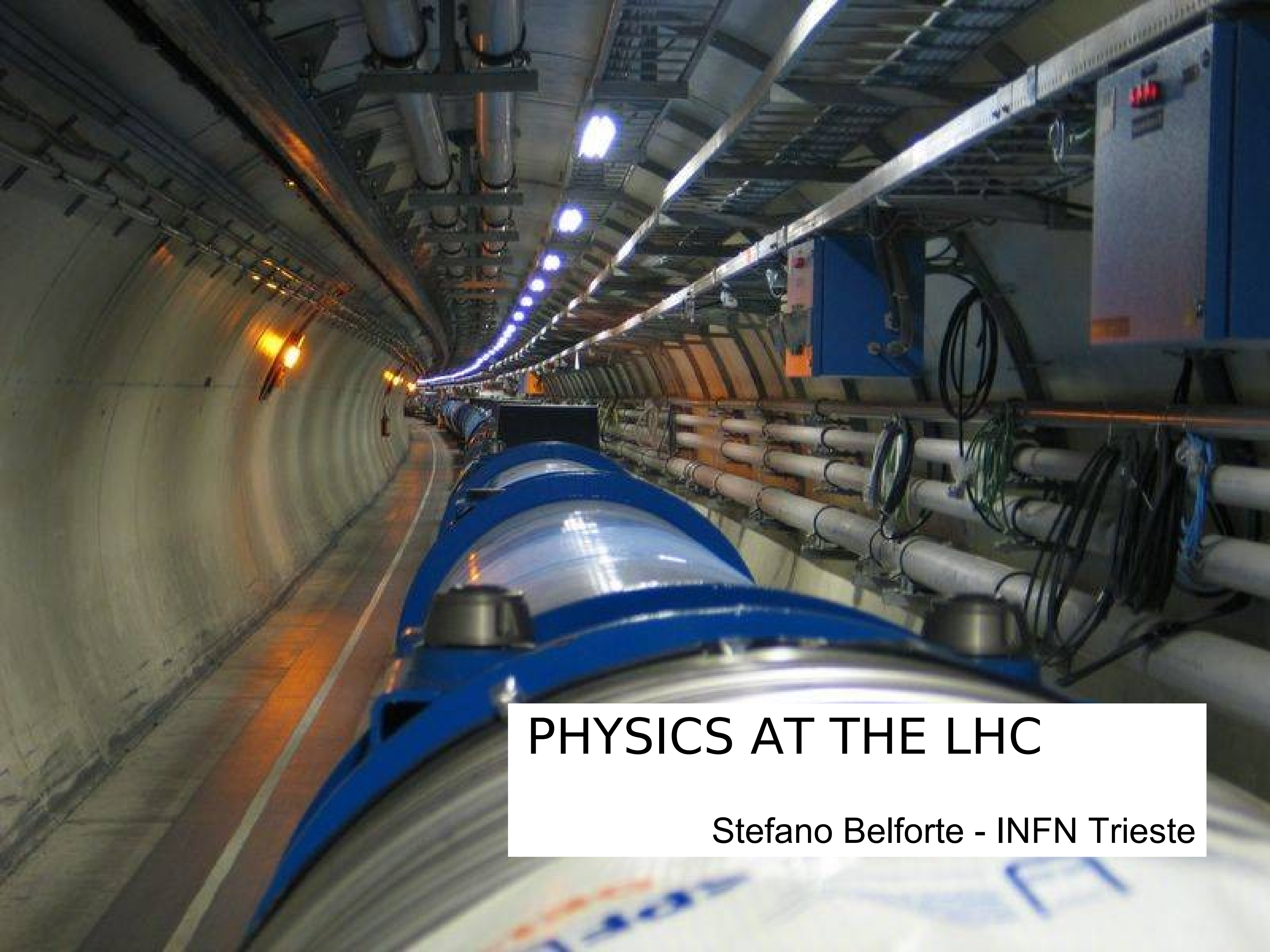


PHYSICS AT THE LHC

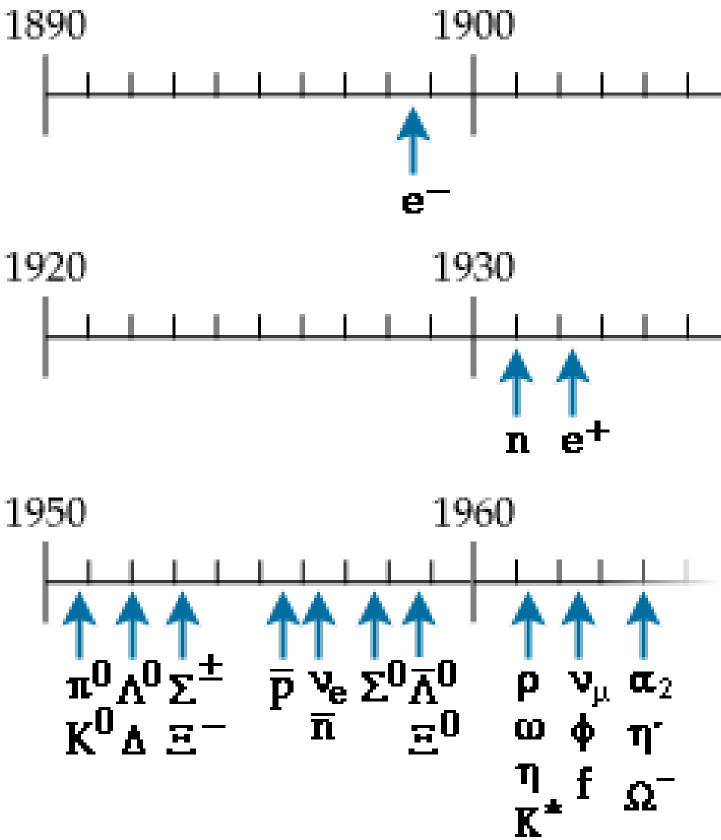
Stefano Belforte - INFN Trieste

FISICA A LHC

- E' la continuazione della fisica a energia di frontiera
- Un nuovo step in una lunga catena di acceleratori
  - ....
  - SppS $\rightarrow$ W/Z
  - LEP $\rightarrow$ conferma di precisione modello standard
  - Tevatron $\rightarrow$ top
  - LHC $\rightarrow$????
- Non e' “la misura di”, “la ricerca di” e' andare a cercare in una regione inesplorata
- In particolare la cosiddetta “scala di massa del TeV”
  - Dove la descrizione corrente del mondo intorno a noi va in crisi
- Una finestra di opportunita' per una grande avventura intellettaule

Too many discoveries?

"Giovanotto, se io fossi in grado di ricordarmi il nome di tutte queste nuove particelle avrei fatto il botanico e non il fisico." (Enrico Fermi)



All of them elementary particles?

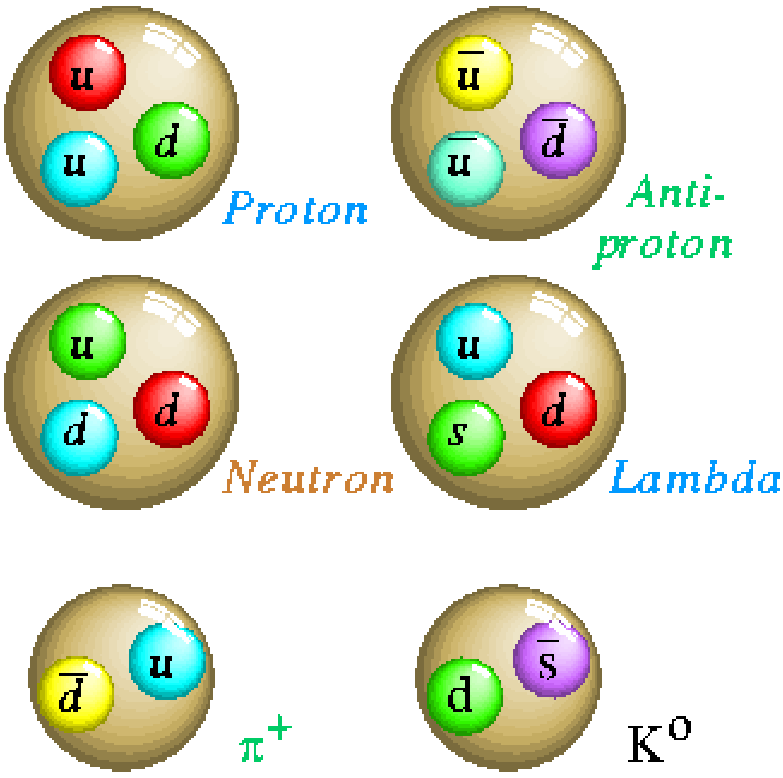
Quarks

Murray Gell-Mann finds a mechanism to explain the common sub-structures of all the discovered hadrons...

Barions: 3 quark
Anti-barions: 3 anti-quark
Mesons: 1 quark and 1 anti-quark

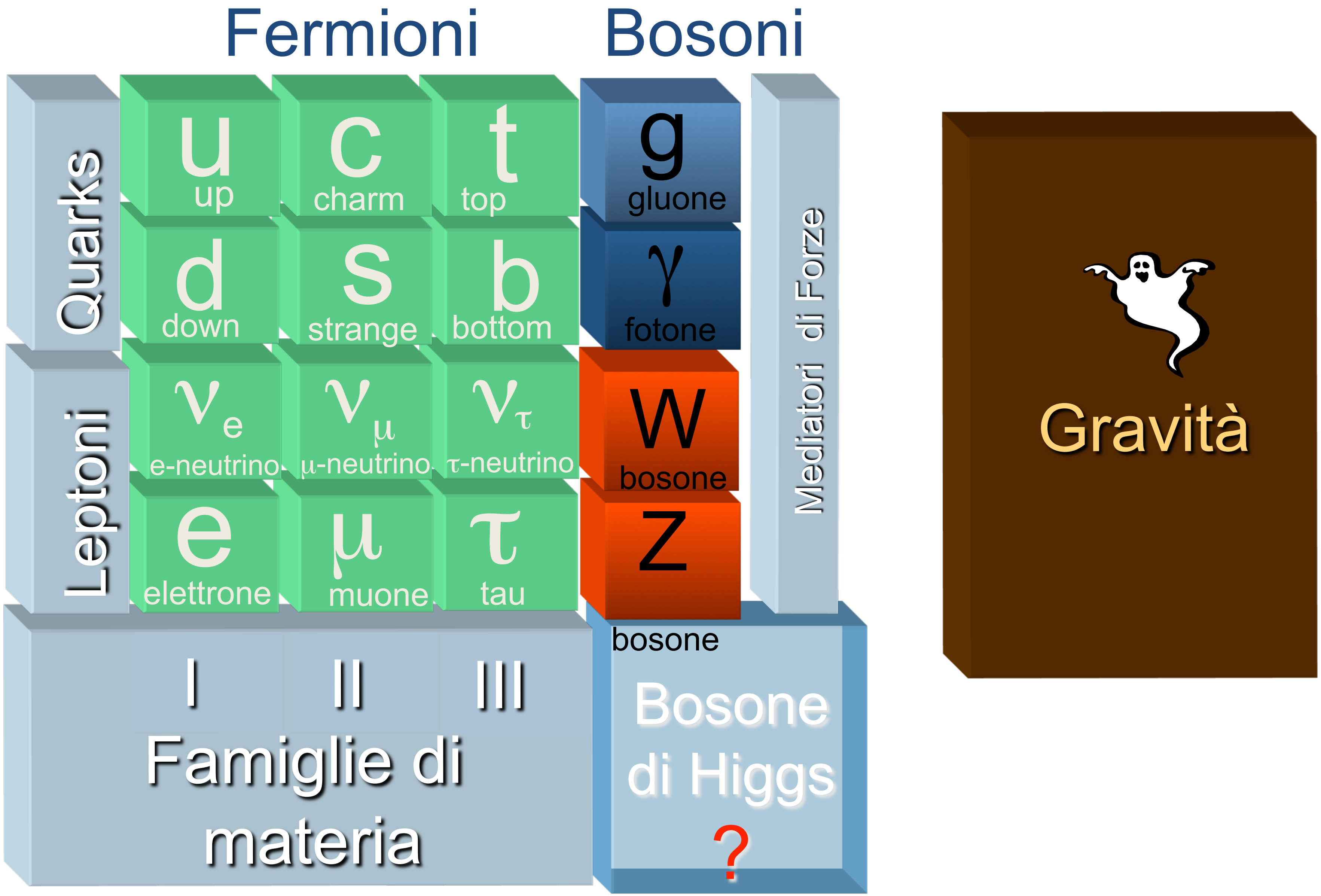
"Three quarks for Muster Mark!
Sure he hasn't got much of a bark
and sure any he has it's all beside
the mark."

— James Joyce, Finnegan's Wake



Charges: u +2/3, d –1/3, s –1/3

Il Modello Standard, 1970-2000

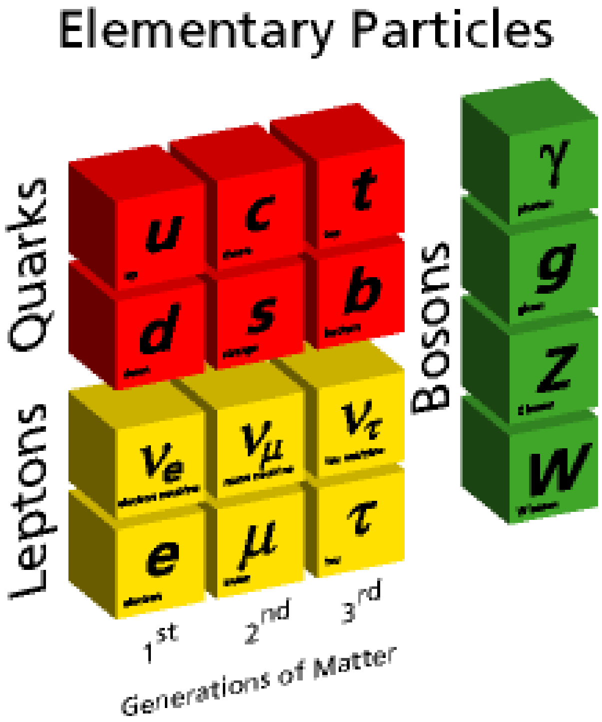


The Standard Model

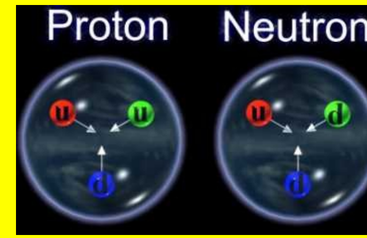
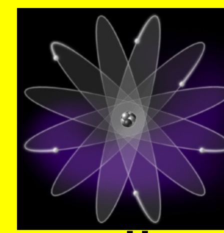
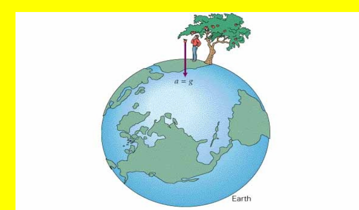
- Today we have a simple framework to describe the constituents of matter and their interactions: the Standard Model.

- According to the SM, the elementary constituents of the whole Universe are 12, grouped in 3 families, each of one containing 2 quarks and 2 leptons.

- Anti-matter has to be added (for each particle a corresponding anti-particle with opposite charge



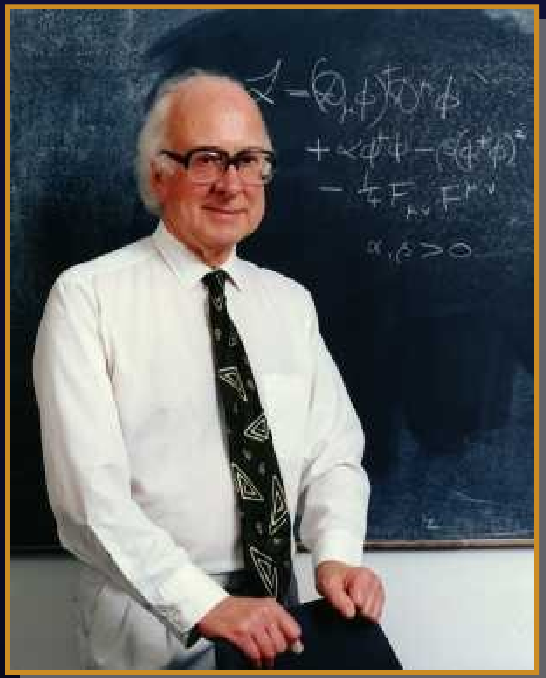
Forces in Nature

Force	Intensity	Bosons	Happens in:
Nuclear force	~ 1	Gluons (no mass)	
Electromagnetic	~ 10^{-3}	Photons (no mass)	
Weak nuclear	~10^{-5}	W^+,W^-,Z^0 (heavy)	beta radioactive decay
Gravitation	~10^{-38}	Gravitons (?)	

The SM is more then a list of blocks

- E' una formulazione delle interazioni (Lagrangiana) che deriva da ed incorpora principi di simmetria elementari che hanno straordinario potere predittivo:
  - Invarianza di Lorentz
  - Invarianza di gauge locale
- Fornisce una descrizione unificata delle interazioni deboli ed elettromagnetiche (Weinberg-Salam) in base ad un ulteriore simmetria di gauge
- La differenziazione di questa simmetria elementare in una lagrangiana debole con bosoni massivi (W/Z) ed una elettromagnetica con bosoni a massa zero (fotone) avviene attaverso il meccanismo di Higgs

Peter Higgs



- A scottish physicist who, more than 40 years ago, proposed a mechanism for particles to acquire a mass.

- Higgs supposed that the vacuum contains a field which can "slow down" particles.

To slow down a particle corresponds to give it a mass

- Bigger or smaller
- If the particle is insensitive to this force, the particle remains massless

Il Bosone di Higgs

- Weinberg e Salam hanno usato il meccanismo di Higgs per unificare la forza debole ed elettromagnetica
- A conclusione della procedura la Lagrangiana elettrodebole contiene un nuove termine: il quanto di forza del campo di Higgs, una particella di spin 0 chiamata Bosone di Higgs
- I fermioni del modello standard si accoppiano col Bosone di Higgs (Yukawa coupling) la costante di accoppiamento caratteristica di ognuno ne determina la massa

- Tutti questi accoppiamenti introducono anche molte costanti arbitrarie
  - Misurate sperimentalmente
  - Ma non derivate da principi primi unificatori

Il Modello Standard

- Granze eleganza concettuale
- Stupefacente accordo con una quantita' enorme di dati sperimentali:
  - Trent' anni di ricerca, Nessuna discrepanza :-(
  - Ogni indizio di “crisi” risolto con un affinamento delle tecniche di calcolo
- Rafforza : Fisica = ricerca di principi unificatori

- Ma molte costanti adattate ad hoc
  - Parton Distribution Functions, Form Factors: incorporano la nostra ignoranza sulla struttura interna degli adroni ma in teoria e' perche' non sappiamo fare I conti nella regione non perturbativa, non perche' c'e' fisica non capita

- Ci sono anche difficolta' di consistenza interna, lo SM non puo' essere la fine della storia

Beyond the Standard Model?

- The Standard Model makes very accurate predictions about the nature of matter, nucleus, atoms, stars, you and me
- It is compatible with all the measurements performed
-
- But:
  - It is based on an element not yet observed: the Higgs
  - It presents some mathematical difficulties
  - It does not include gravity
  - It does not explain the existence of dark matter
- The answers to these questions can be found in new experiments, like the LHC!

Cose c'e' oltre lo SM ?

- In passato si e' partiti da crisi “sperimentali”
  - Gli spettri atomici
  - Il vento d'etere
  - La radiazione di corpo nero
  - L'effetto fotoelettrico

- Ora il modello standard spiega ~tutto :-(
  - Tranne la materia oscura
  - Ma l'evidenza cosmologica e' solo indiretta

- Le difficolta' dello SM sono soprattutto teoriche
  - Non e' una buona “teoria del tutto” (TOE)
  - La ricerca di una descrizione diversa finora e' stata guidata solo dalla ricerca di ulteriore unificazione e riduzione dei parametri liberi

Grand Unified Theories GUT

- Weinberg e Salam hanno unificato forza debole ed elettromagnetica
- E quella forte ?

- L'unico modello consistente sopravvissuto finora richiede SuperSimmetria

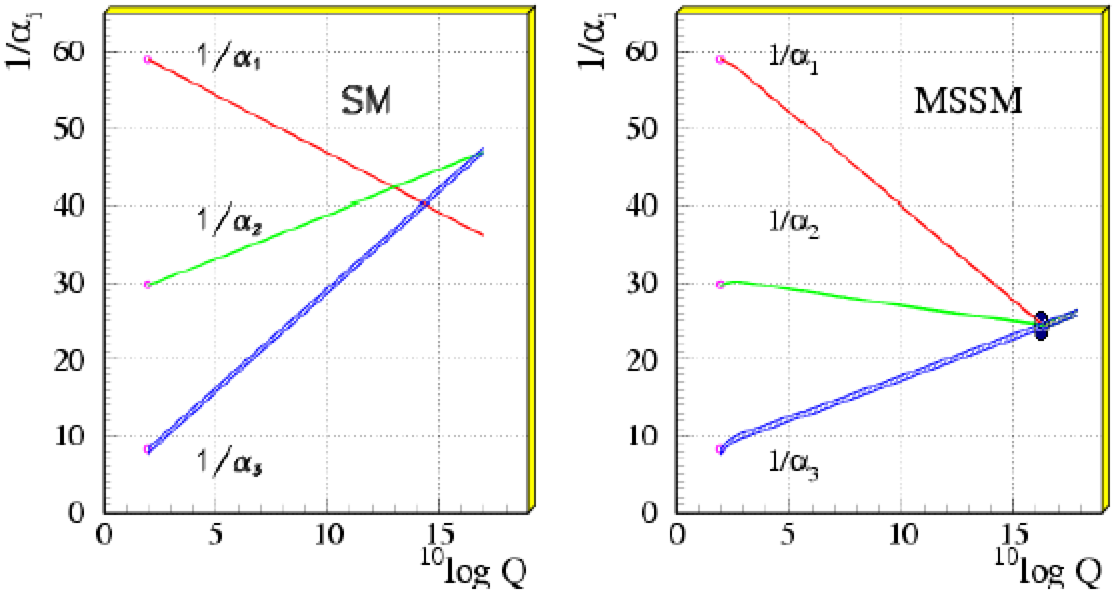


Figure 15.1: Gauge coupling unification in non-SUSY GUTs on the left vs. SUSY GUTs on the right using the LEP data as of 1991. Note, the difference in the running for SUSY is the inclusion of supersymmetric partners of standard model particles at scales of order a TeV (Fig. taken from Ref. 21). Given the present accurate measurements of the three low energy couplings, in particular $\alpha_s(M_Z)$, GUT scale threshold corrections are now needed to precisely fit the low energy data. The dark blob in the plot on the right represents these model dependent corrections.

E la gravita' ?

