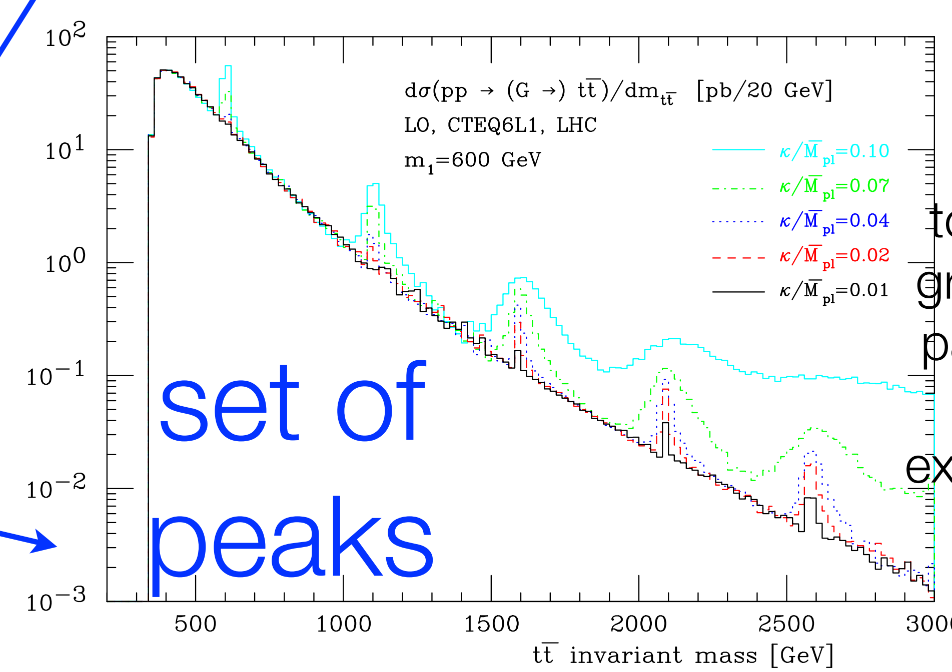
Z' or
new strong bosons

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]

