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SFB 676 – Projekt B2

Physics at the LHC

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HGF Monte Carlo School – Hamburg – 14th March 2011

PHYSICS AT THE TERA SCALE Helmholtz Alliance

Outline

Introduction

Performance of Detectors

Rediscovery of the Standard Model

Beyond the Standard Model

Summary

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Rediscovery of the Standard Model

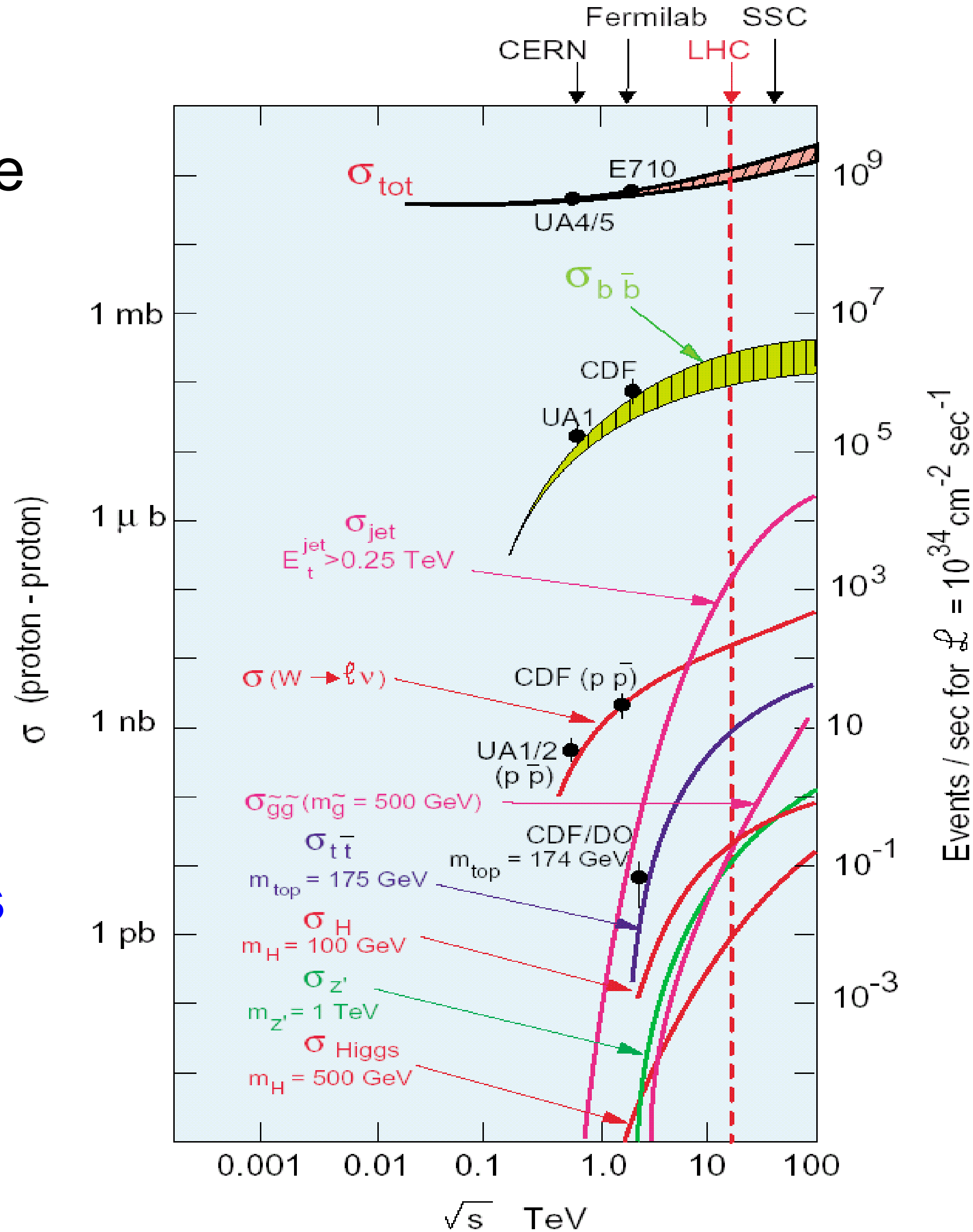
Beyond the Standard Model

Summary

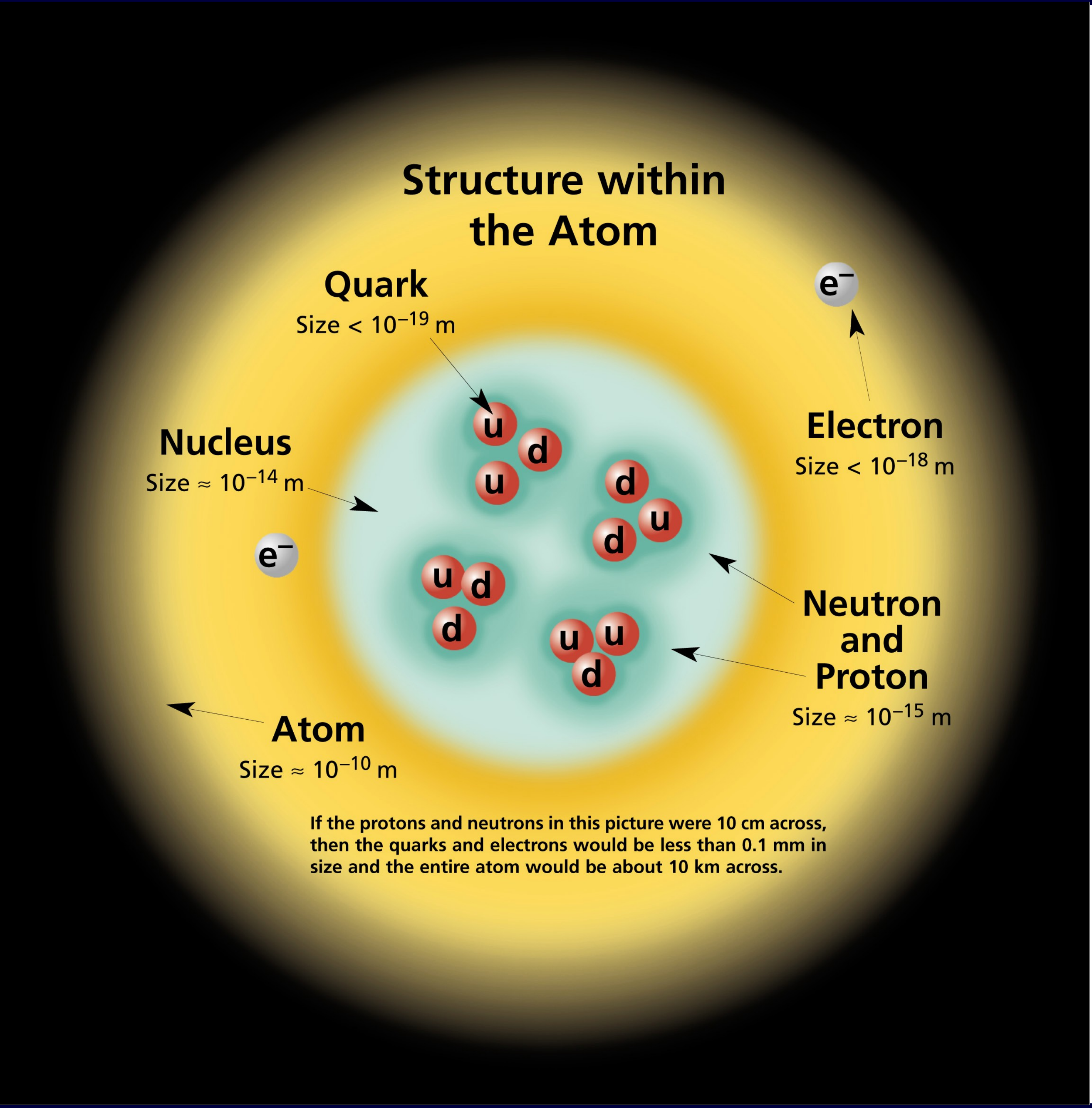
Physics at the LHC