- La relativita' generale e' fisica classica, non quantistica
- L'unico modo trovato finora di mettere assieme gravita' e quanti e' attraverso la Super Simmetria
- In particolare la teoria delle (super)stringhe e' quanto di piu' vicino esita ad una TOE
  - Descrizione consistente della gravita' quantistica che contiene il Modello Standard con un numero molto piccolo di parametri liberi, ma molte assunzioni libere

Nel Modello Standard ci sono molte altre cose che non capiamo

Per esempio:

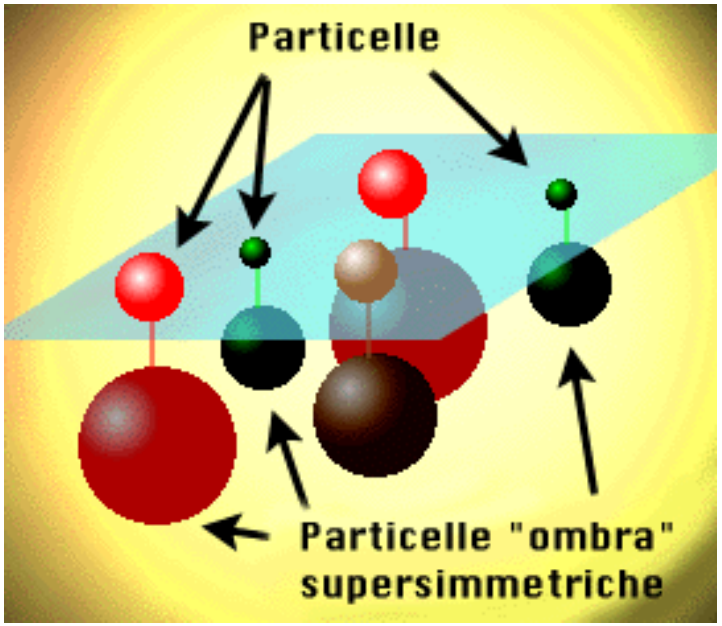
Perche le generazioni sono 3? C'e' una sottostruttura?

Perche le masse sono quelle che sono?

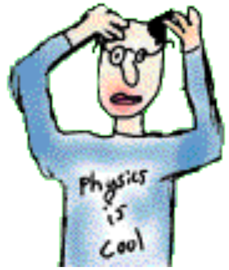
Dov'e' finita l'antimateria creata nel Big-Bang?

Dove la mettiamo la gravita'?

La soluzione a questi ed altri problemi non e' nota. La possibilita' piu` accettata al momento e' che il Modello Standard sia solo una parte di una teoria piu` grande chiamata la "Supersimmetria"



- Alcuni fisici, nel tentativo di unificare la gravita' con le altre forze fondamentali, hanno suggerito che ogni particella fondamentale dovrebbe avere una particella "ombra" (shadow). Sono piu' di 20 anni che cerchiamo queste particelle supersimmetriche



Ricapitoliamo

- Il Modello Standard spiega tutte le misure fatte finora
  - Ma richiede il Bosone di Higgs (non ancora osservato)

- La souzione di molte difficolta' teoriche del MS e l'unificazione con la gravita' per ora e' stata ottenuta solo in teorie supersimmetriche
- SUSY: non c'e' piu' “IL” Bosone di Higgs
  - Ce ne sono molti
  - Molto piu' elusivi

- Ma allora cosa si cerca a LHC ?

But we really don’t know enough to get it right.

We need to know a lot more, and most fundamentally we need to know from the LHC whether the idea of supersymmetry at accelerator energies is correct.

La fisica a LHC

- Esplorare la scala di energia del TeV
- Dove ci aspettiamo che il MS vada in crisi e compaiano segnali di "nuova fisica"

- Verificare il MS in questa regione nuova, cercare discrepanze tra le predizioni e le misure
- Osservare nuovi fenomeni (particelle)
  - SUSY
  - Higgs
  - Nuove famiglie di quark/leptoni
  - Nuove interazioni (Z', W')
  - Struttura composta dei quark
  - …
  -

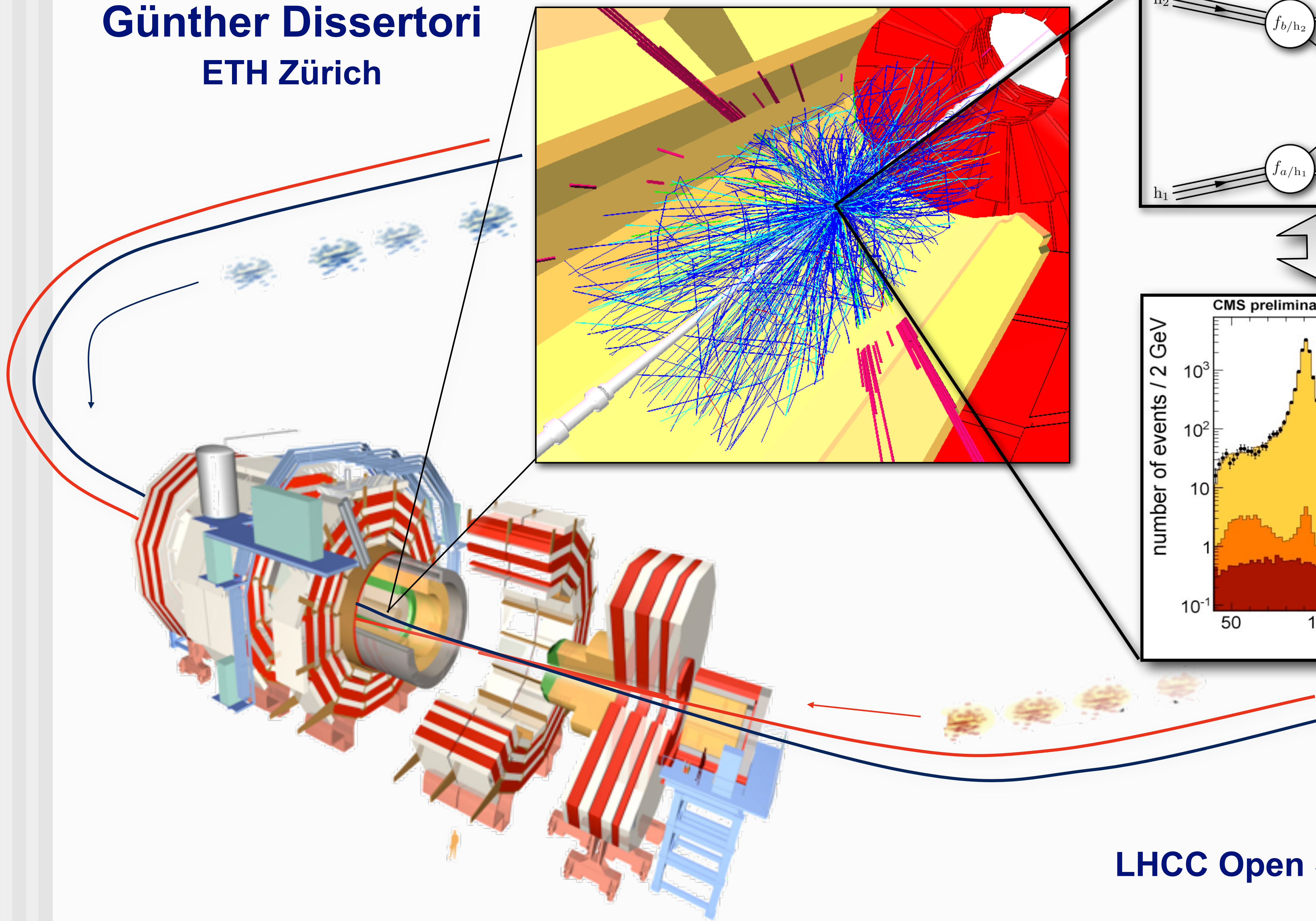
LA RICETTA

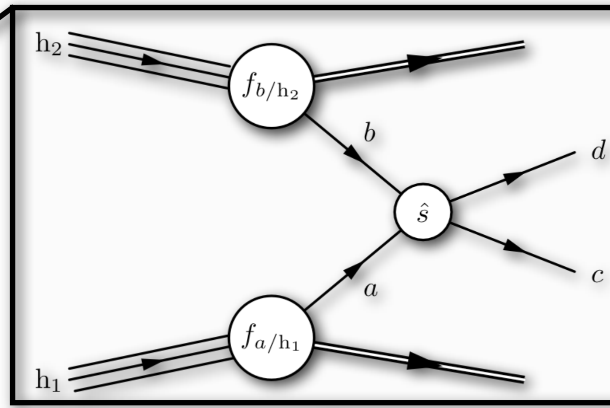
- L'Higgs (o il partner supersimmetrico del gluone) non si trovano colle pinzette come pepite d'oro in miniera

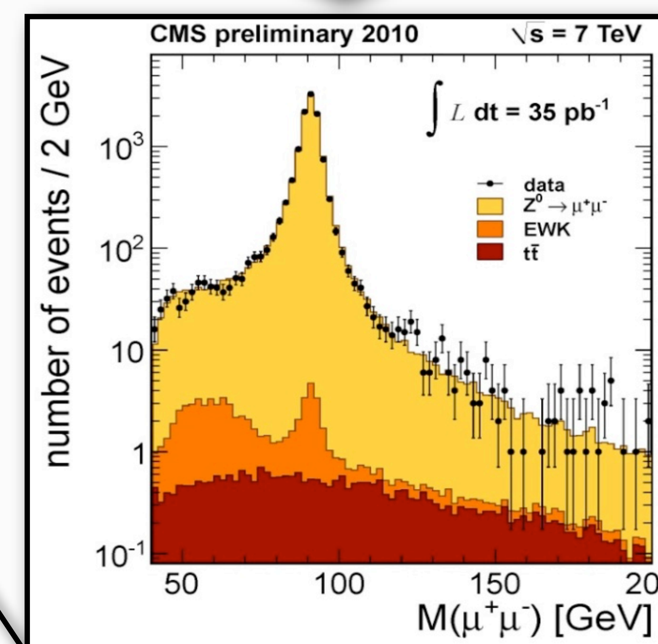
- Misurare una quantita' fisica, in genere una distribuzione
- Confrontare con previsione teorica + simulazione della risposta del rivelatore
- Assicurarsi di aver capito la simulazione
- Aggiustare la previsione teorica fino a riprodurre I dati sperimentali
  - Con i manici a disposizione nel MS
  - Ricorrendo a previsioni/modelli beyond-Standard Model !!
  - Nulla funziona: La novita' !!!!!!!

CMS Status Report

Günther Dissertori
ETH Zürich

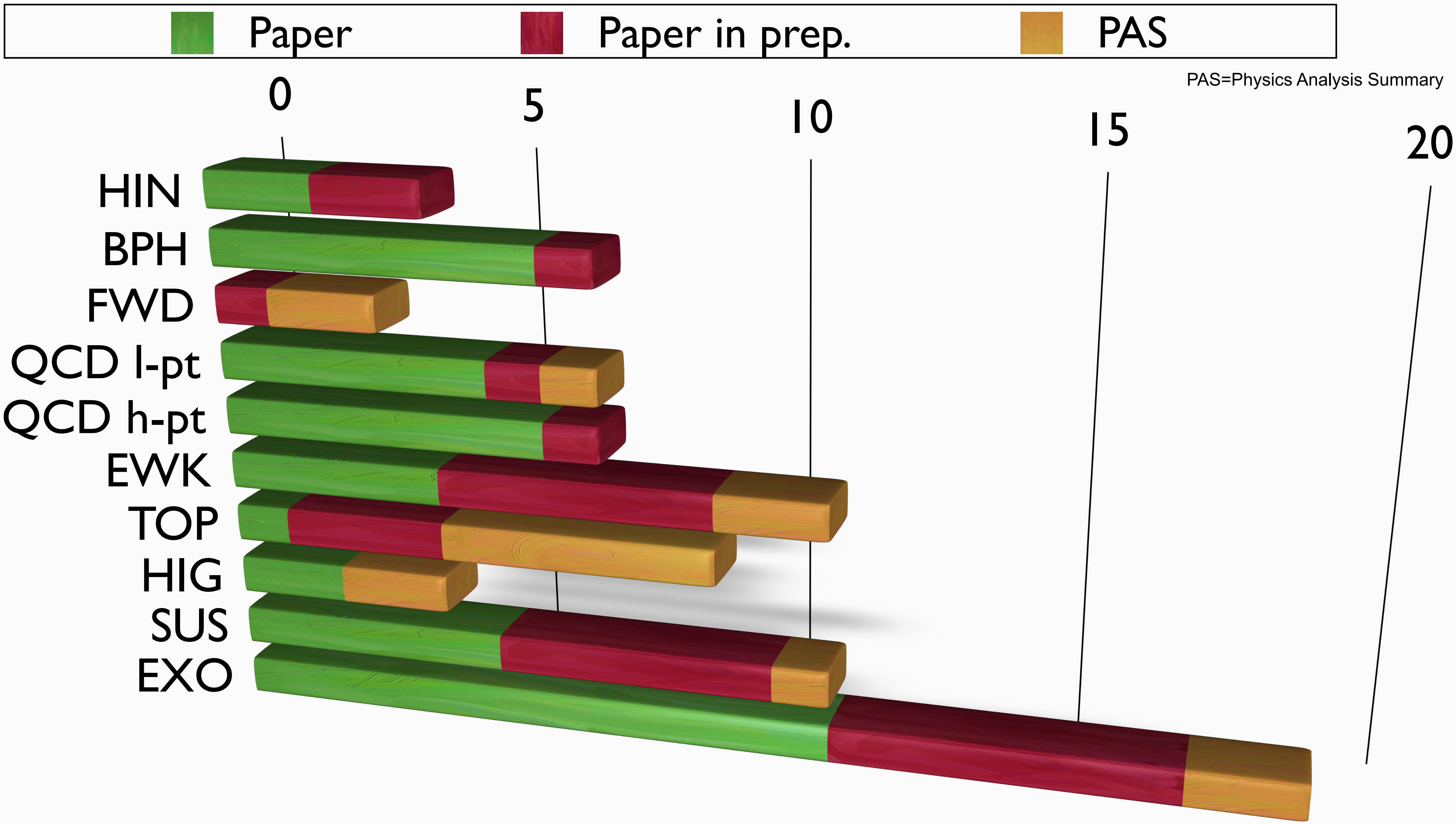






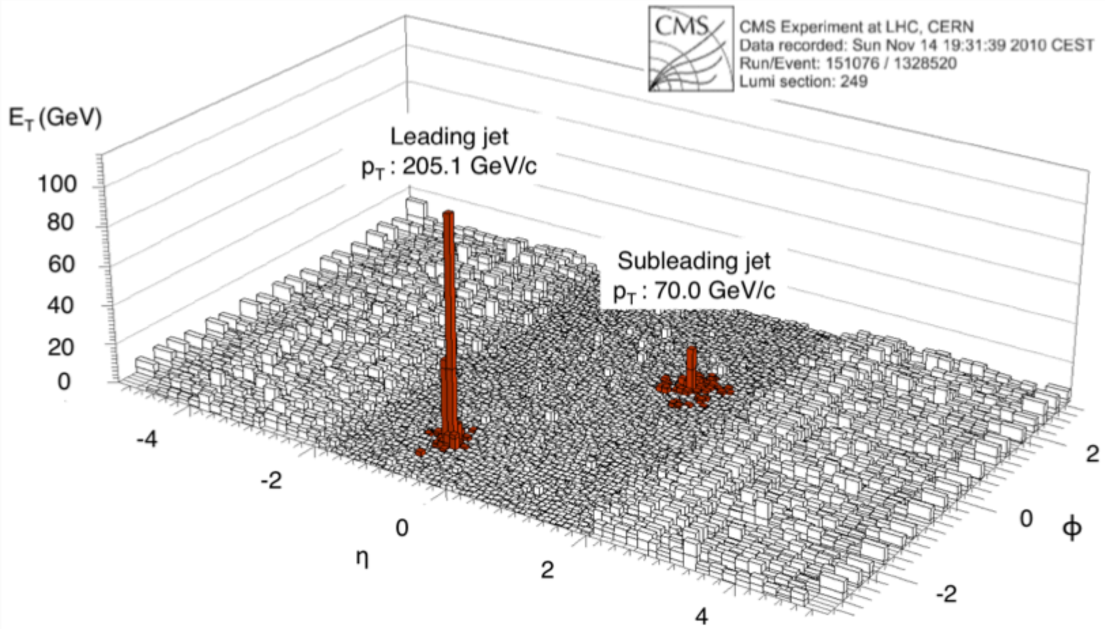
LHCC Open Session

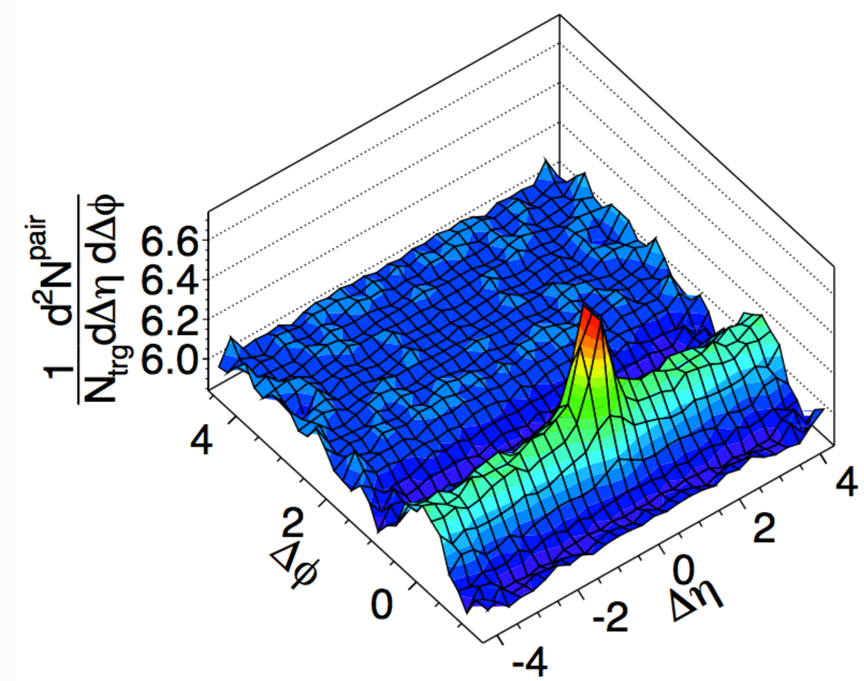
List of physics analyses



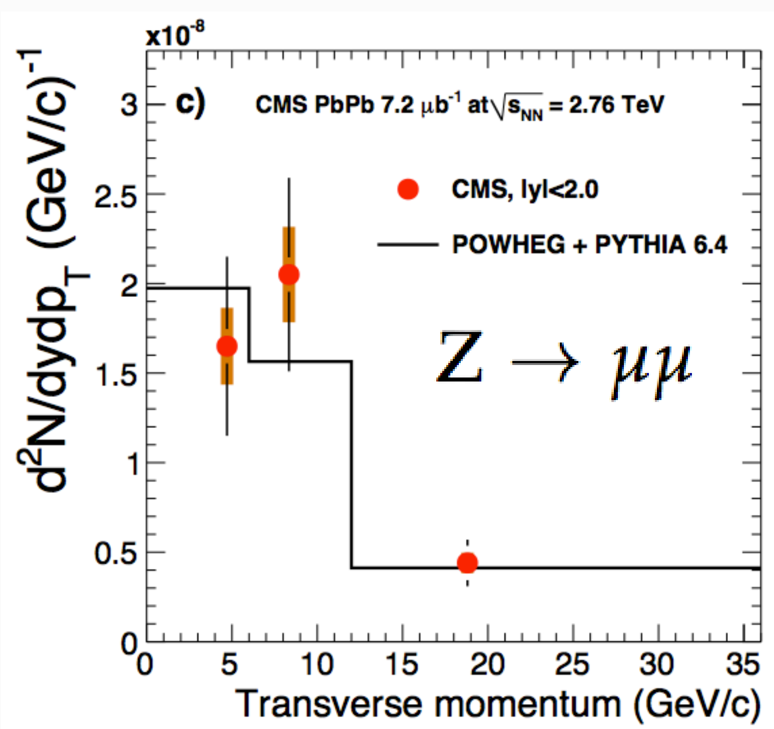
In total : **82** analyses approved based on 2010 data
42 papers (published, submitted, or close to submission)

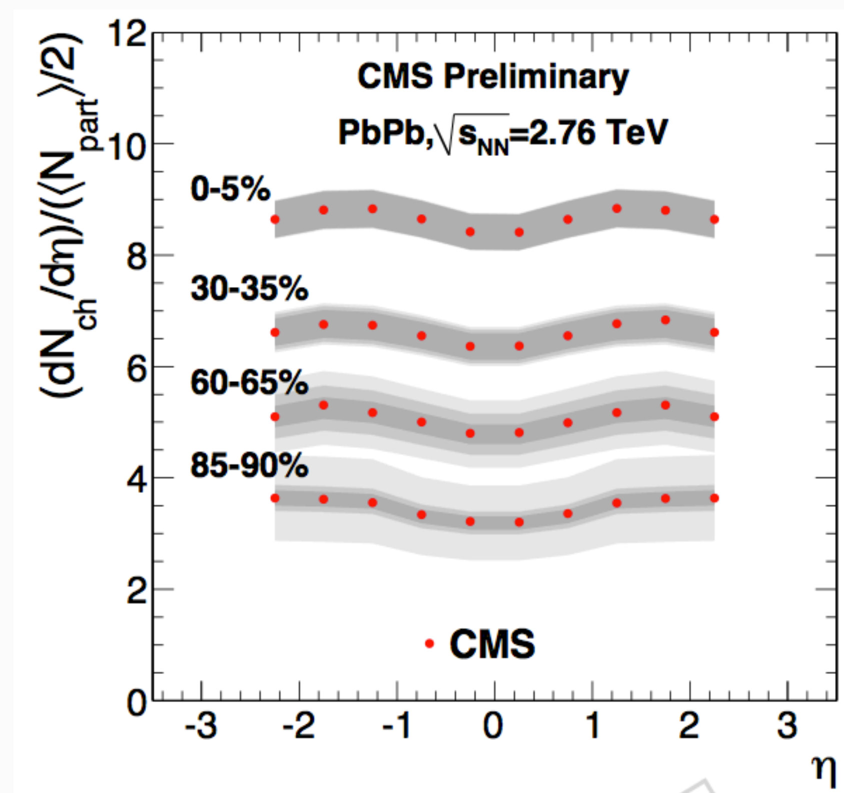
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults