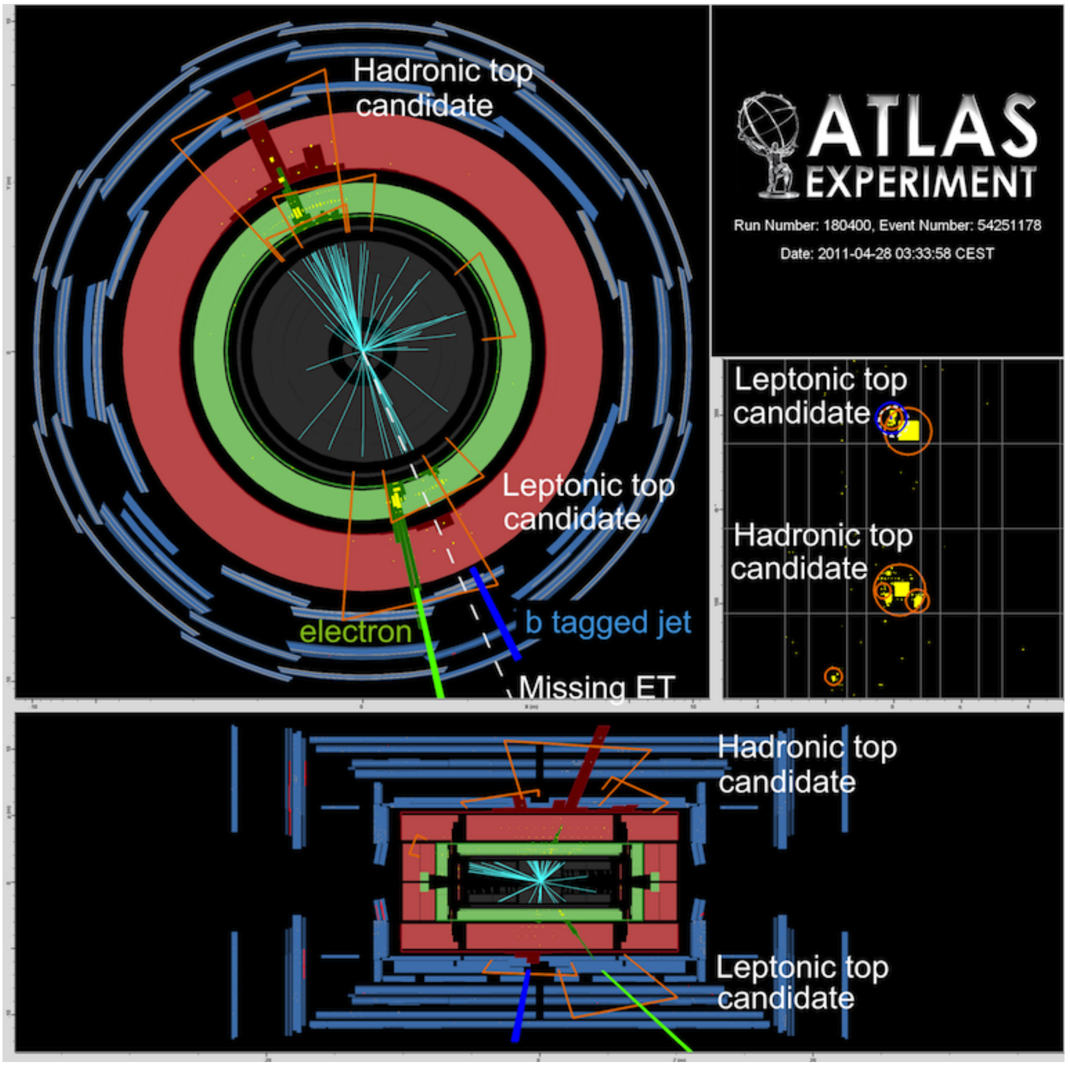


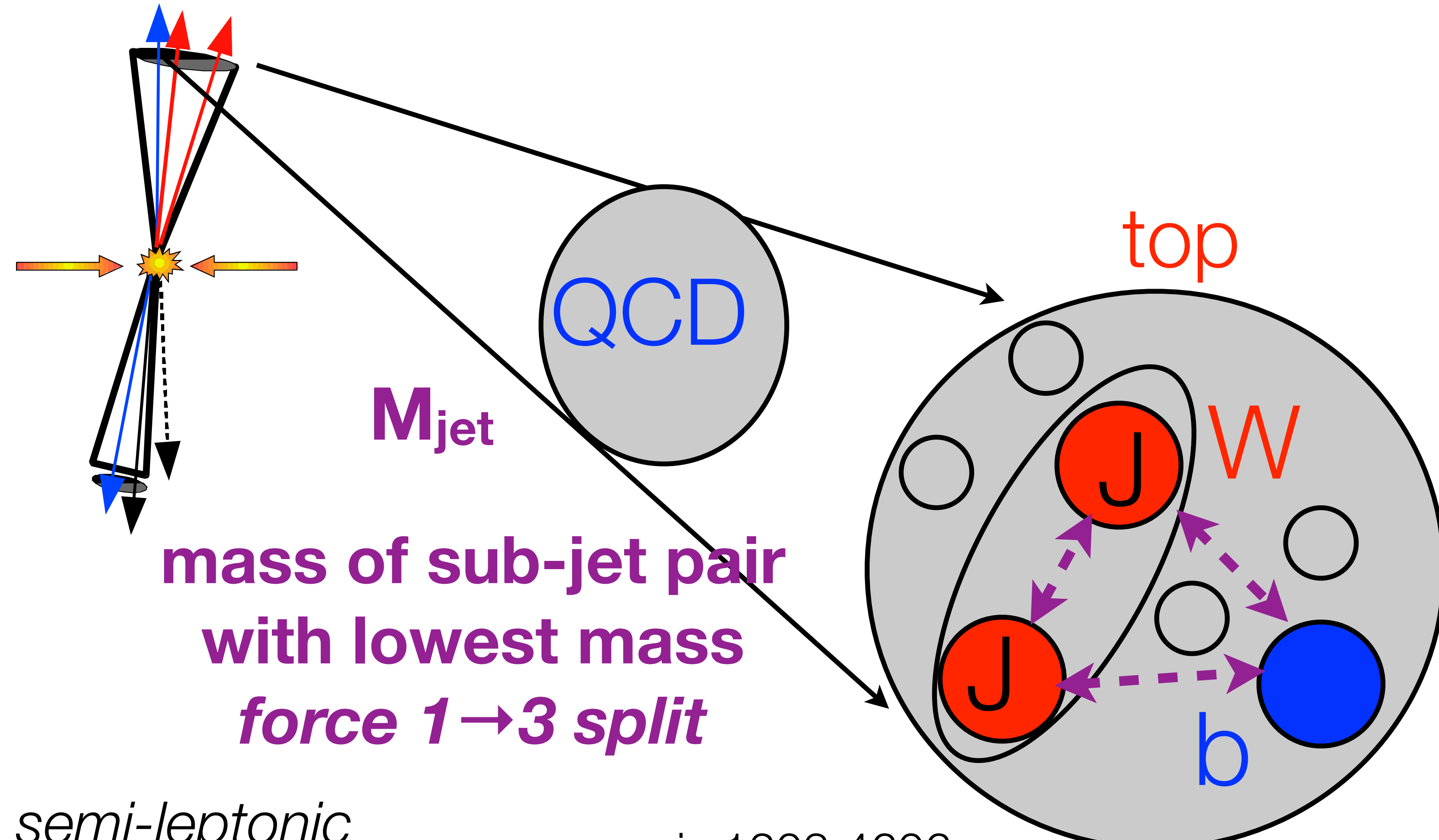
tower of KK gravitons ; all particles in 1 "warped" extra dim (RS)

arxiv:0712.2325

ATL-CONF-2011-087

Going Boosted (with ATLAS)