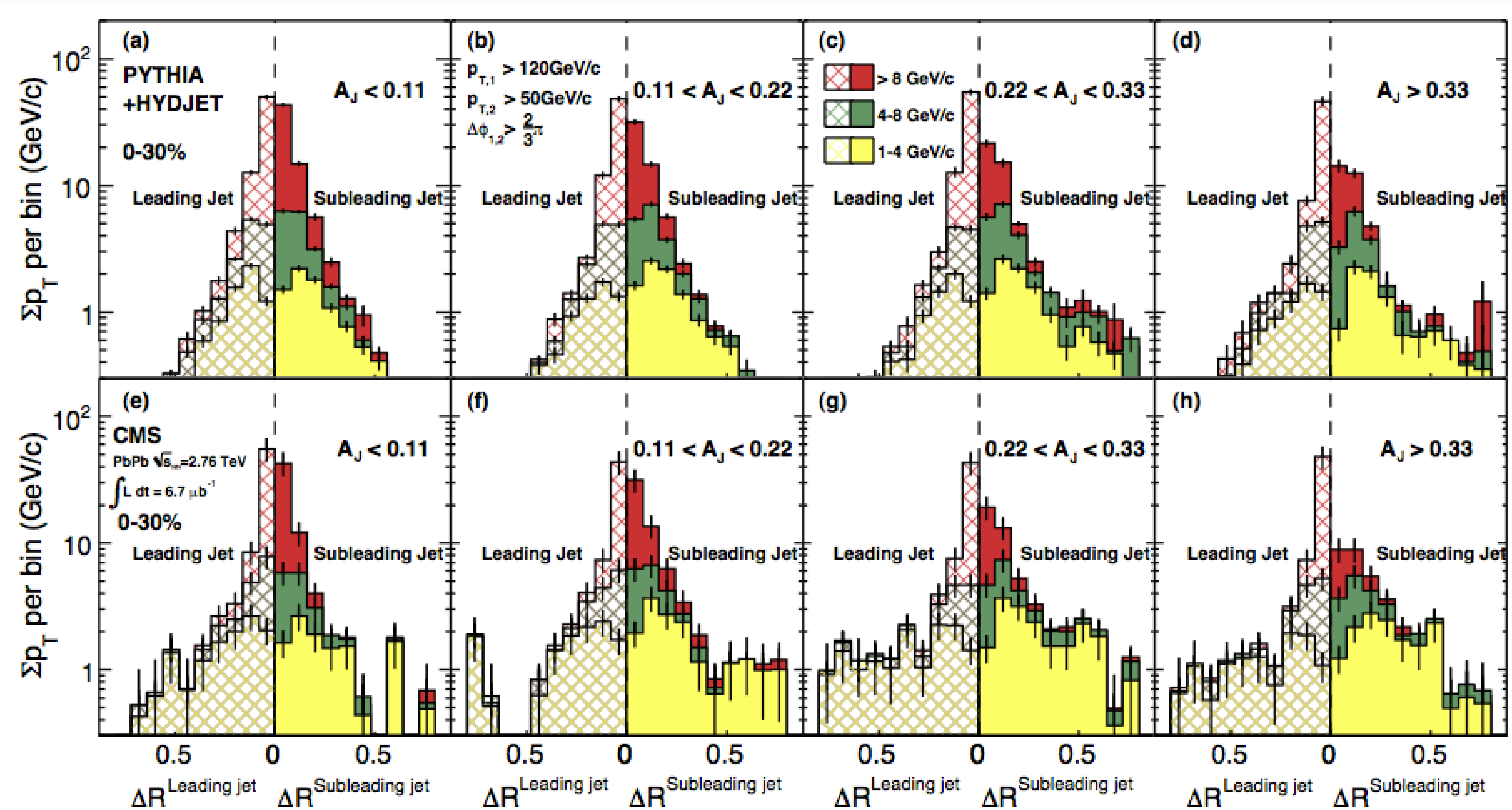
Heavy Ion Physics





Jet Quenching

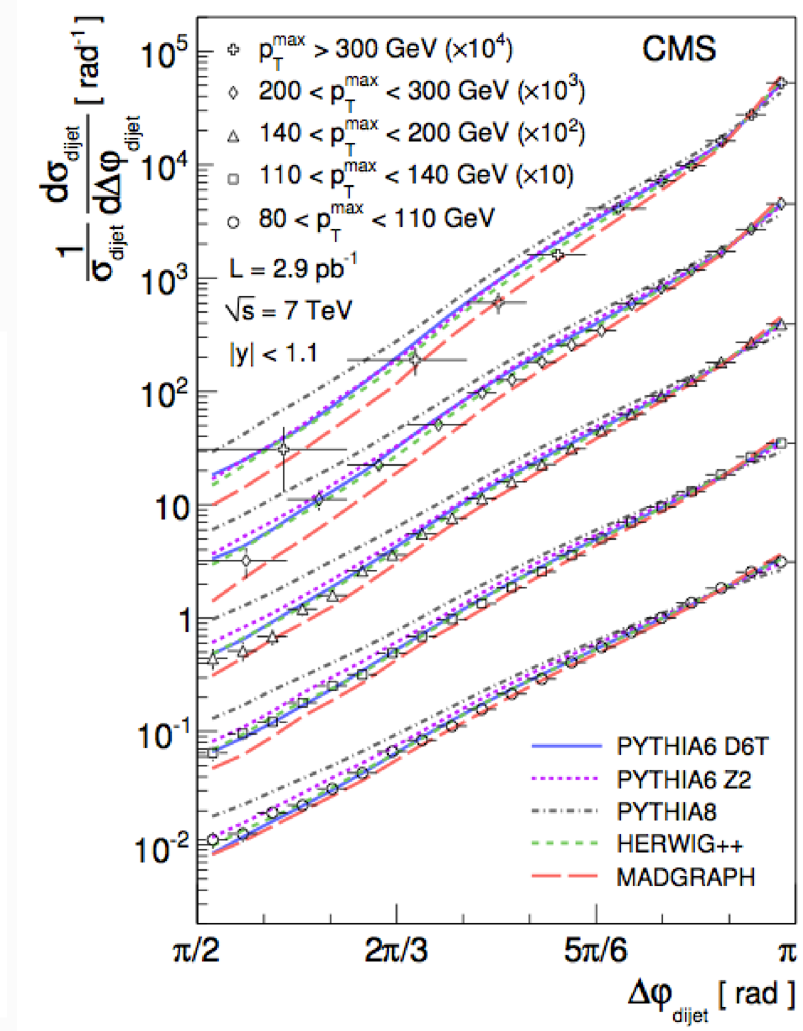
arXiv:1102.1957 ; CMS-HIN-10-004 ; CERN-PH-EP-2011-001. Submitted to Physical Review C

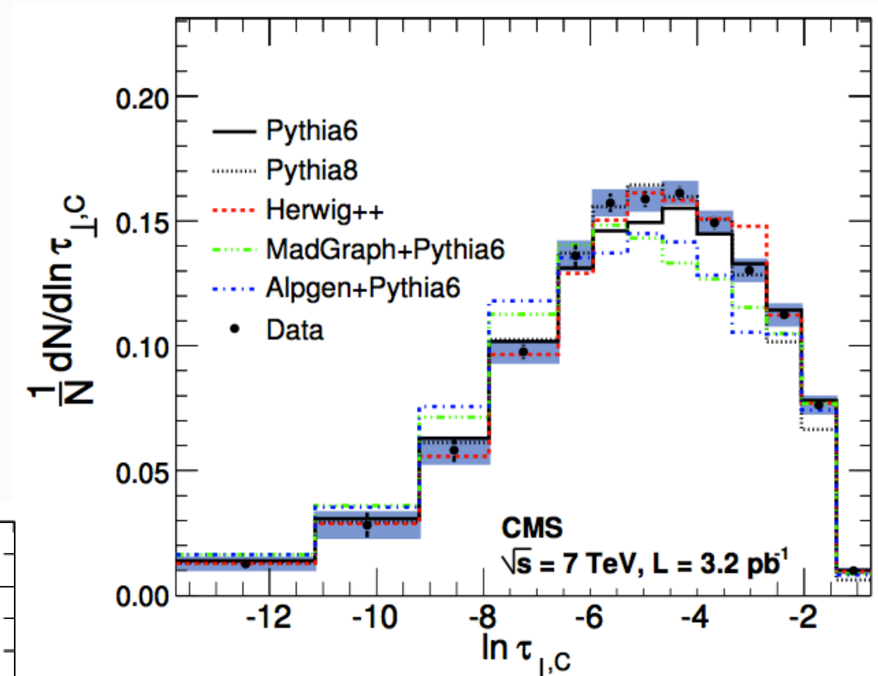


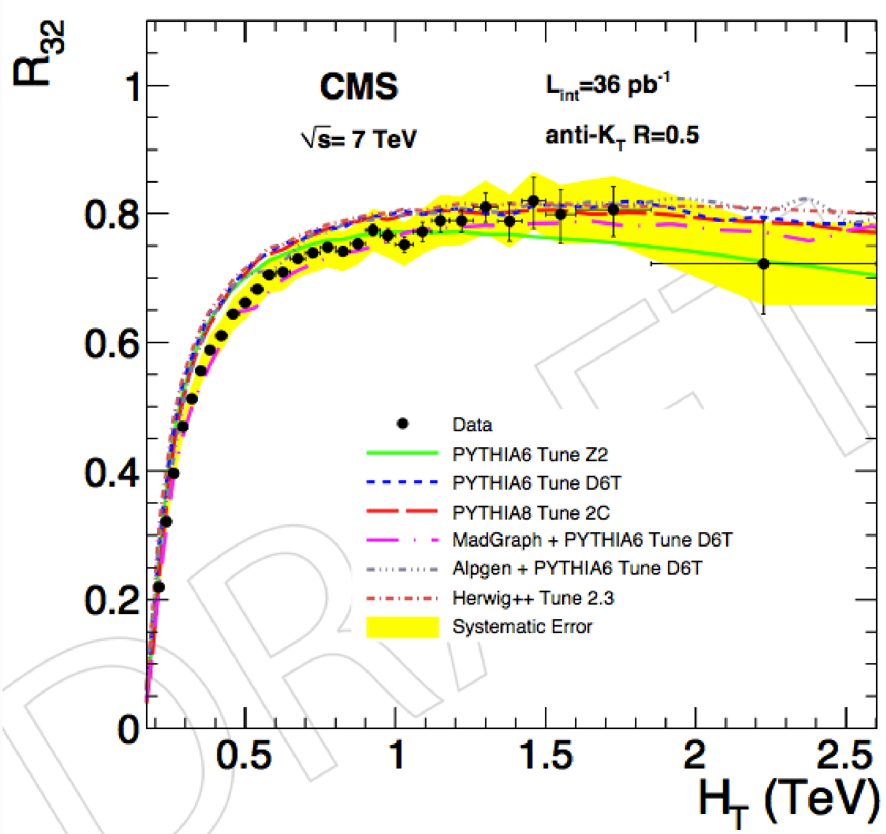
- The phenomenon of jet quenching in Heavy-Ion collisions is now described in detail and well understood.
- The di-jet momentum balance is fully recovered if we consider the low p_T tracks distributed over a wider angular range wrt the jet axis.

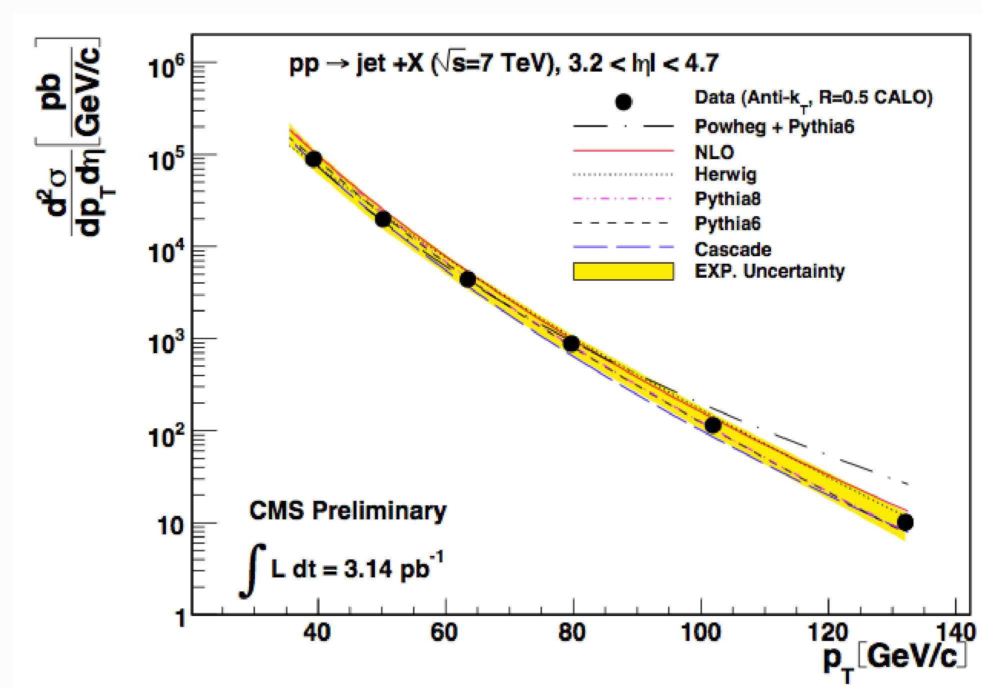
The studies of Heavy-Ion collisions have already gone well beyond the mere observations of new effects!

Production of Jets



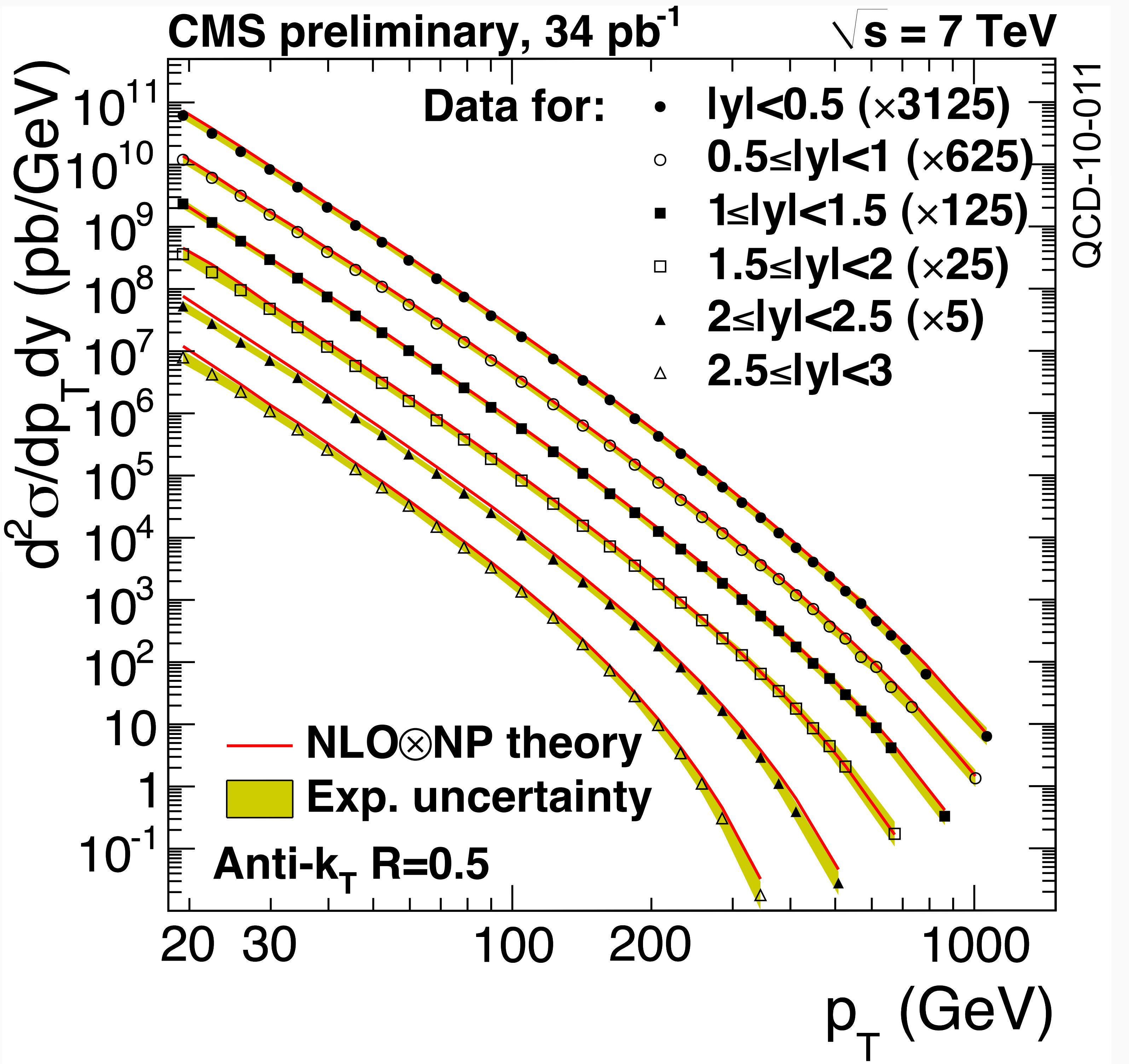






Inclusive jet cross section

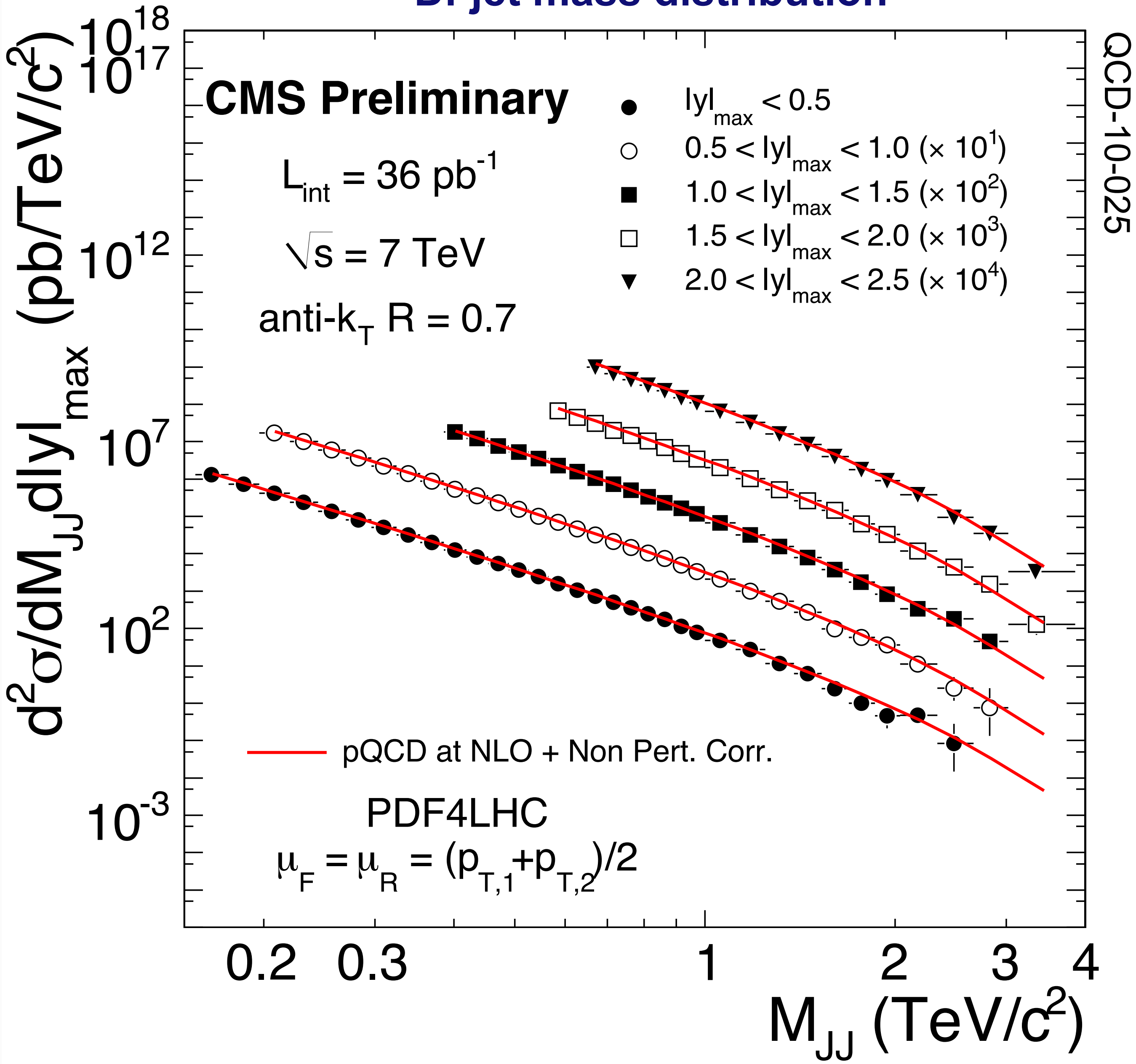
- From p_T=18 GeV to p_T~1 TeV!
- Extending to very low p_T thanks to Particle Flow
- JES uncertainties: ~3-5 %
- Corrected to particle level
- Inclusive jet p_T spectra are in **good agreement with NLO QCD**
- Consistent results obtained using calo-jets



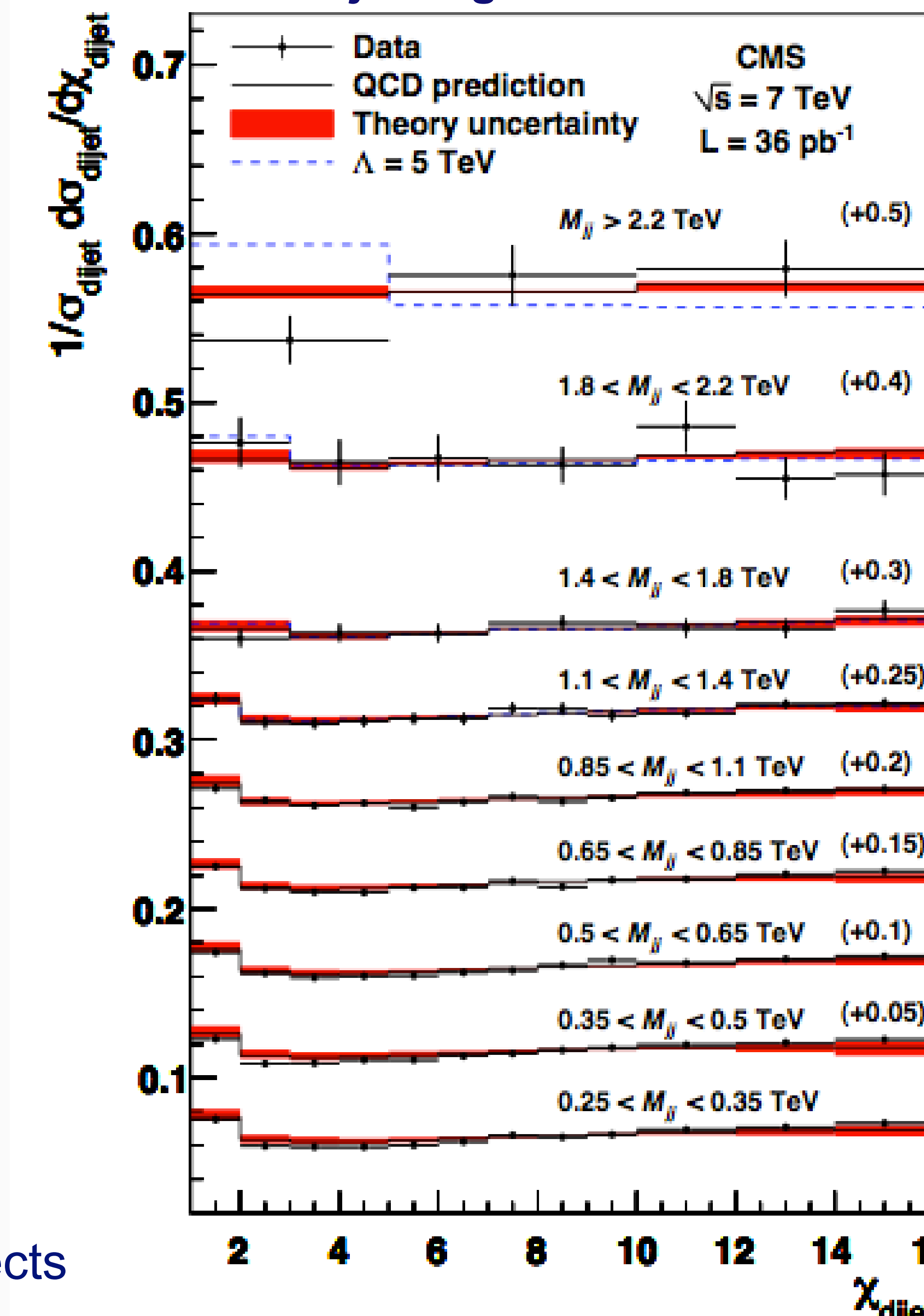
Further jet distributions

ETH Institute for Particle Physics

Di-jet mass distribution



Di-jet angular correlations

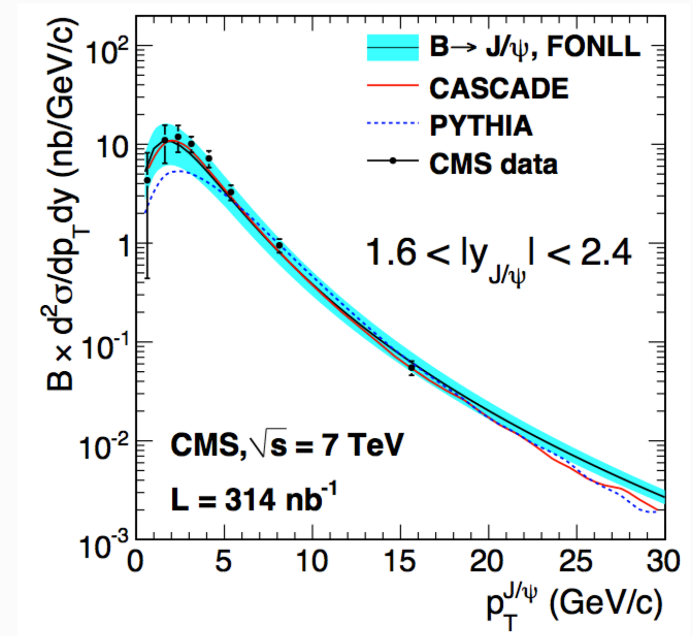


arXiv:1102.2020, submitted to PRL

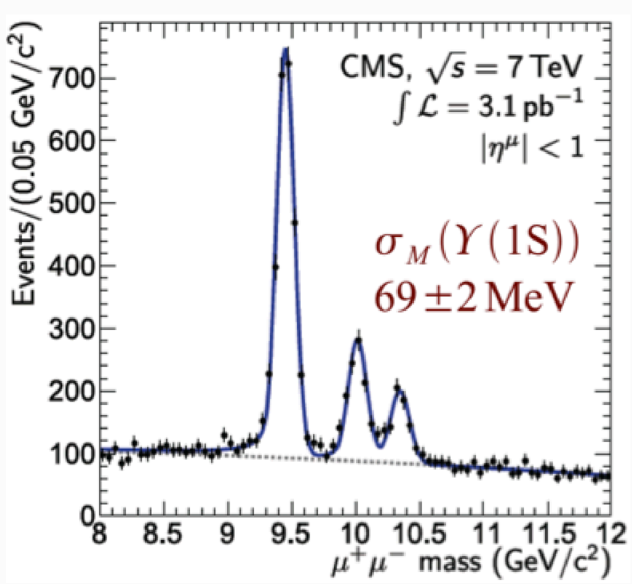
- All distributions unfolded/corrected for detector effects

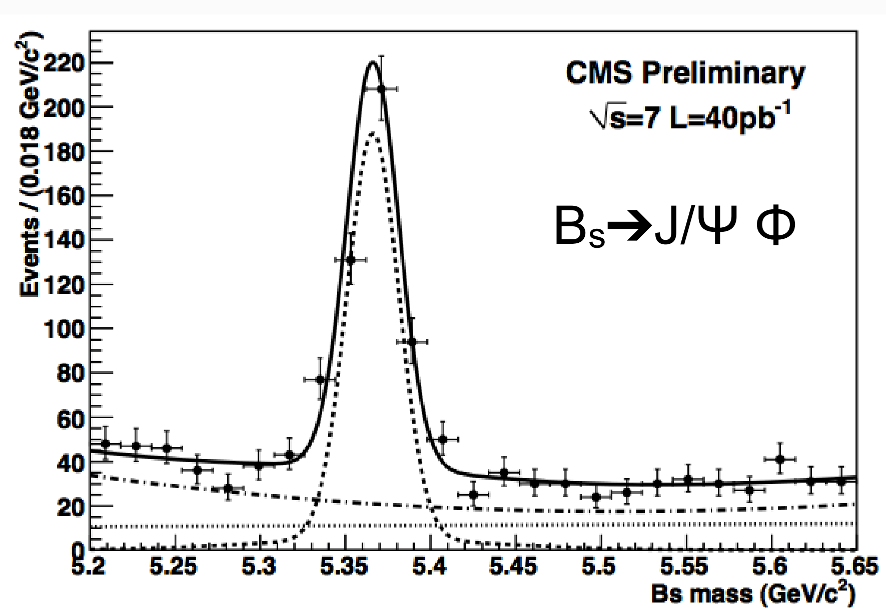
Achieved excellent understanding of jet production, over very wide phase space. Start to constrain Monte Carlo models.

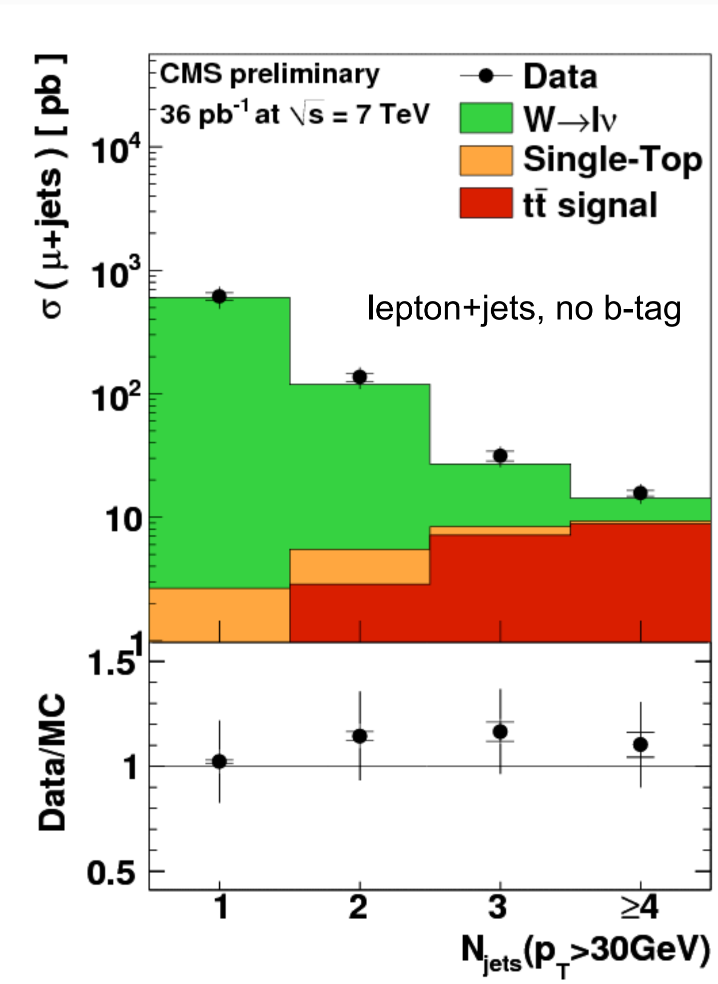
Production of “heavy” quarks:



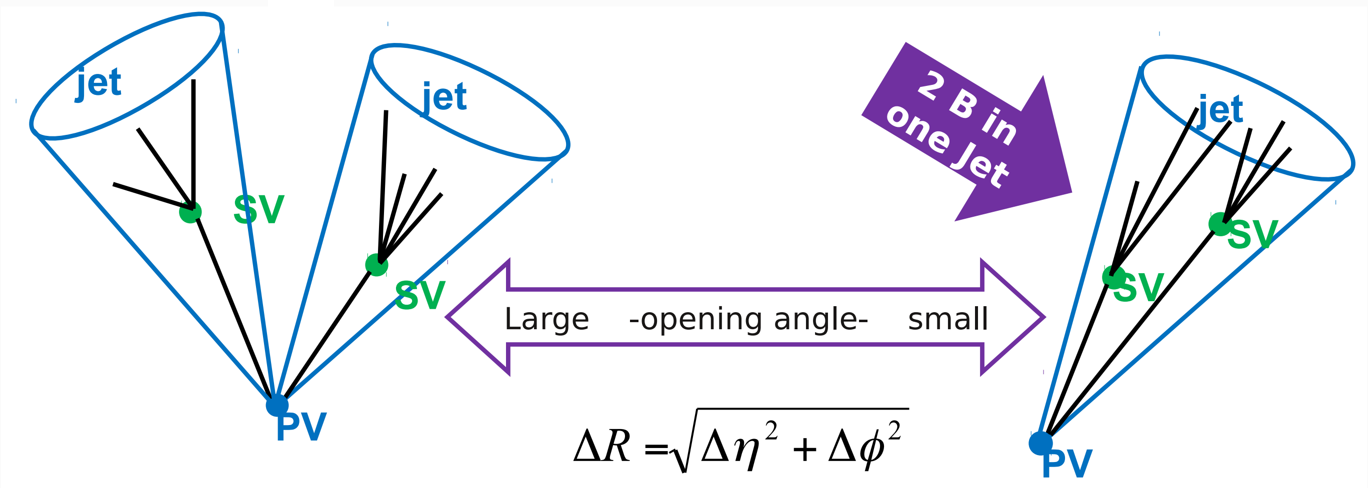
s → Quarkonia → b → top

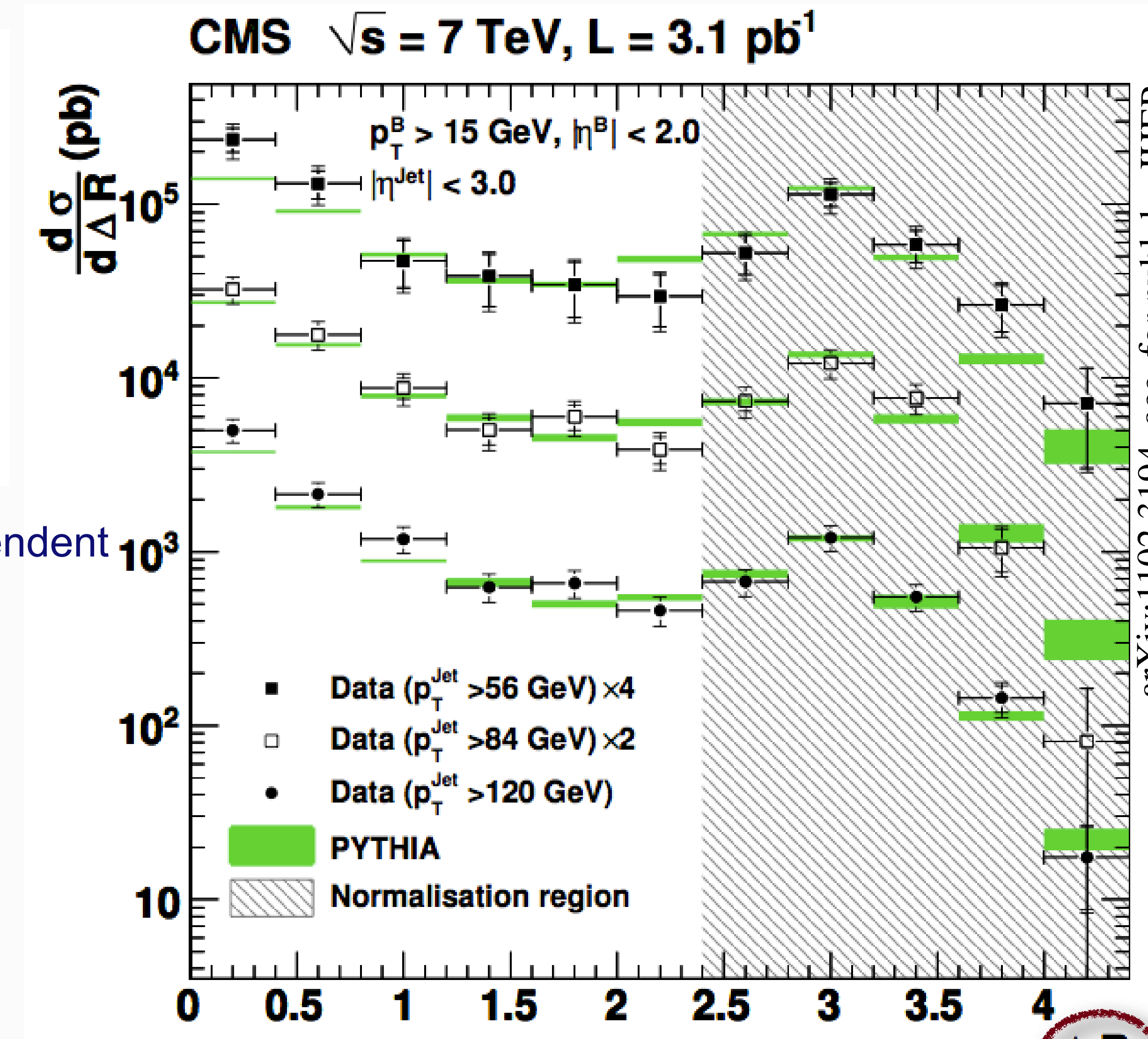






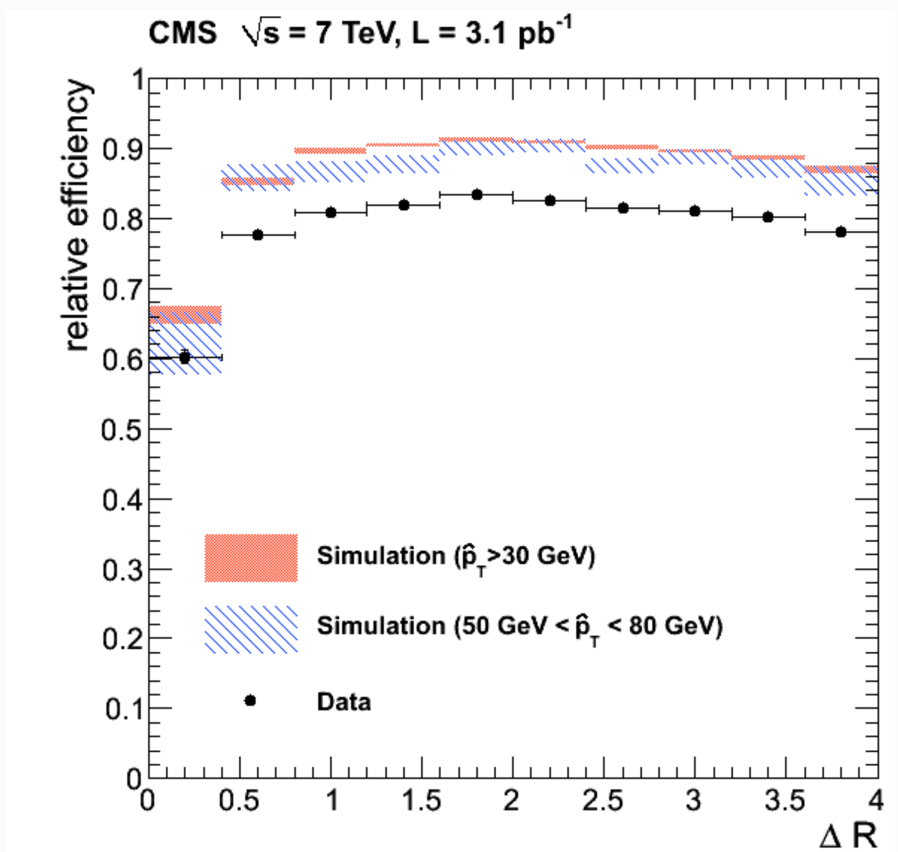
B-hadron angular correlations





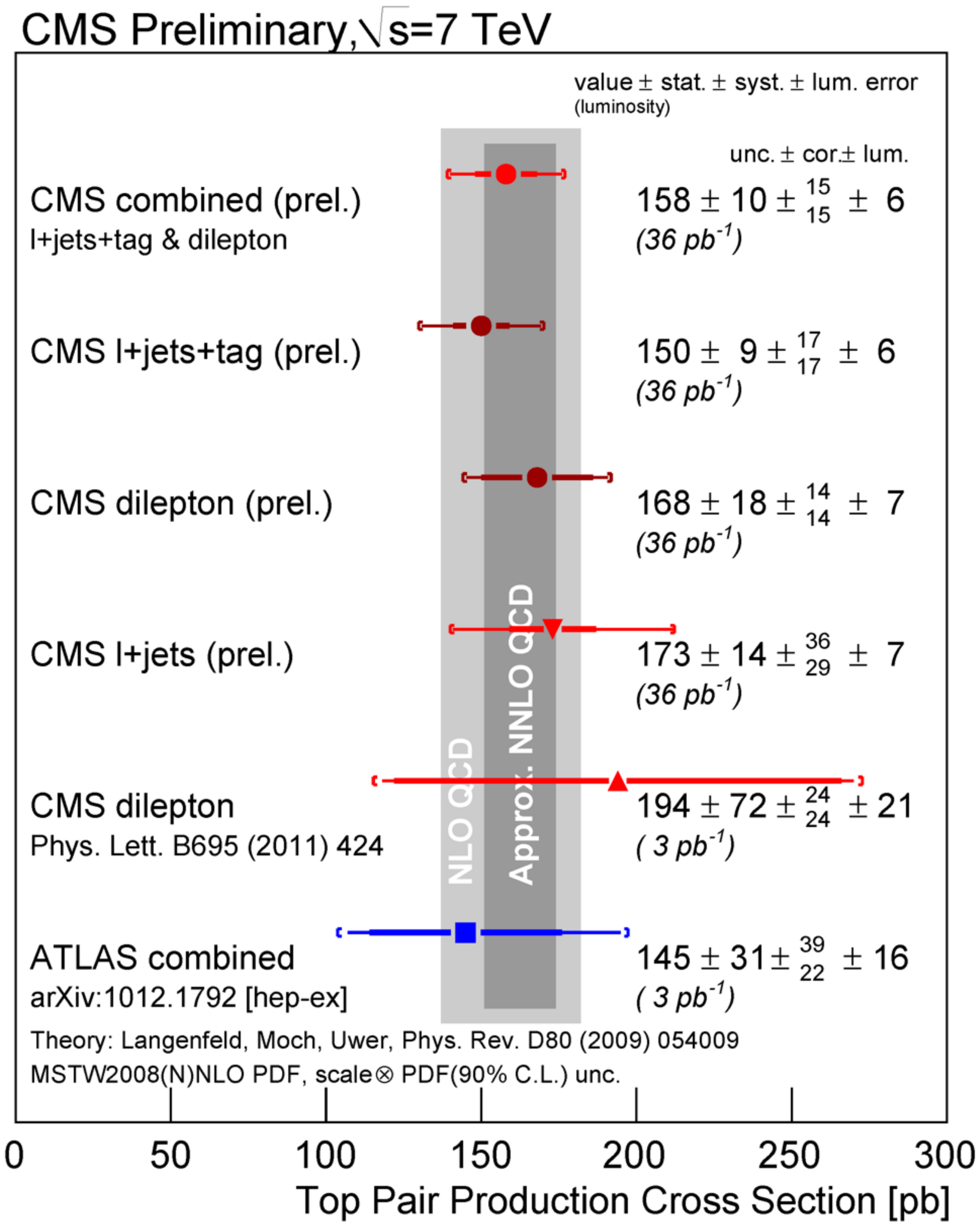
MC normalized to shaded region for shape comparison in the collinear BB region

New: Secondary vertex finder seeded with high IP tracks, jet independent

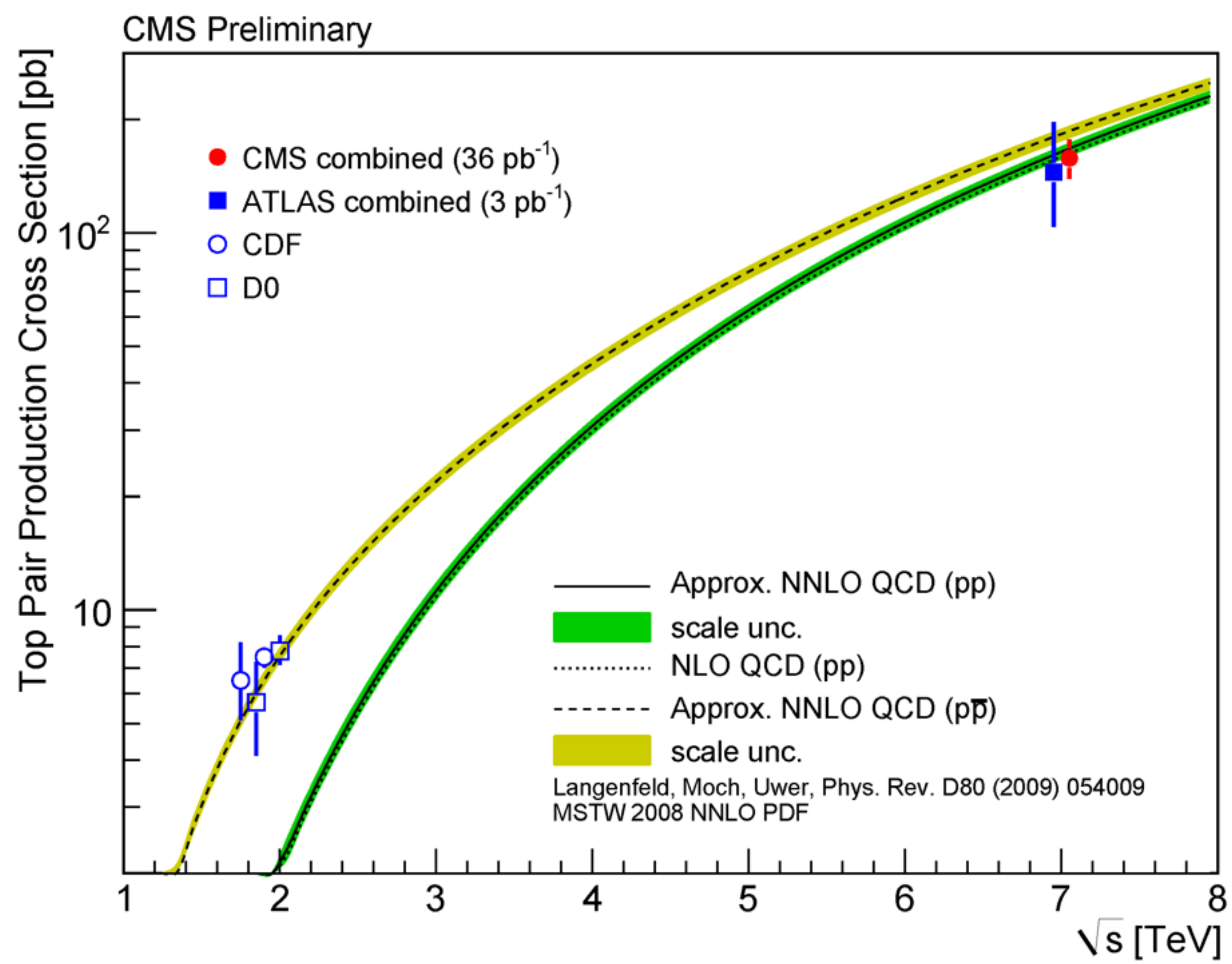


- Sizable fraction of total BB cross section from collinear B-hadron pairs
- Fraction of collinear BB production increases with leading jet p_T