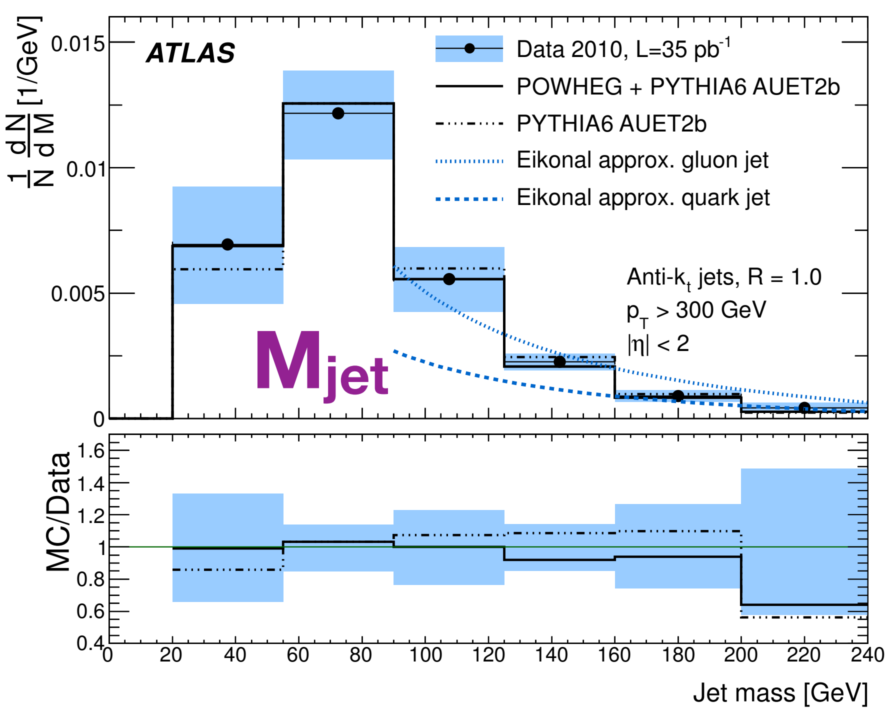
mass of sub-jet pair with lowest mass

force 1→3 split

semi-leptonic di-top-jet candidate

arxiv:1203.4606 **submitted to JHEP**

submitted to Phys Rev D arxiv:1206.5369

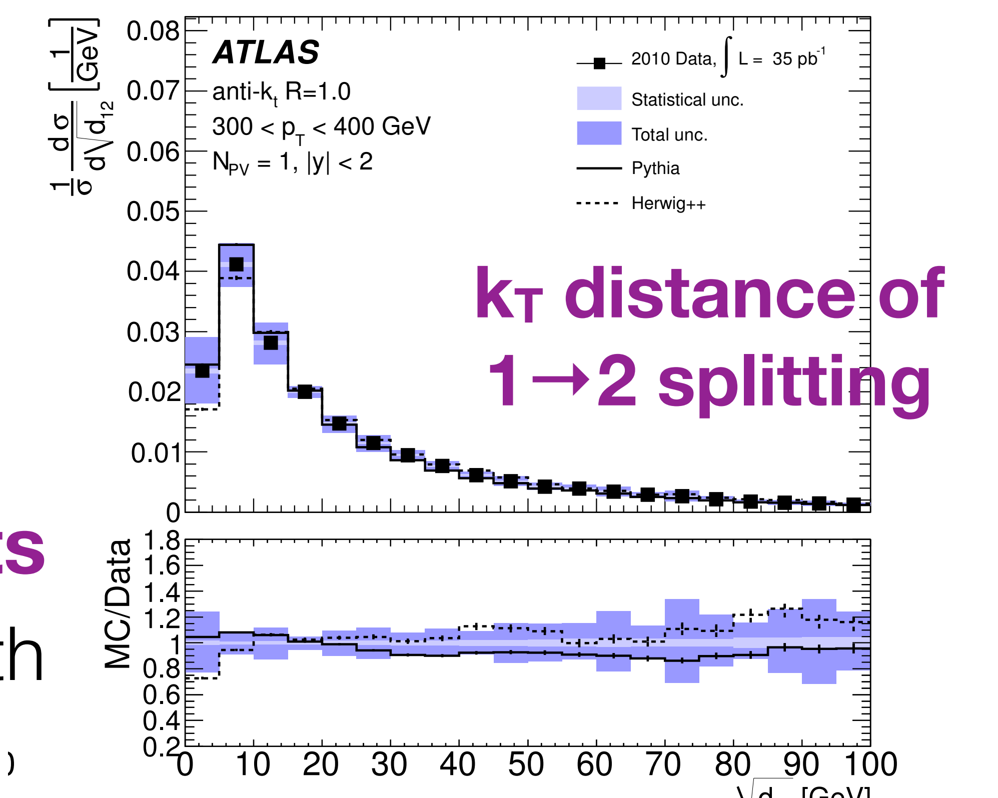


NEW!

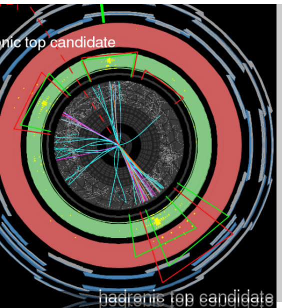
Tag top jets

Understand substructure of large cone (fat) jets

measured for antik_T with R=1 and R=0.6



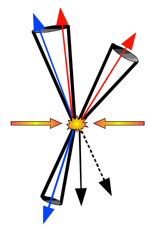
k_T distance of 1→2 splitting

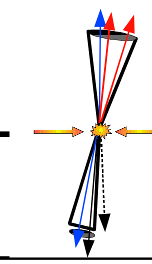


Lepton+jets channel
Event selection

ATLAS-CONF-2012-136

- AKT4: Anti-$k_\perp$ $(R = 0.4)$ jets: $p_T > 25\,\text{GeV}$, $|\eta| < 2.5$
- AKT10: Anti-$k_\perp$ $(R = 1.0)$ jets: $|\eta| < 2.0$, $p_T > 350\,\text{GeV}$, $m > 100\,\text{GeV}$, $\sqrt{d_{12}} > 40\,\text{GeV}$ (expect $\sqrt{d_{12}} \approx m_t/2$ for $t \to bW$)





	resolved	boosted
trigger	single lepton trigger	fat jet (AKT10) trigger
leptons	1 lepton ($e^\pm$ or $\mu^\pm$), $p_T > 25\,\text{GeV}$ additional lepton ($e^\pm$ or $\mu^\pm$) veto, $p_T > 20\,\text{GeV}$	
	lepton trigger match	—
$\not{E}_T$	$e^\pm$: $\not{E}_T > 30\,\text{GeV}$, $\mu^\pm$: $\not{E}_T > 20\,\text{GeV}$	
m_T^W	$e^\pm$: $M_T(W) > 30\,\text{GeV}$, $\mu^\pm$: $M_T(W) + \not{E}_T > 60\,\text{GeV}$	
jets	$\geq 4(3)$ jets (if one jet $m_{\text{jet}} > 60\,\text{GeV}$)	"leptonic jet": AKT4 jet "hadronic jet": AKT10 jet
b-tag	≥ 1 b-tag using AKT4 jets $(\varepsilon_b = 70\,\%)$	

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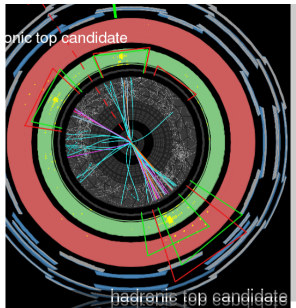