Top cross section and mass



TOP-11-001



TOP mass: dilepton

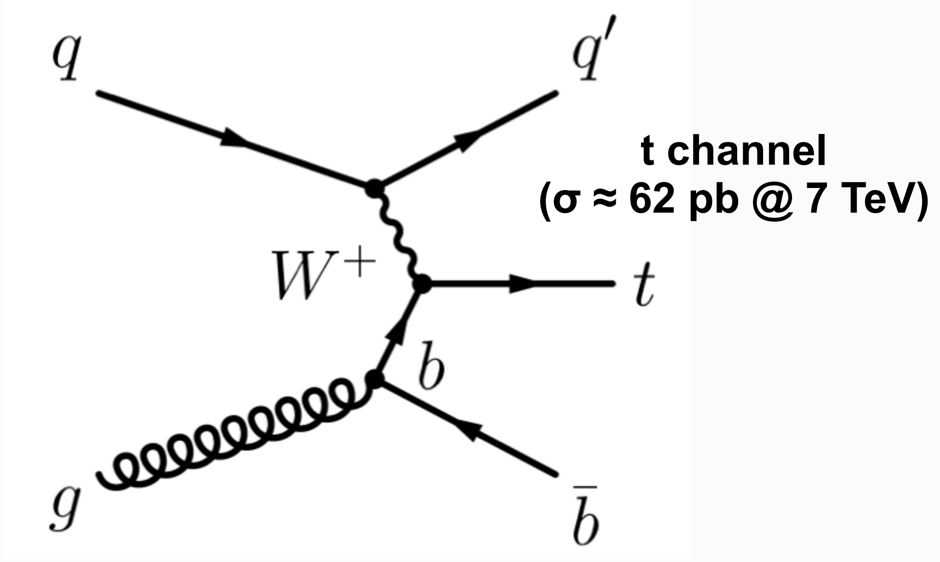
TOP-10-006

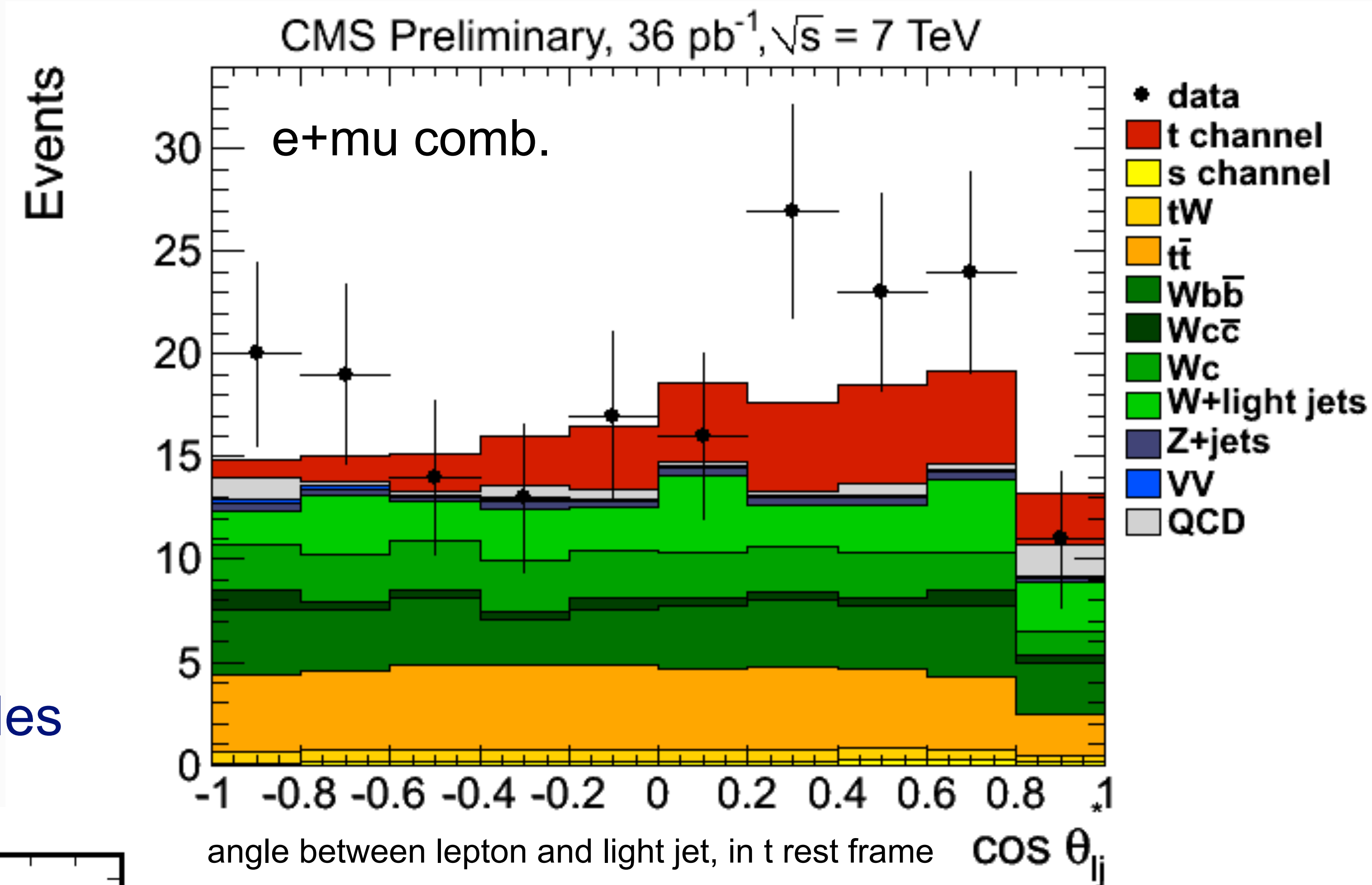
Method	Measured m_{top} (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$	0.65
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$	0.35
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$	χ^2/dof=0.040 (p-value=0.84)

Syst. uncertainty dominated by:
JES (3.1 GeV)
b-JES (2.5 GeV)

Single top production

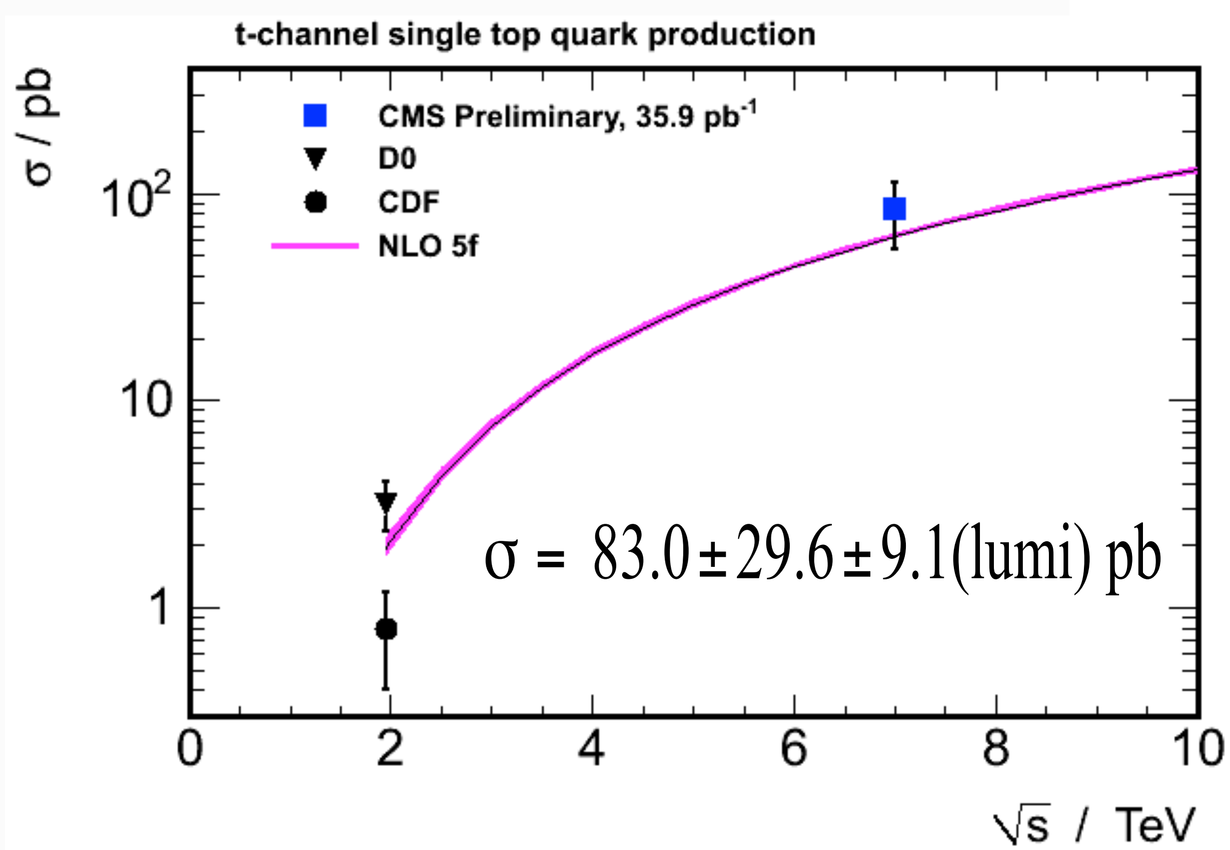
TOP-10-008





Two methods employed:

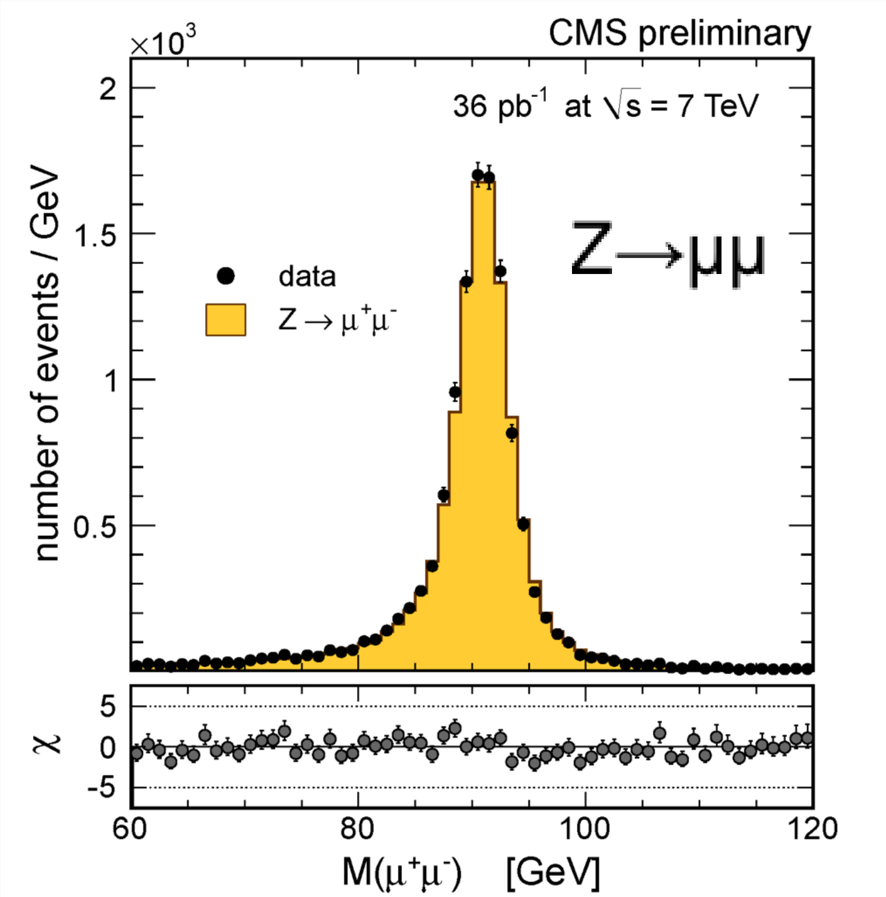
- Cut based using angular info
- BDT, based on kinematic observables



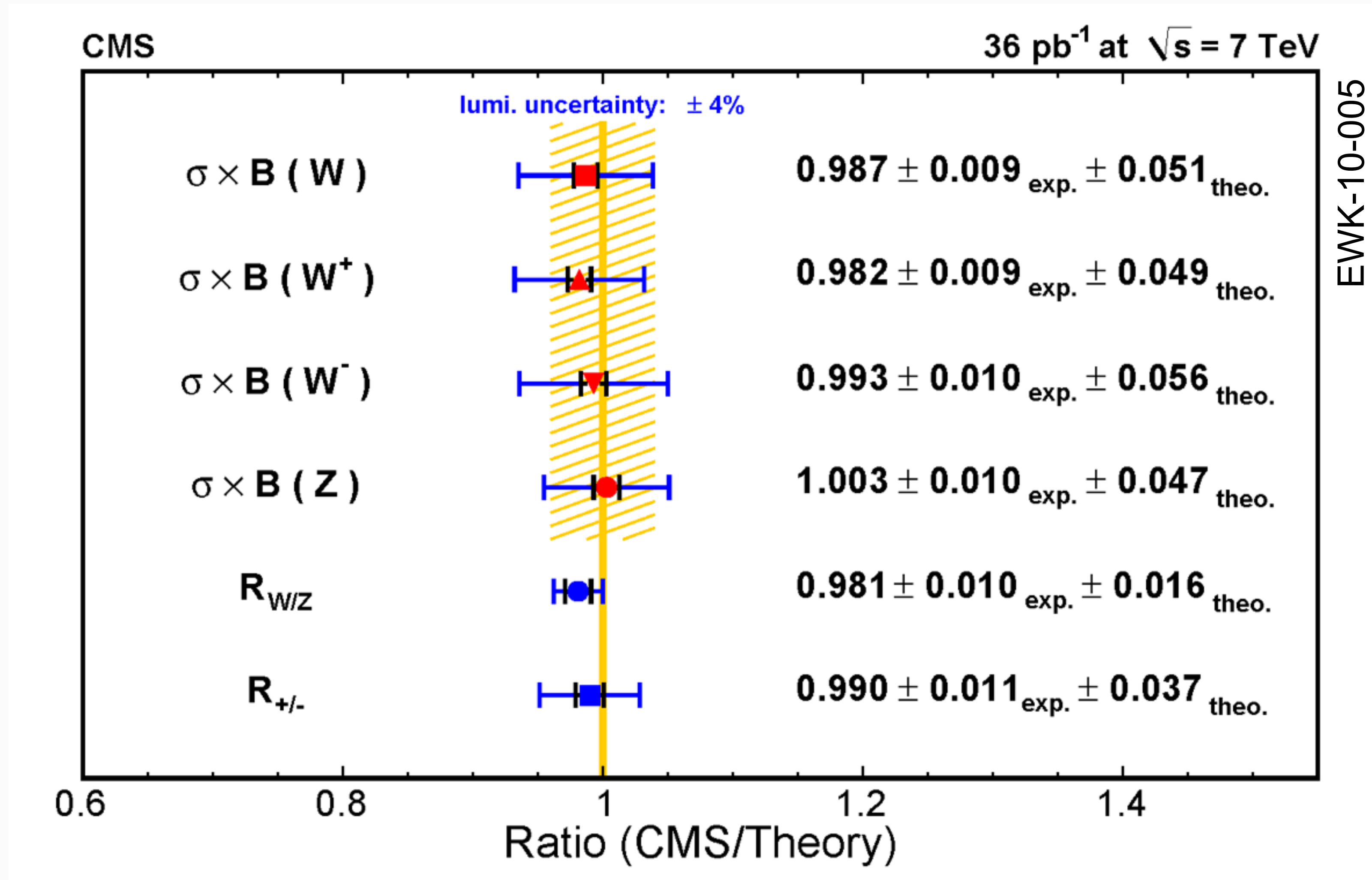
An example of finding **tiny** signals with leptons, MET, b-tag & jets

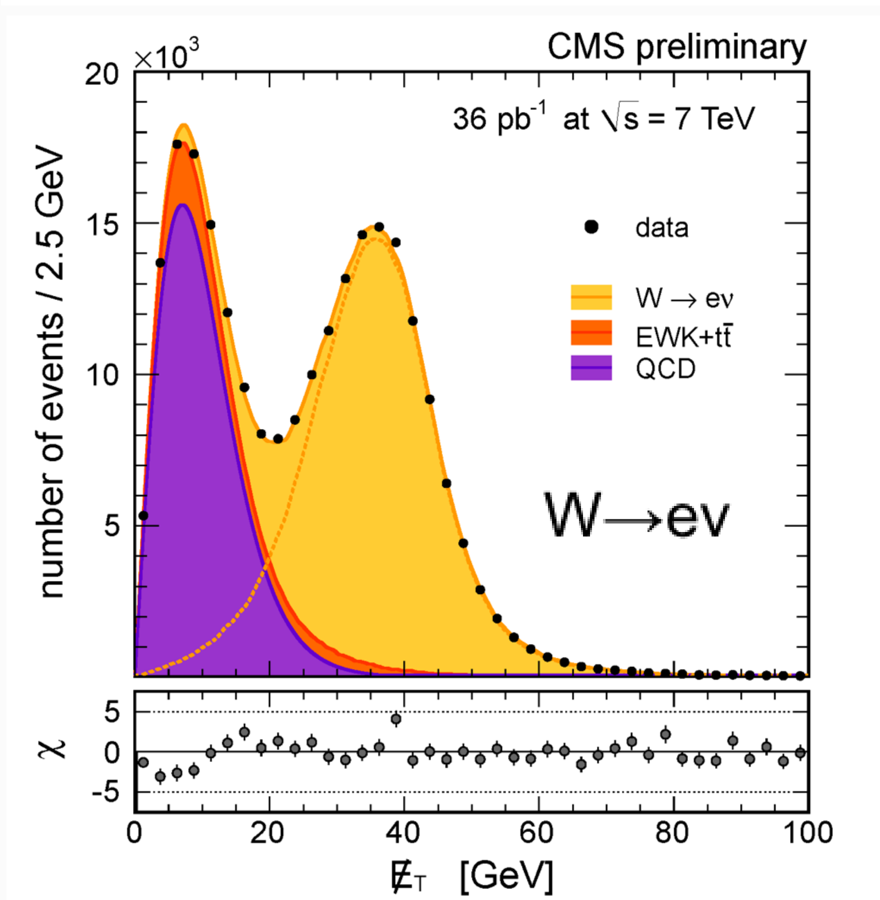
Showing the readiness for challenging searches such as low-mass Higgs

Inclusive W and Z production



- 3 pb^{-1} results published, JHEP01(2011)080
- new prelim. results for 36 pb^{-1}
- Z important tool : data-driven methods for controlling lepton eff, scale, resolution, E_{Tmiss} (hadronic recoil).
- In general excellent data-MC agreement

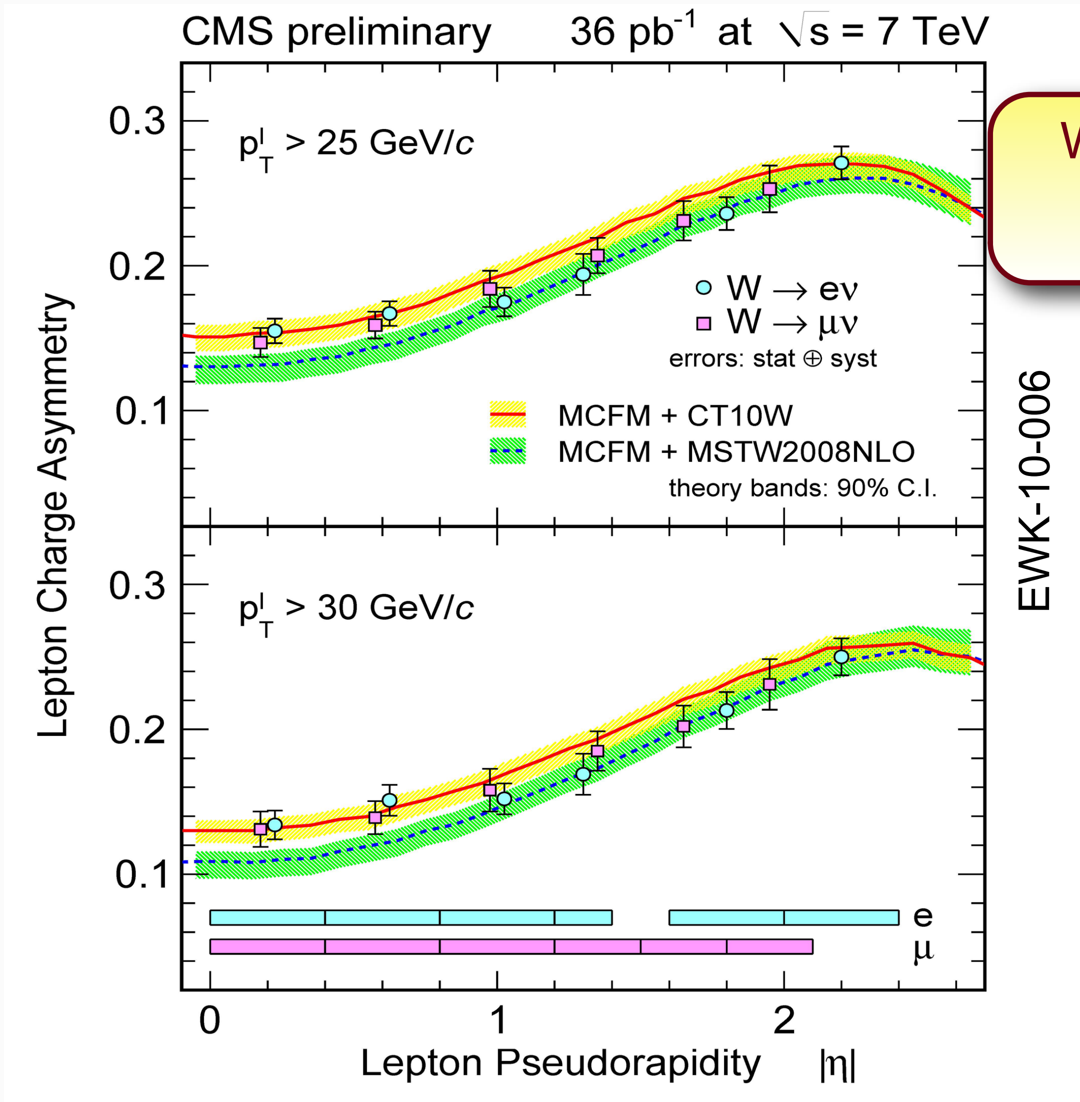




Amazing precision reached (~1% experimental !)
Start to put important constraints on theory (NNLO, PDFs)

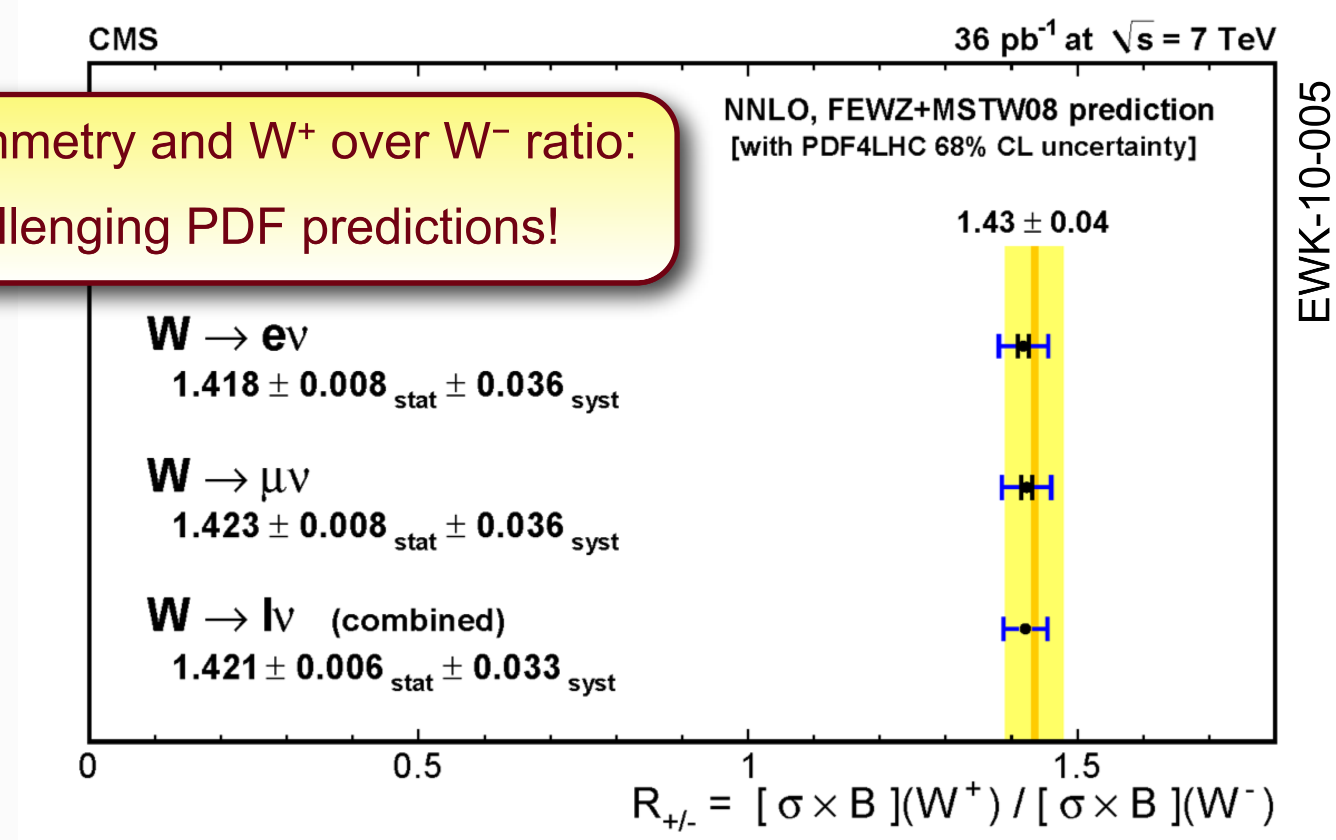
W properties, constraining PDFs

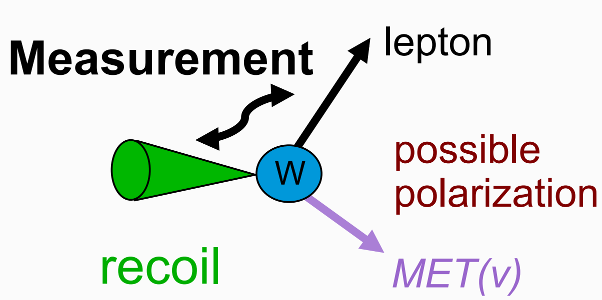
ETH Institute for Particle Physics



W asymmetry and W⁺ over W⁻ ratio:

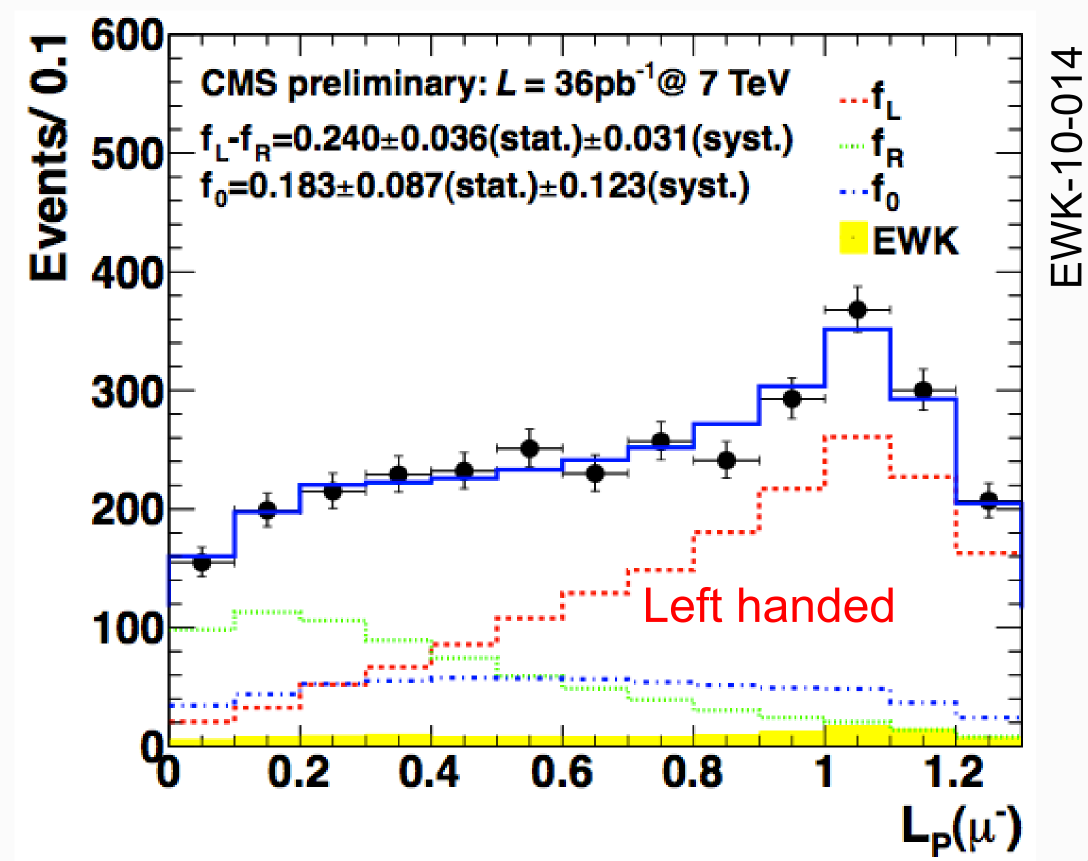
Challenging PDF predictions!





$$LP = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

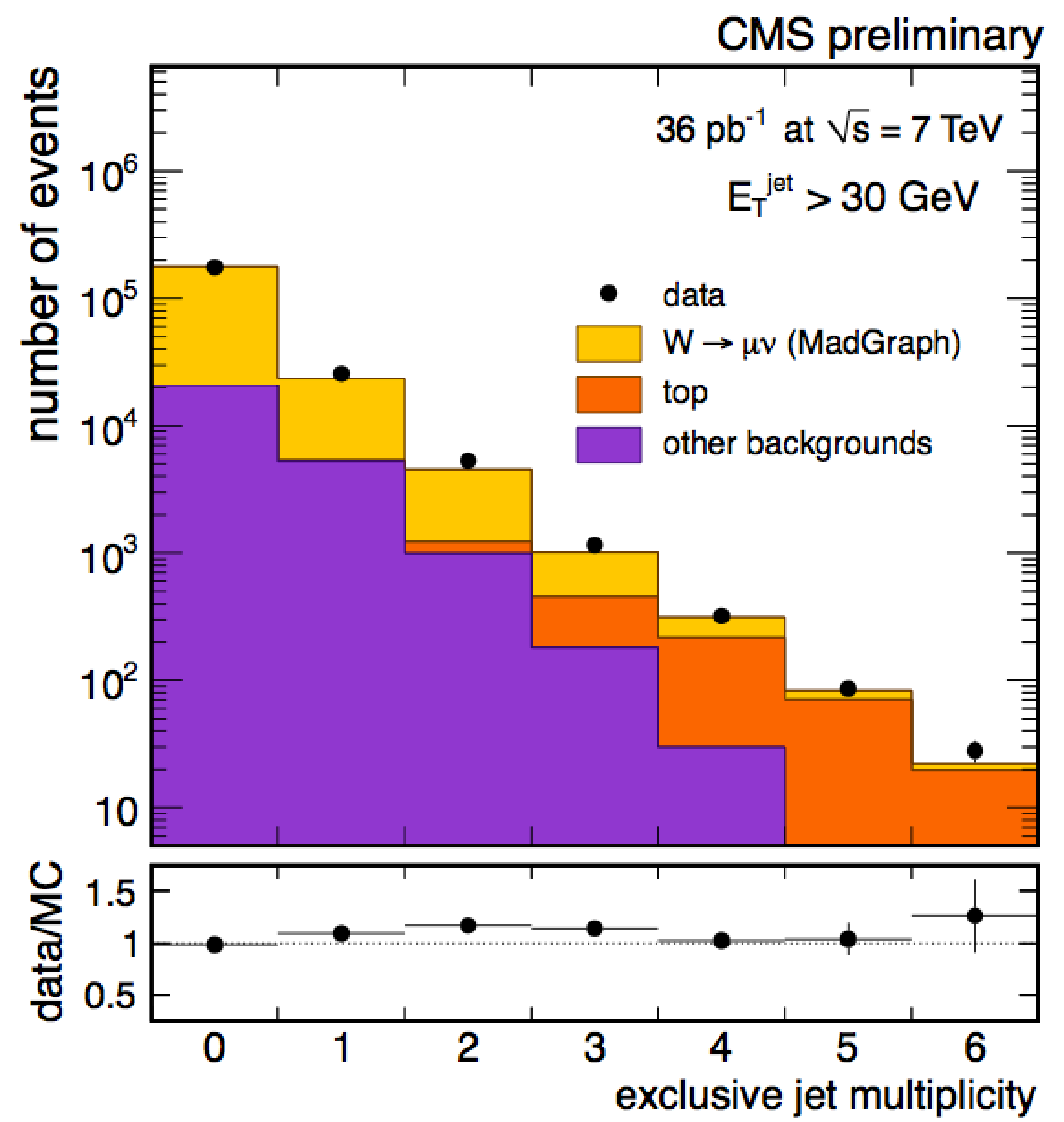
$$p_T(W) > 50\,\text{GeV}$$

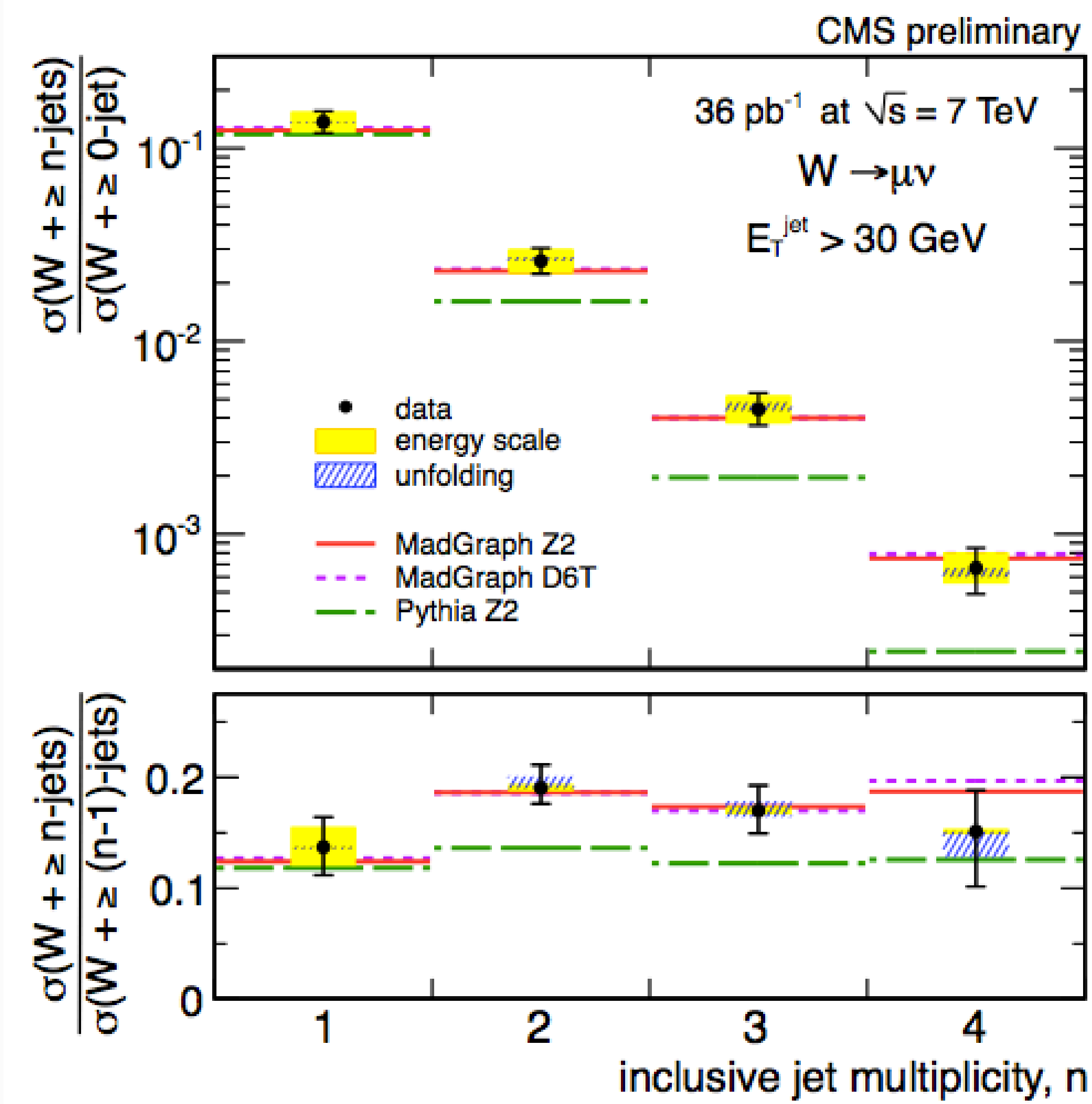


First measurement of W polarization: both W⁺ and W⁻ preferred left-handed

W/Z+jets

EWK-10-005



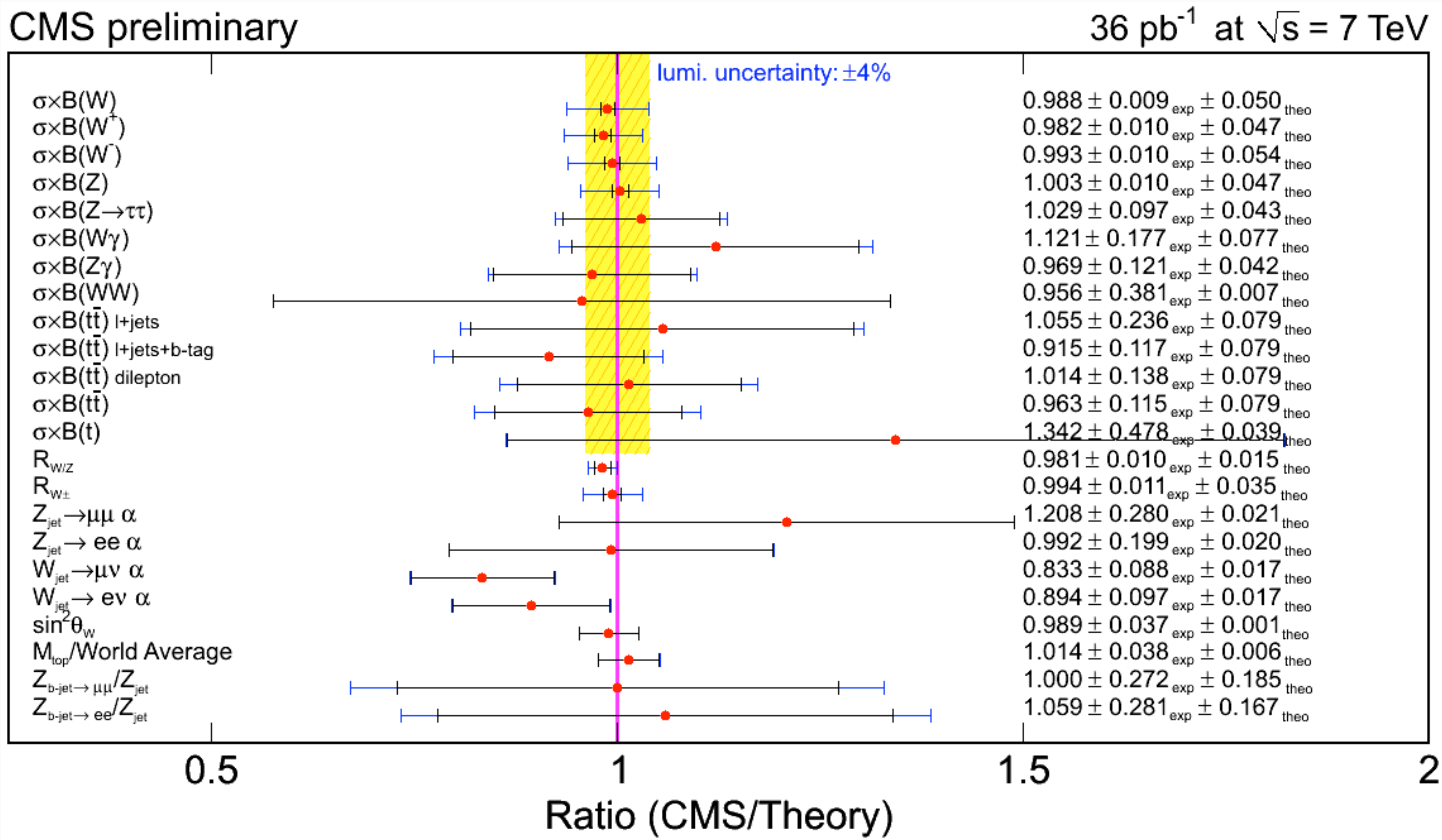


- **simultaneous** extraction of W signal and top background
  - 2D fit to M_T and N_{bjets} distributions
- final distributions: **unfolded to particle level**
- presented for experimental lepton and jet acceptance, eg. p_{Tjet} > 30 GeV

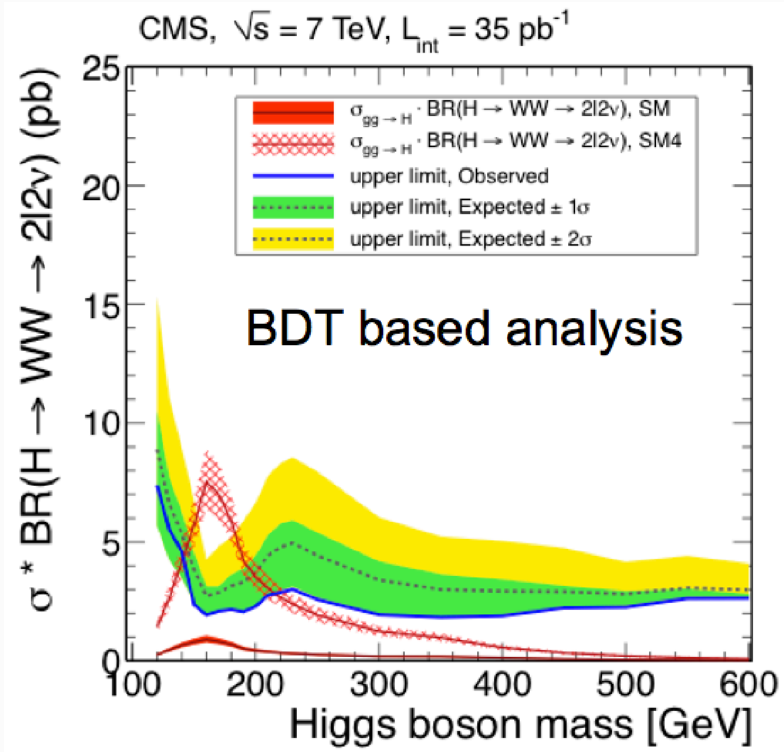
Excellent agreement with ME+PS matched Monte Carlo model.

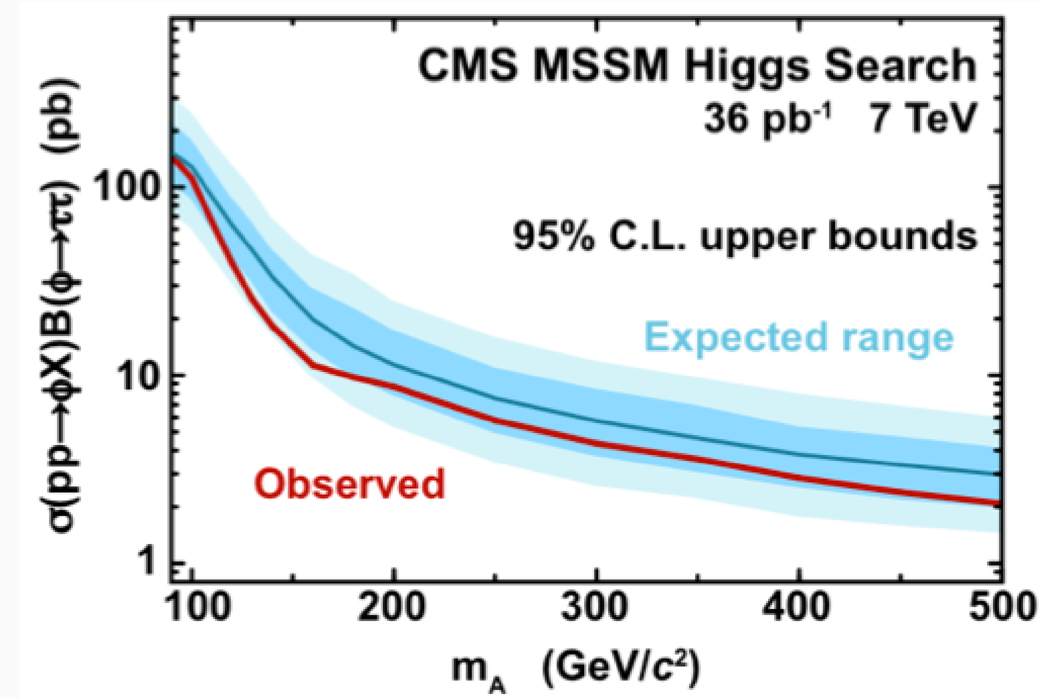
Also tested: Berends-Giele scaling

Summary of SM measurements

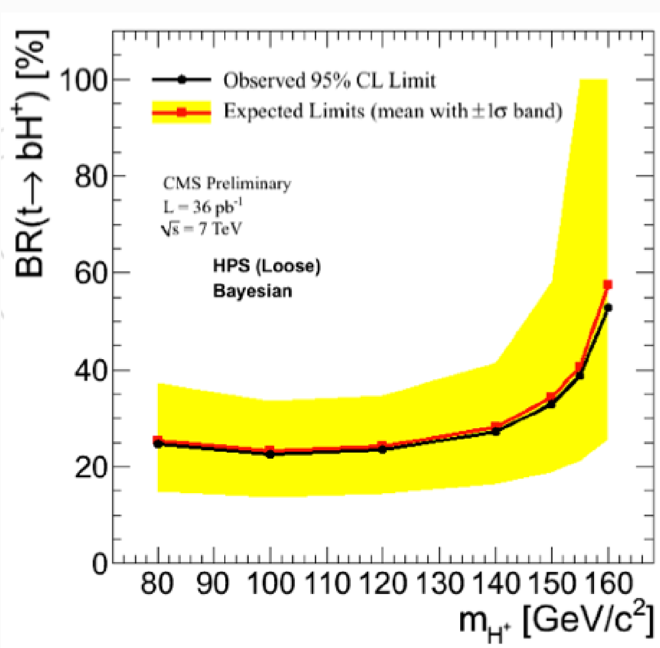


from P.C.Harris, Moriond EWK 2011

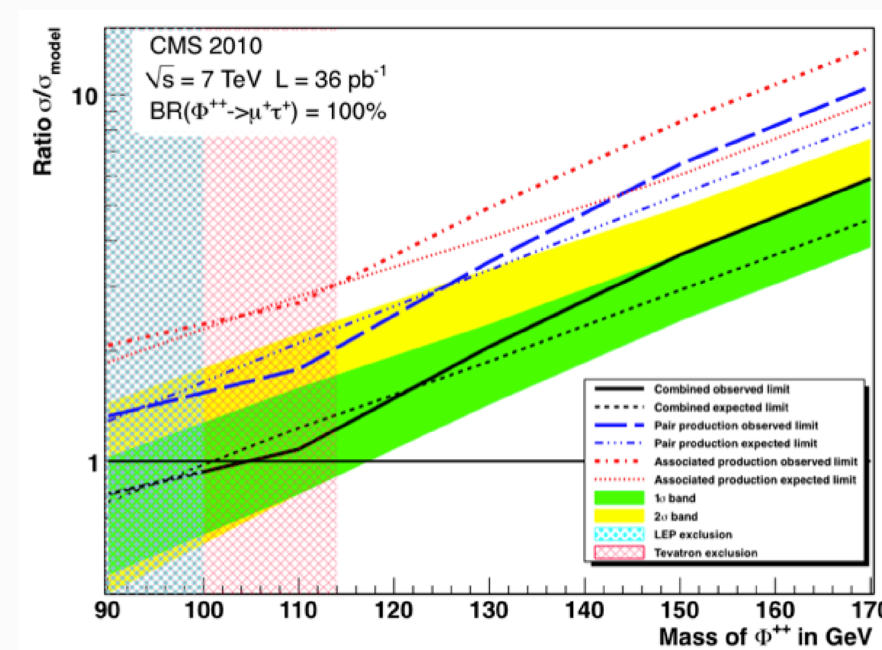




Higgs searches



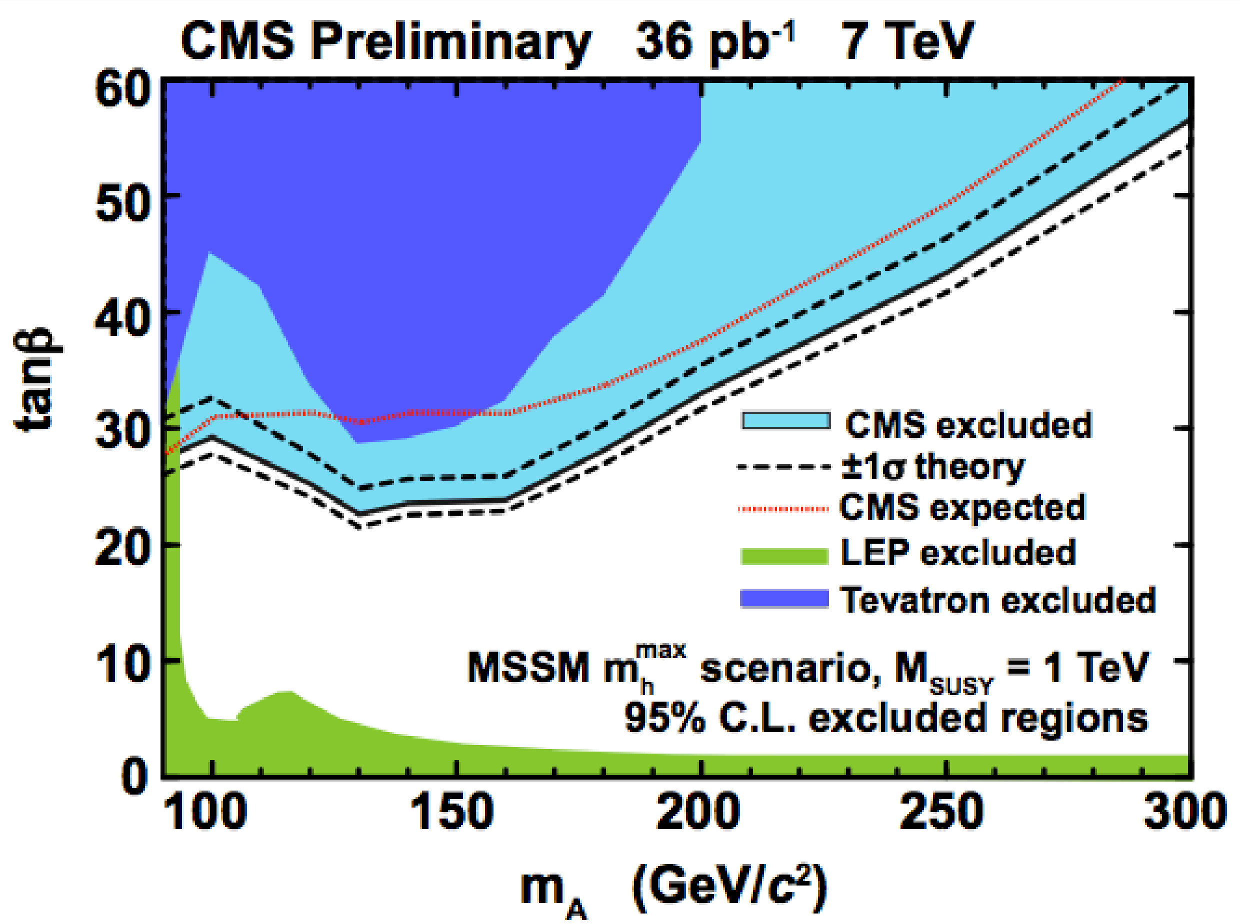
see also recent talks by
- C. Veelken, Moriond EWK-11
- V. Sharma, Moriond EWK-11
- A. Tapper, CERN Seminar, March 15