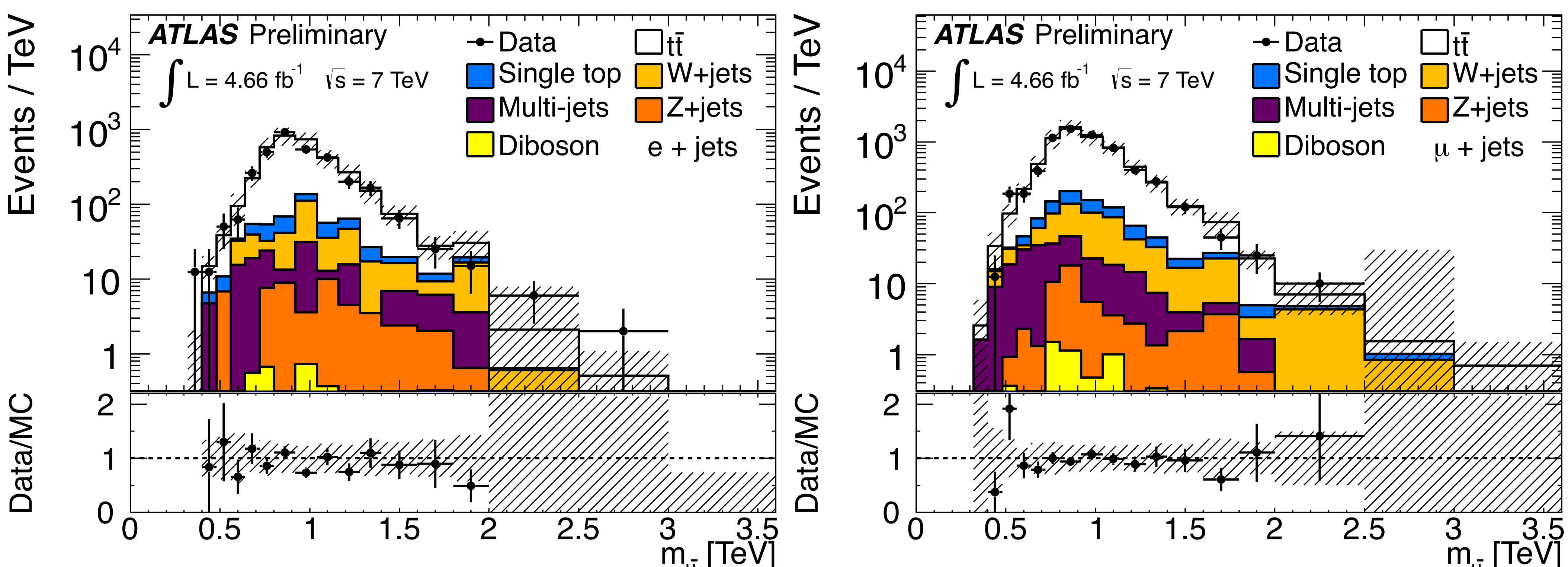
Lepton+jets channel

"Mini-isolation" for leptons and specialised trigger

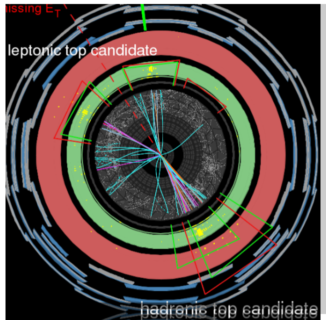
ATLAS-CONF-2012-136

(S Fleischmann, TOP2012)

- Standard ATLAS lepton isolation (relative isolation with fixed cone size) has bad efficiency when the top gets boosted
- "Mini-isolation" with shrinking cone size $\Delta R(\ell, \text{track}) < k_\perp / p_T^\ell$ gives strong improvement in efficiency for leptons from boosted t
- Fat jet trigger (240 GeV anti-$k_\perp$, $R = 1.0$ jet)
  - At high mass: Better efficiency than single-lepton trigger (nearly 100% efficient)
  - Plateau of trigger reached at $p_T \gtrsim 350\,\text{GeV}$



ATLAS-CONF-2012-136



Lepton+jets channel
ATLAS-CONF-2012-136

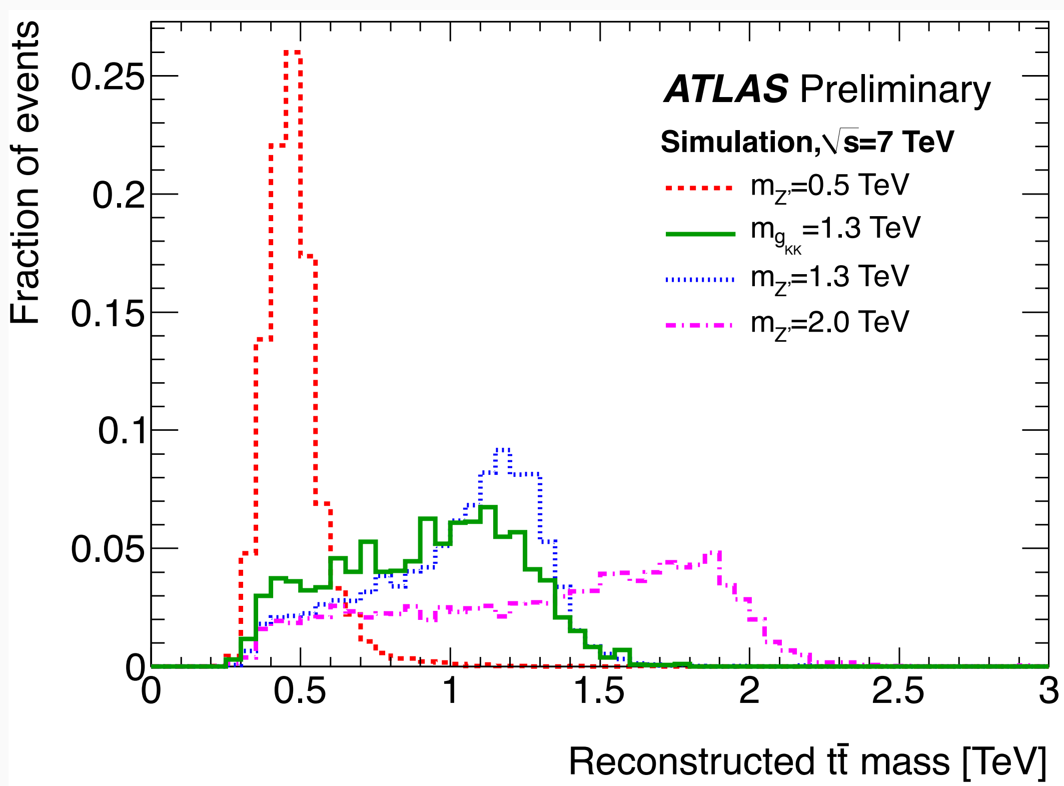
$t\bar{t}$ reconstruction

(S Fleischmann, TOP2012)

- Longitudinal component p_z of neutrino momentum computed by $W^{\pm}$ mass constraint on lepton + $\not{E}_T$ system

Resolved

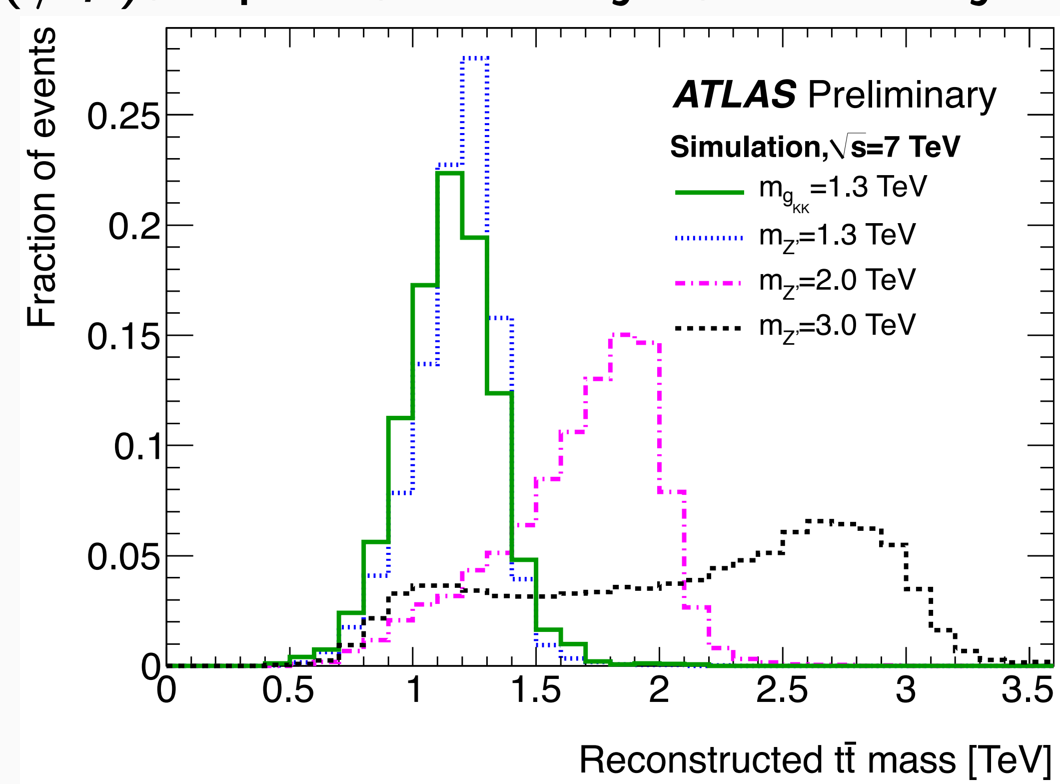
Use jet combination with minimal χ^2 including W (m_{jj}) and t (m_{jjb}, $m_{j\nu b}$) mass constraints