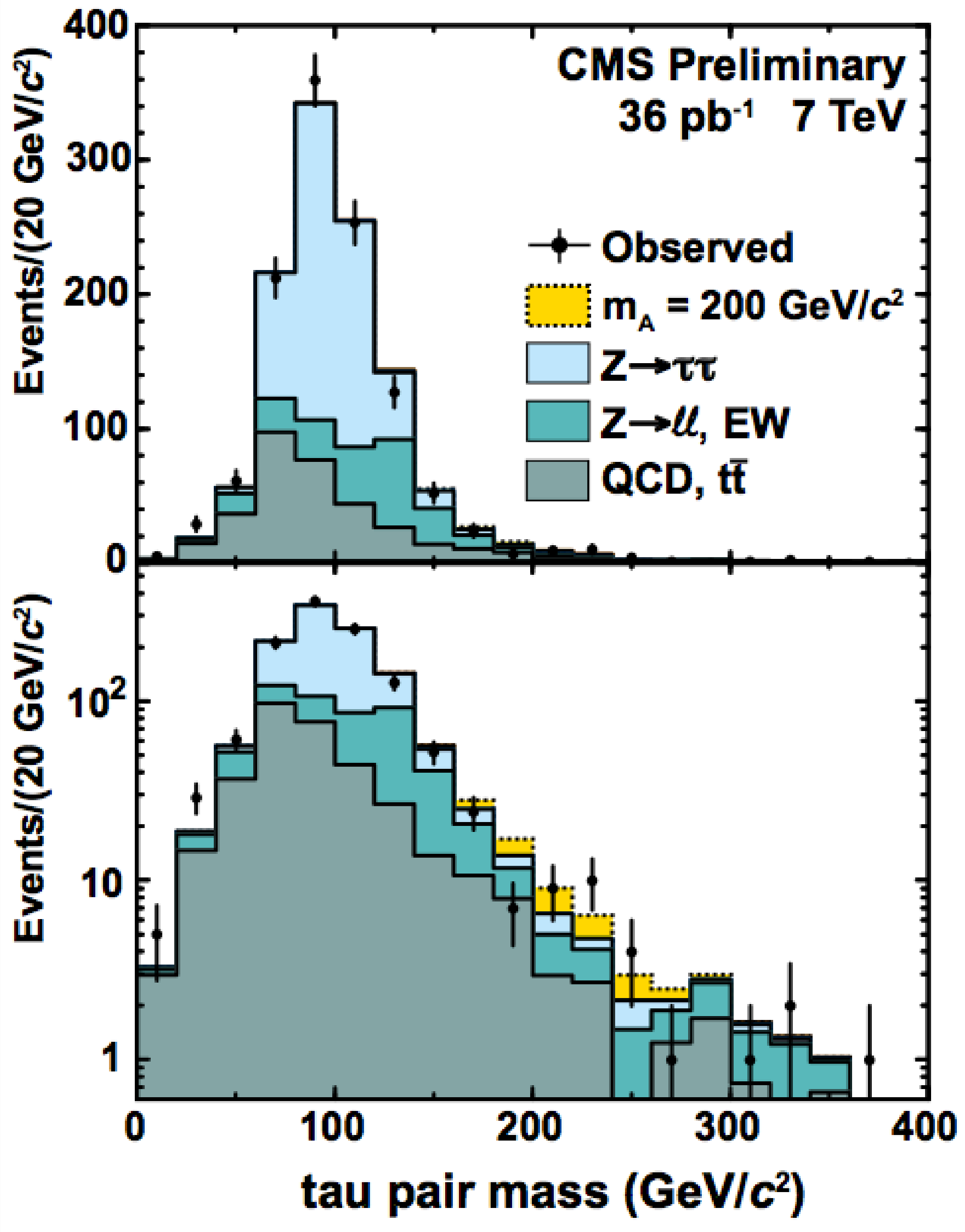


H→ττ

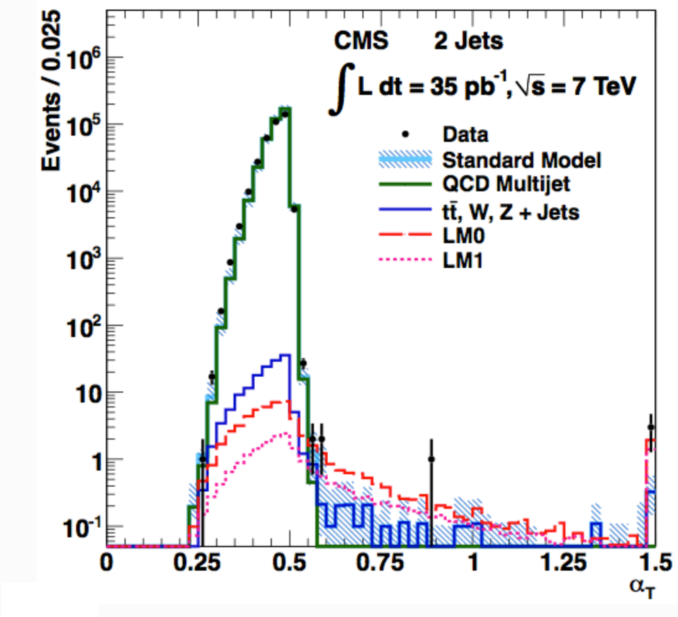
HIG-10-002

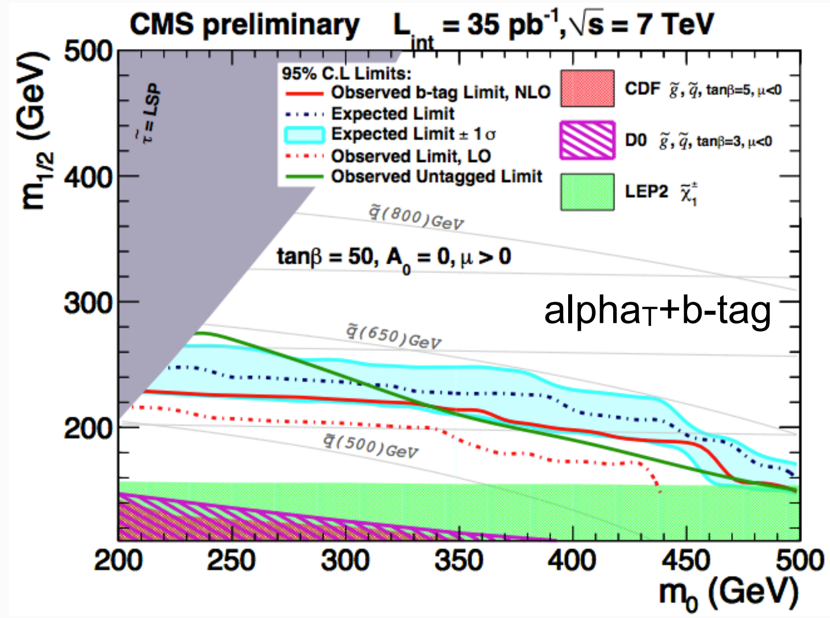
- Channels used: e-mu, e-had, mu-had
- improved mass reconstruction (better resolution) using likelihood, based on tau decay kinematics of visible decay products and E_{Tmiss}
- first limits on MSSM Higgs production, already improving on the Tevatron results

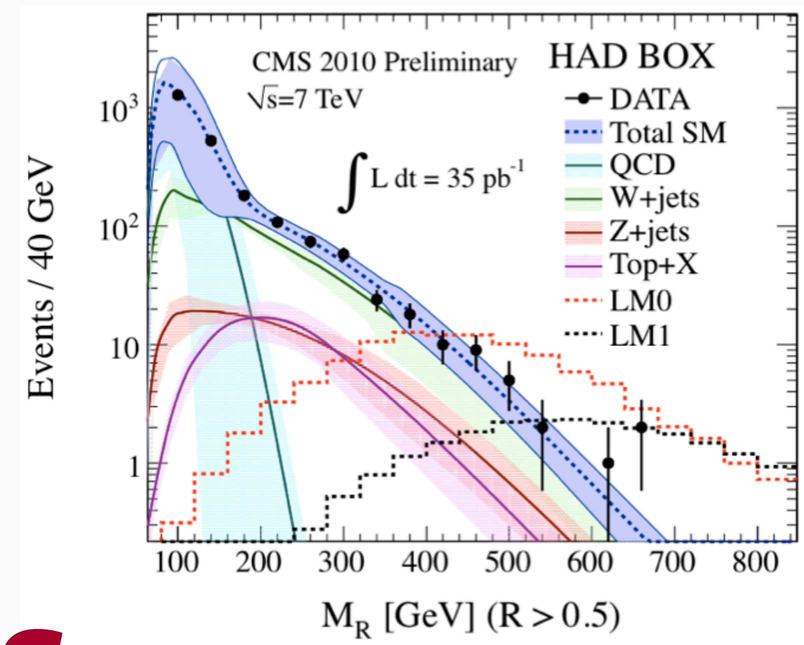




The hunt for MSSM Higgs(es) is open.
Tau channel will play prominent role.

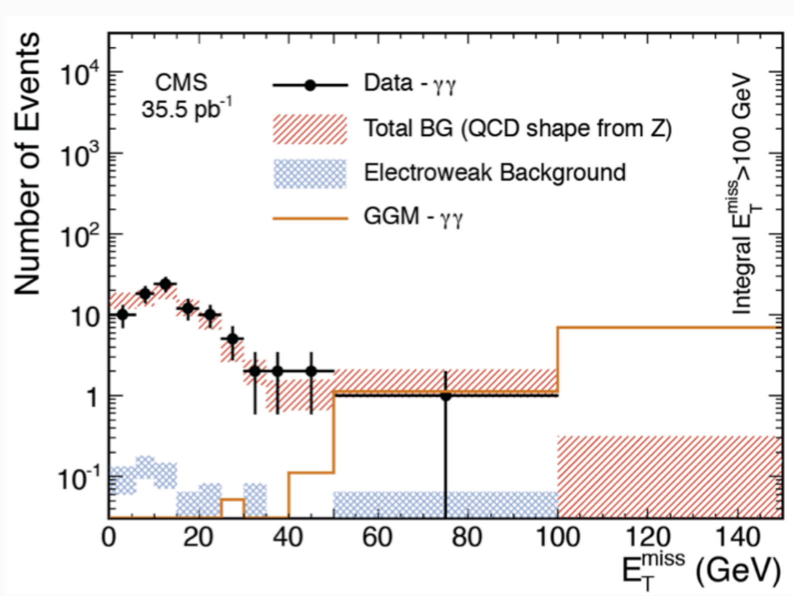


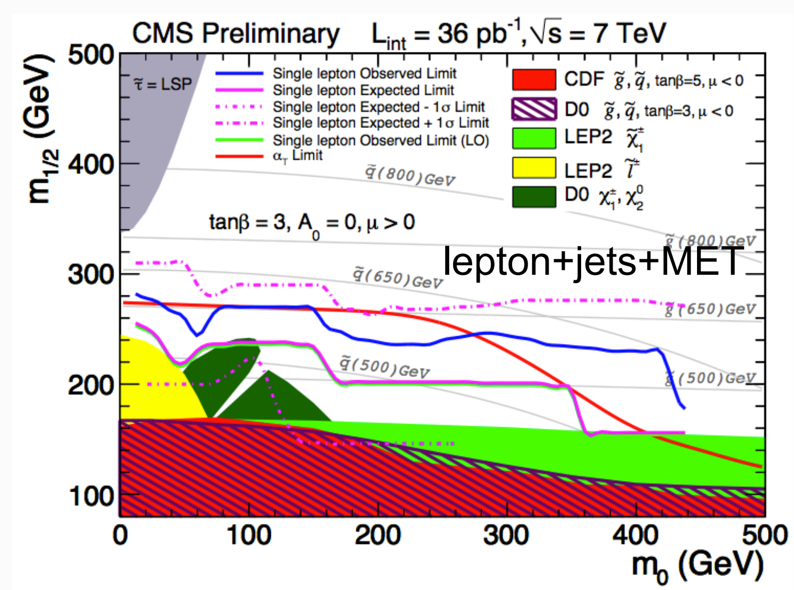


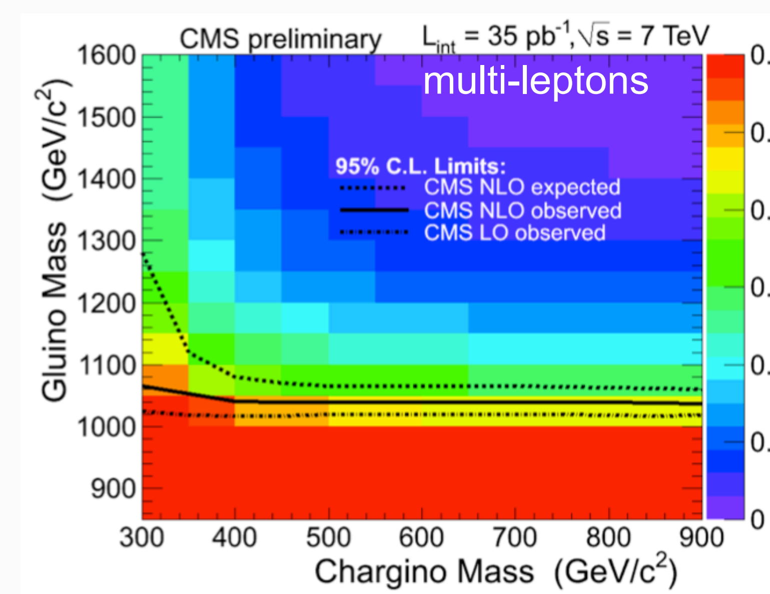


see also talks by
- C. Bernet, Moriond EWK-11
- A. Tapper, CERN, March 15

Searches for Supersymmetry



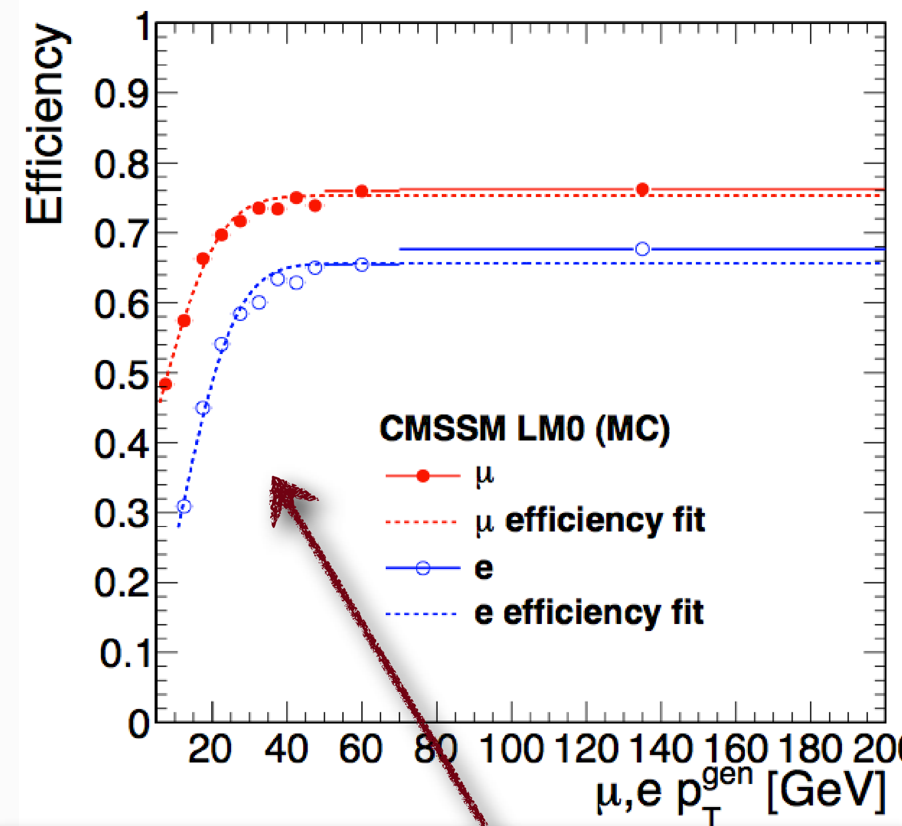




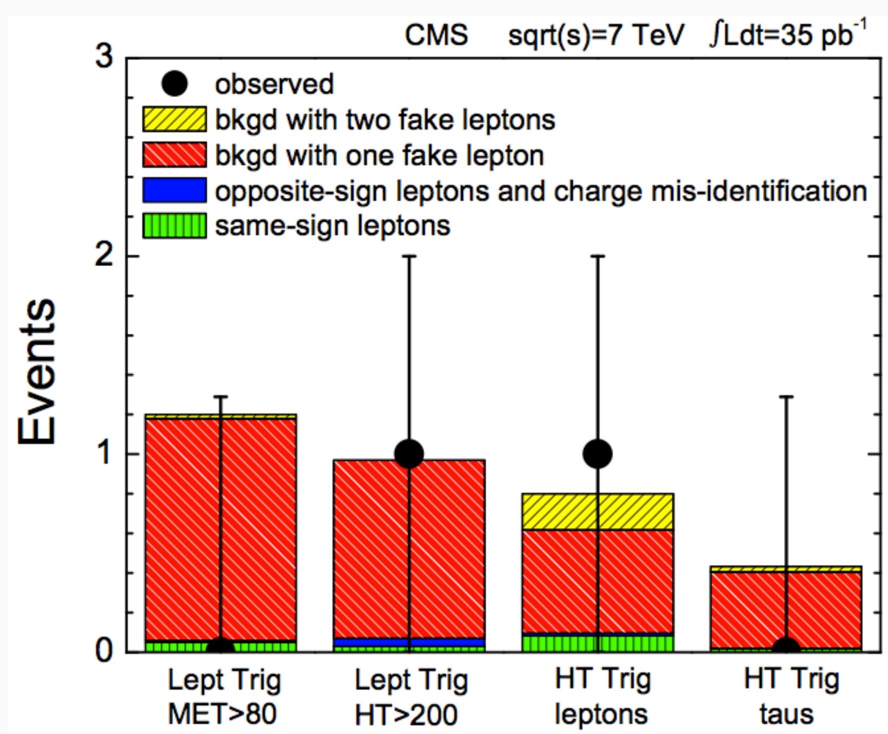
Example: same-sign dilepton

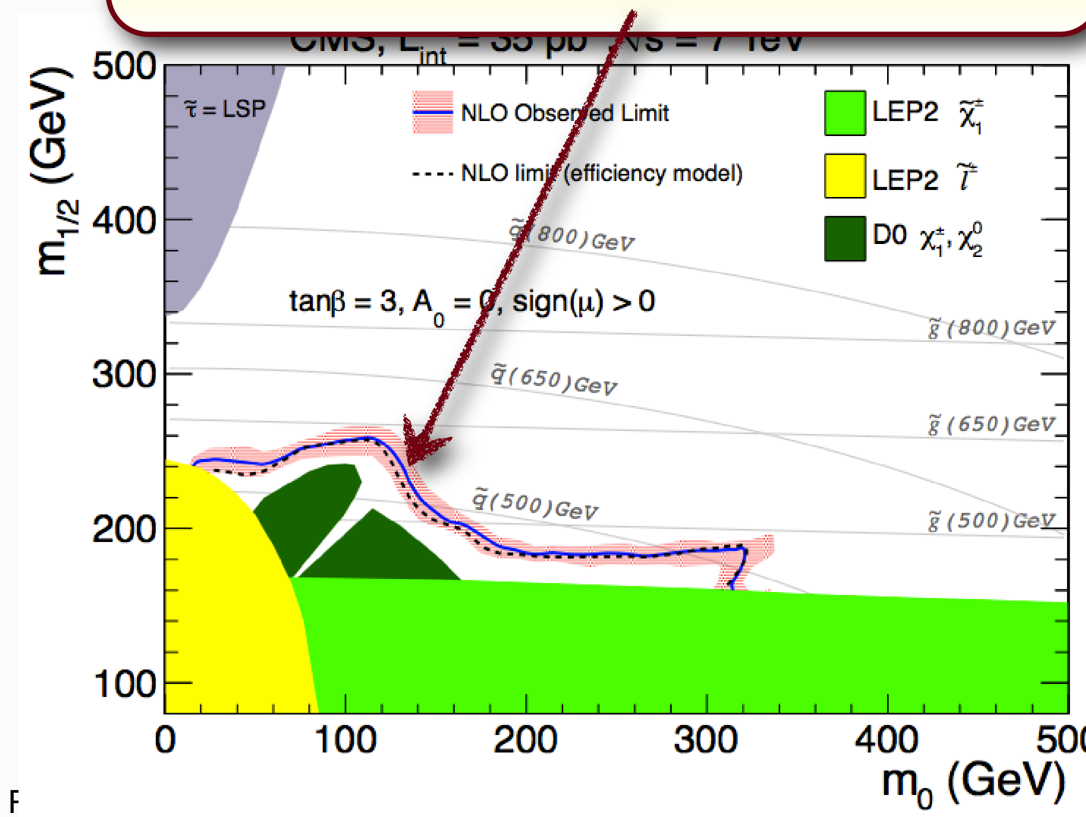
SUS-10-004

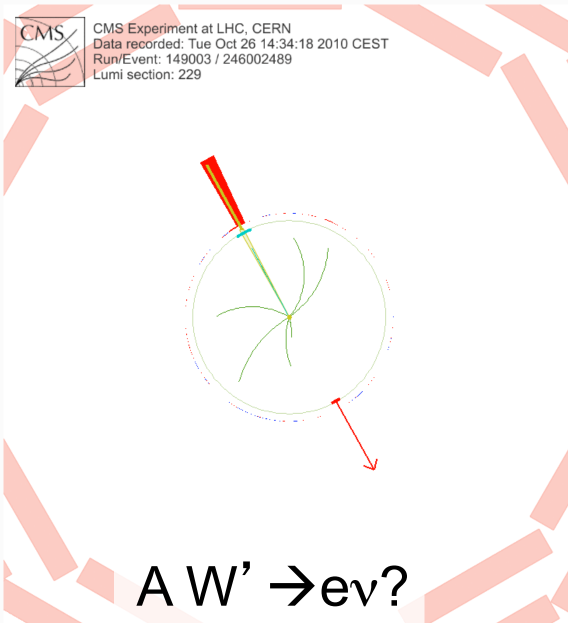
- Two different trigger approaches
  - HT or lepton p_T
- Baseline selection:
  - 2 same sign, isolated leptons (e or μ)
  - $p_{T,1}$>20, $p_{T,2}$ > 10 GeV
  - ≥ 2 jets: p_T > 30 GeV, |η|<2.5
  - MET: > 30 GeV (ee and μμ), > 20 GeV (eμ)
- Main background: ttbar (lepton from b)
  - name of the game: jets faking leptons
  - data-driven fake-rate estimations