ATLAS-CONF-2012-136

Boosted

Use sum of neutrino solution ($\not{E}_T$), lepton, AKT4 jet, AKT10 jet



ATLAS-CONF-2012-136

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

Lepton+jets channel

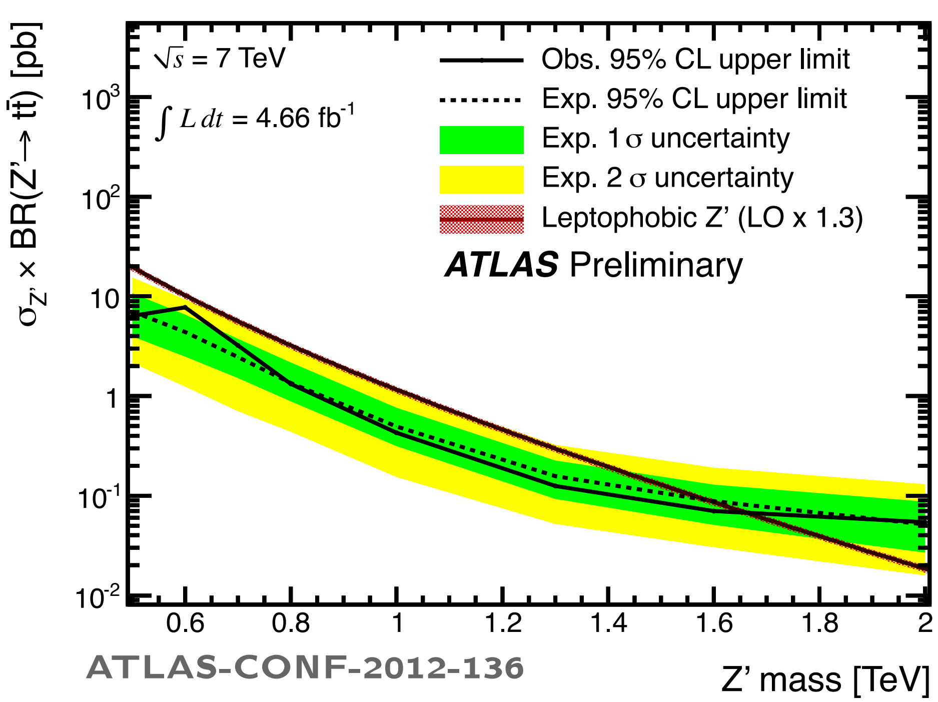
Limits

(S Fleischmann, TOP2012)

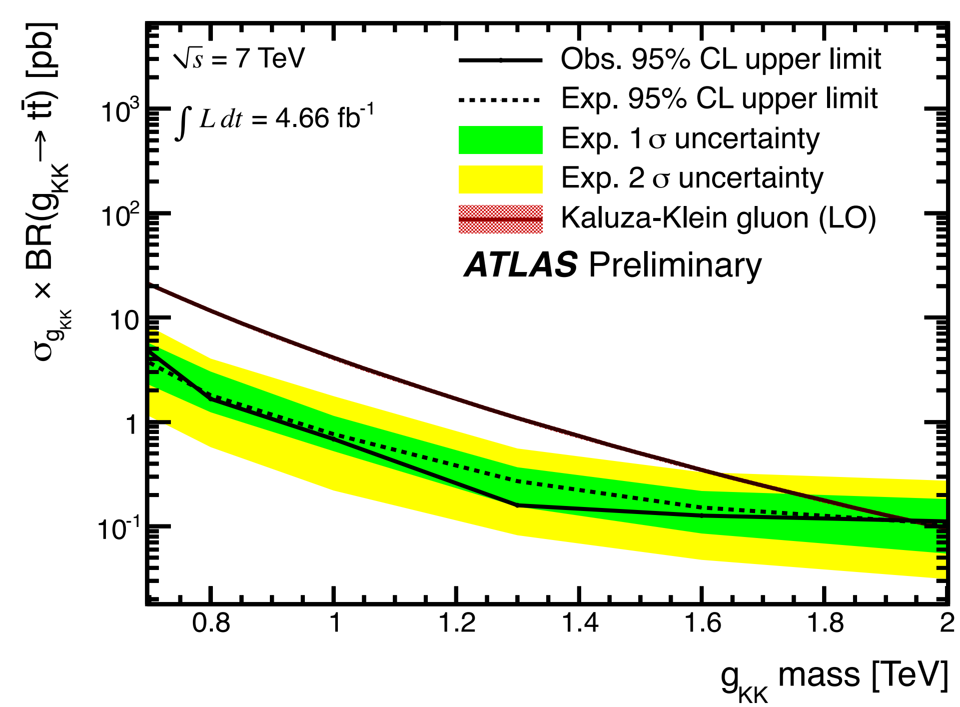
ATLAS-CONF-2012-136

Combined limit of boosted and resolved selection:

- Use the boosted reconstruction, if a single event is selected by the resolved and the boosted selection
- Resolved selection mainly relevant at low $m_{t\bar{t}}$, boosted relevant at high $m_{t\bar{t}}$
- Still some events in resolved selection at high mass, which are not selected by boosted



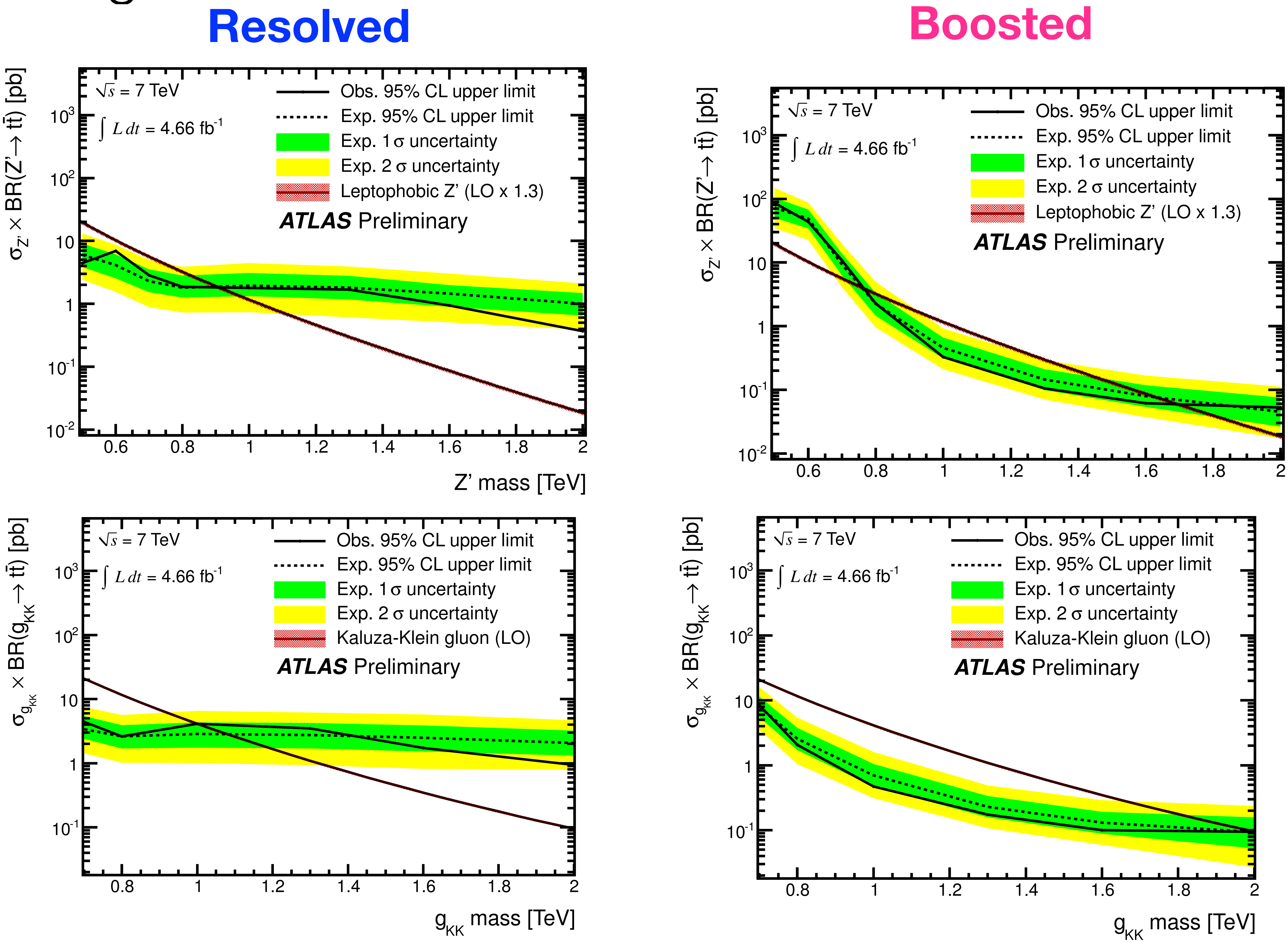
ATLAS-CONF-2012-136



Z' ($\Gamma/m_{Z'} = 1.2\%$) @95% CL: $0.5\,\text{TeV} < m_{Z'} < 1.7\,\text{TeV}$

g_{KK} @95% CL: $0.7\,\text{TeV} < m_{g_{KK}} < 1.9\,\text{TeV}$

Going boosted extends reach!



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 is in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is already underway.**

- The rapidly **increasing data-set and detector understanding** is quickly opening
  - possibility to talk about **top precision physics**
  - **unprecedented phase space for analysis of differential properties and new physics searches linked to top production**
    - ❖ **f***rfrom heavy resonances to dark matter candidates*

- Present differential measurements and searches do not show deviations form the standard model.

- Analysis of full 2011 dataset and 2012 data is in progress. Expect even more new results in coming months. Eager to analyze top quark events with ~20/fb from 2012 !

References and useful tools

- Top2012: International workshop on top phys
- Top Public results from ATLAS
- Top Public results from CMS
- Top Public results from CDF
- Top Public results from D0