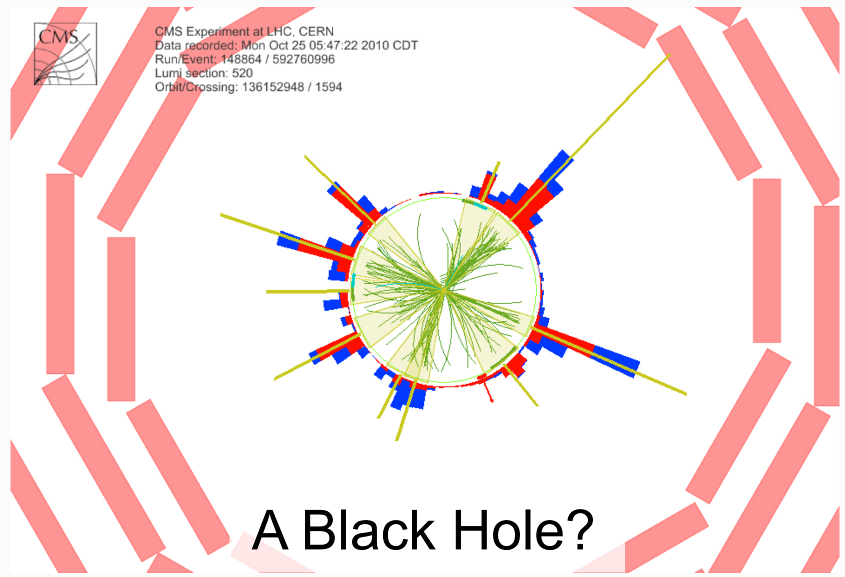
lepton efficiency parametrization agrees with full CMS simulation



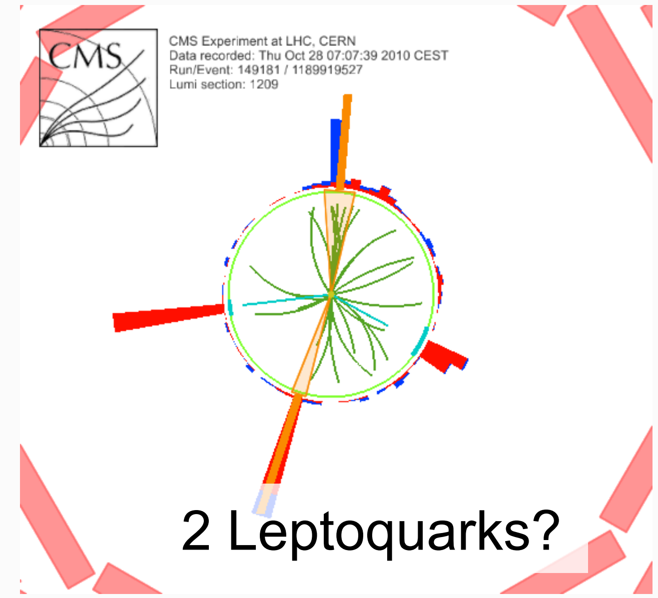




A W' →eν?



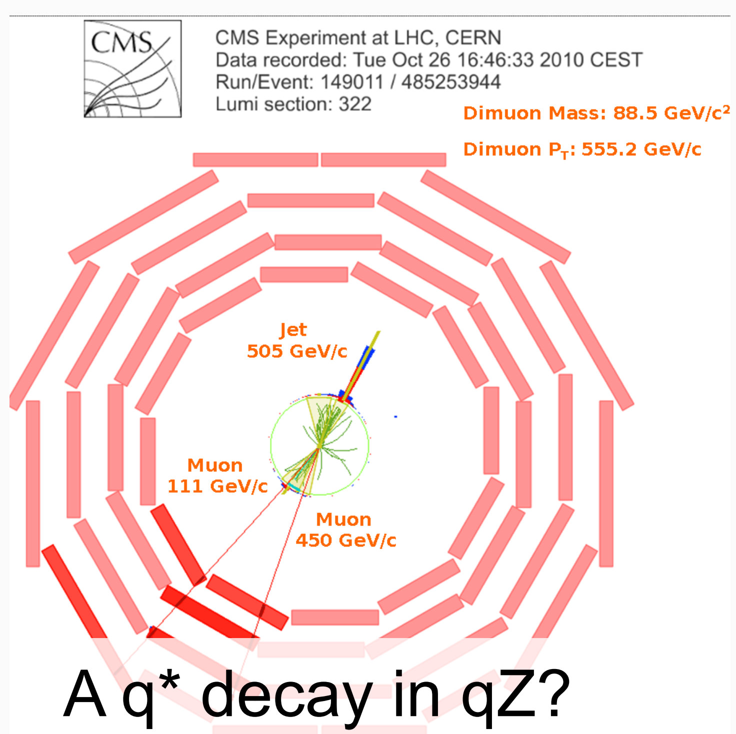
A Black Hole?



2 Leptoquarks?

Exotic signatures

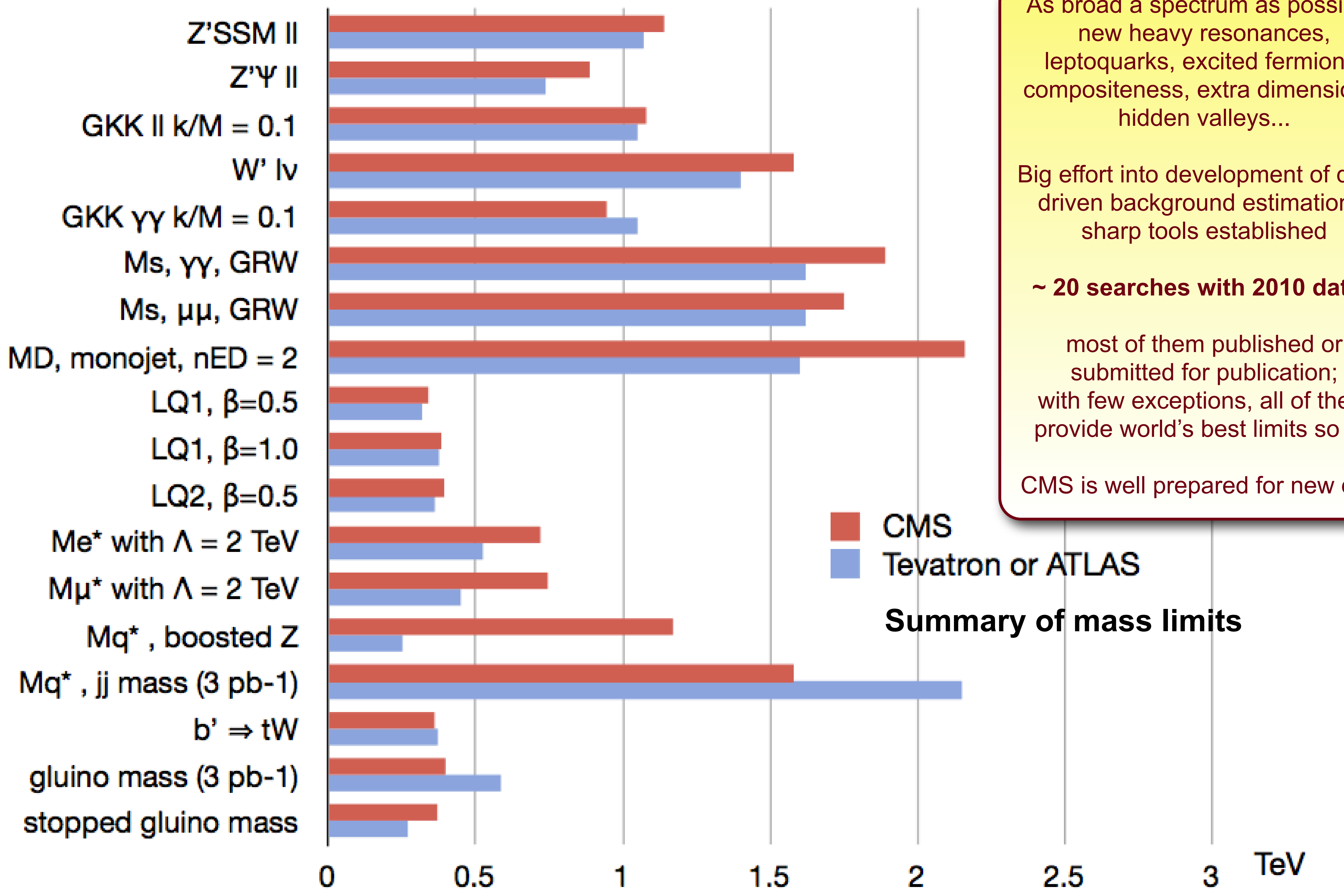
A Di-jet Resonance?



A q* decay in qZ?

see also talk by F. Santanastasio, Moriond EWK-11

And many, many more...



As broad a spectrum as possible: new heavy resonances, leptoquarks, excited fermions, compositeness, extra dimensions, hidden valleys...

Big effort into development of data-driven background estimations: sharp tools established

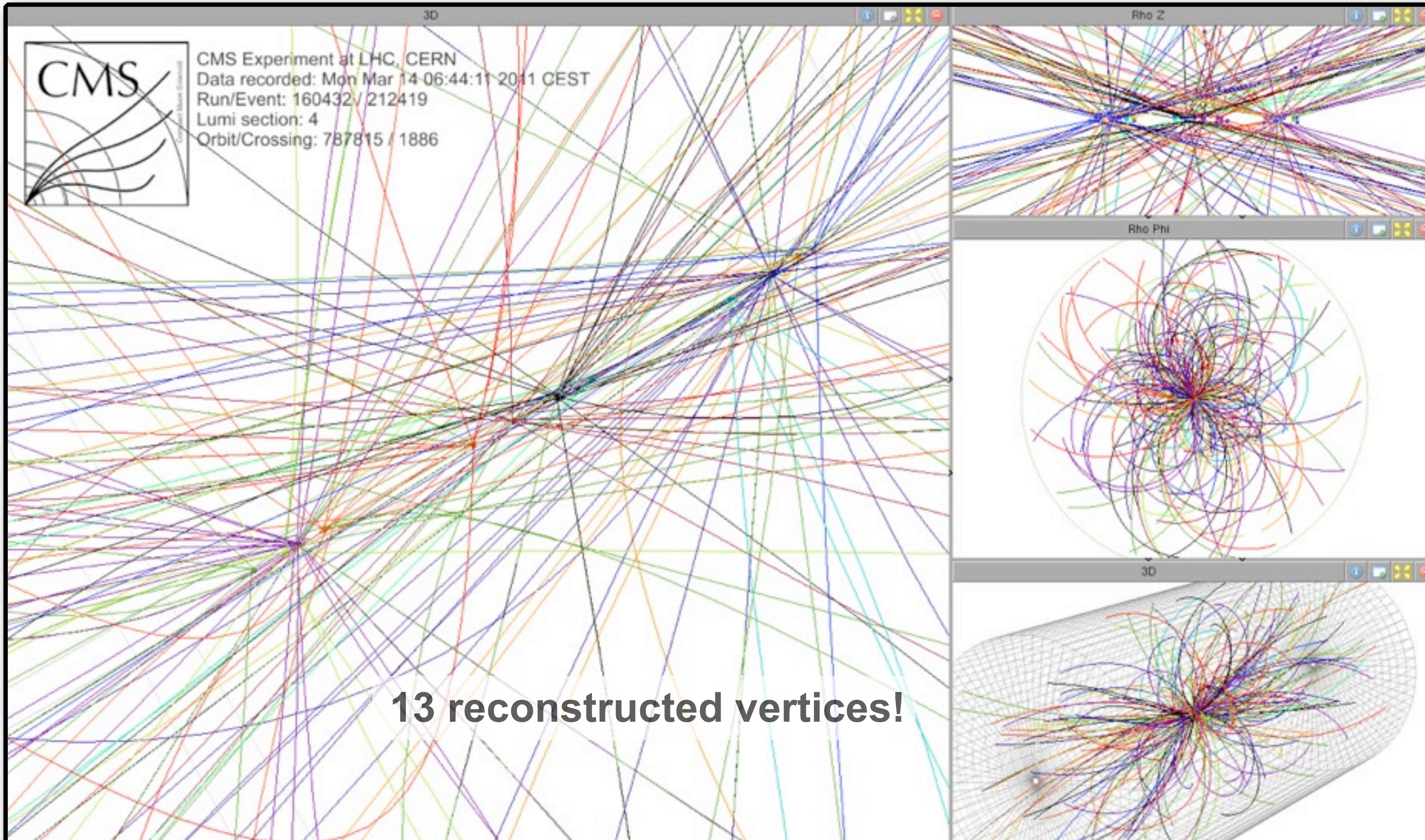
~ 20 searches with 2010 data !

most of them published or submitted for publication; with few exceptions, all of them provide world's best limits so far

CMS is well prepared for new data

CMS is ready for discoveries

New events coming in...



The new challenge: Pile-Up!
CMS is prepared for it on all fronts: Trigger, Reconstruction, Analysis, Computing

(Personal) conclusions

• Too many things we do not know/understand.

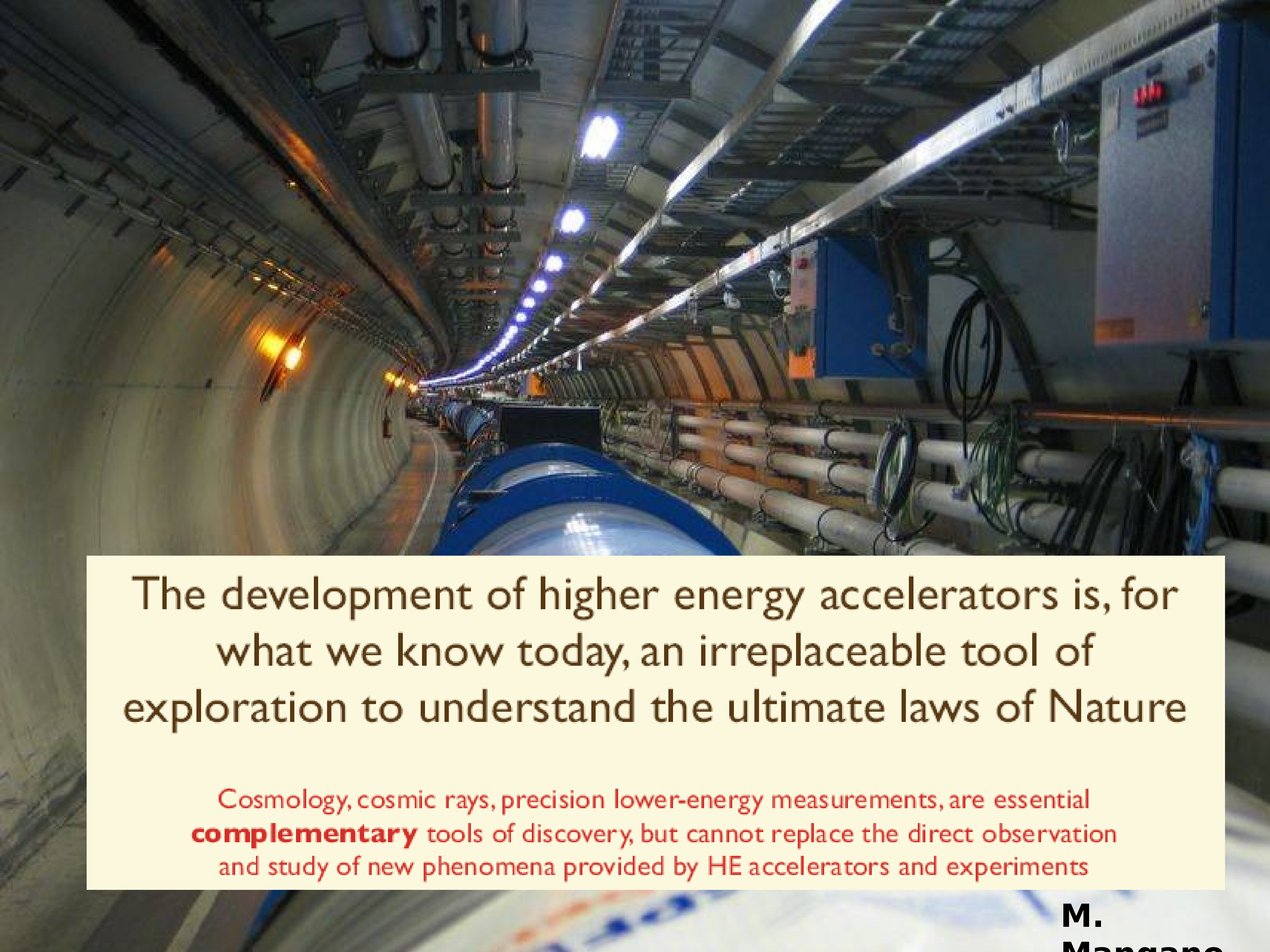
∀ Any good high energy physicist cannot believe the SM is the end of the story.

∀ We are asking some of the most fundamental questions in modern physics.
To answer, the needed tools are of incredible complexity.

∀ Still, one of the most exciting intellectual adventures of mankind

The LHC should help the next step in the understanding of fundamental aspects of the infinitely small and the infinitely large

After it, our view of (particle) physics could change forever



The development of higher energy accelerators is, for what we know today, an irreplaceable tool of exploration to understand the ultimate laws of Nature

Cosmology, cosmic rays, precision lower-energy measurements, are essential **complementary** tools of discovery, but cannot replace the direct observation and study of new phenomena provided by HE accelerators and experiments

M. Mangano

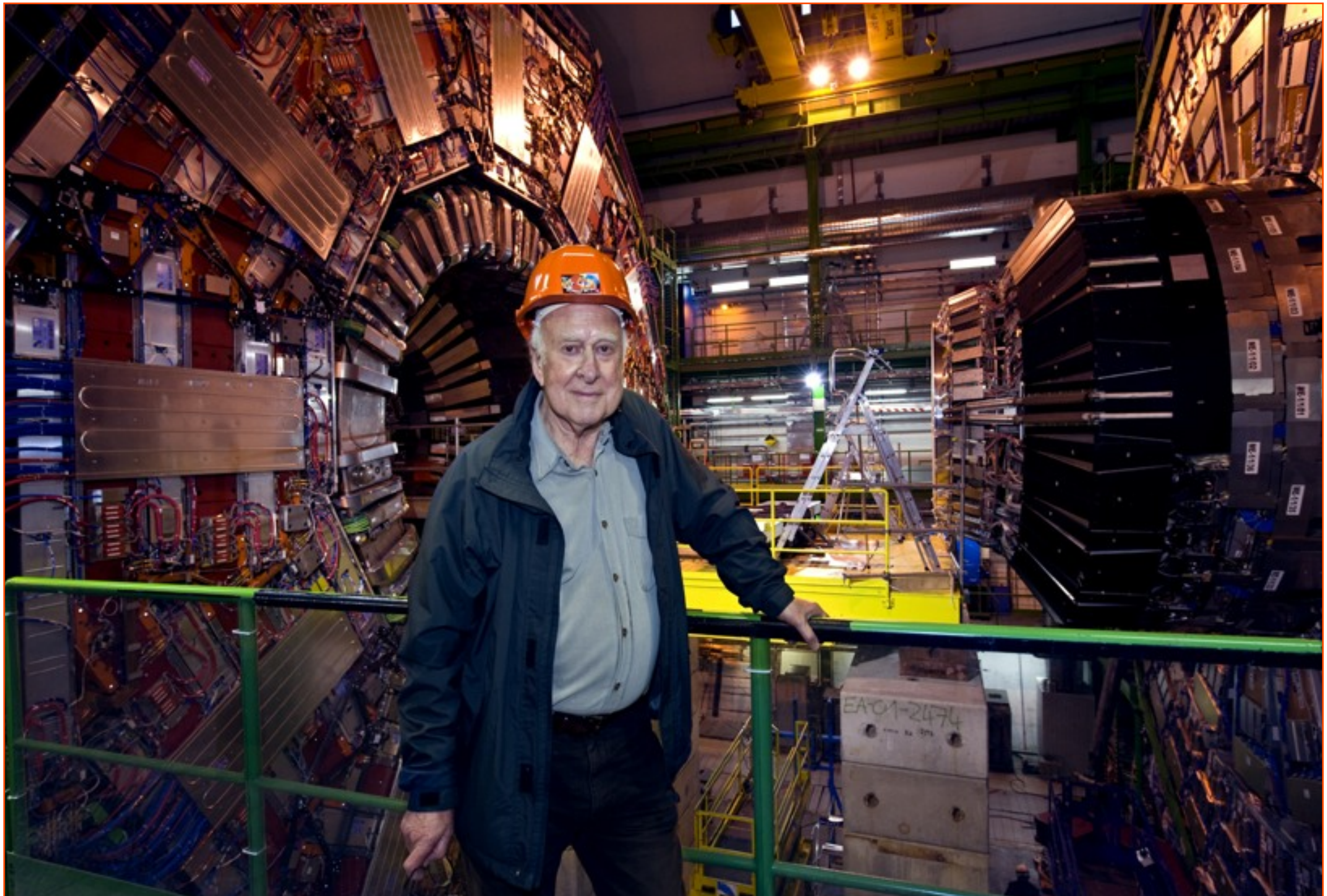
E se non troviamo la SuperSimmetria ?

- Un po' presto per darci per vinti !
- Comunque …

  - We are anyhow in the dark
  - If the LHC does not find SuperSymmetry the dark will be darker

- La fisica teorica non ha bisogno di nuovi interrogativi, per procedere ha bisogno di nuove osservazioni.

L'Higgs a CMS



L'eperimento ATLAS