- SM well established
- New physics expected at TeV scale (stabilizing *VV* cross section → Higgs, unification of gauge couplings → Supersymmetry)
- **SM processes:** many orders of magnitude larger cross sections than typical Higgs/BSM cross sections

→ Searches for Higgs/BSM signatures require a precise understanding of SM processes



Structure of the Proton



LHC is *pp* collider

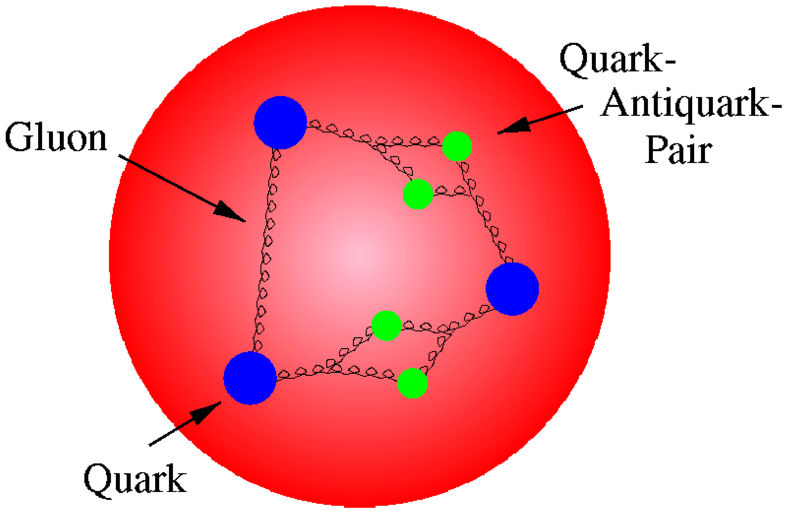
→ High $\sqrt{s}$ of *pp* collision

→ Large cross sections (strong interaction)

→ "Discovery machine"

→ No precise knowledge of $\sqrt{s}$ of hard process

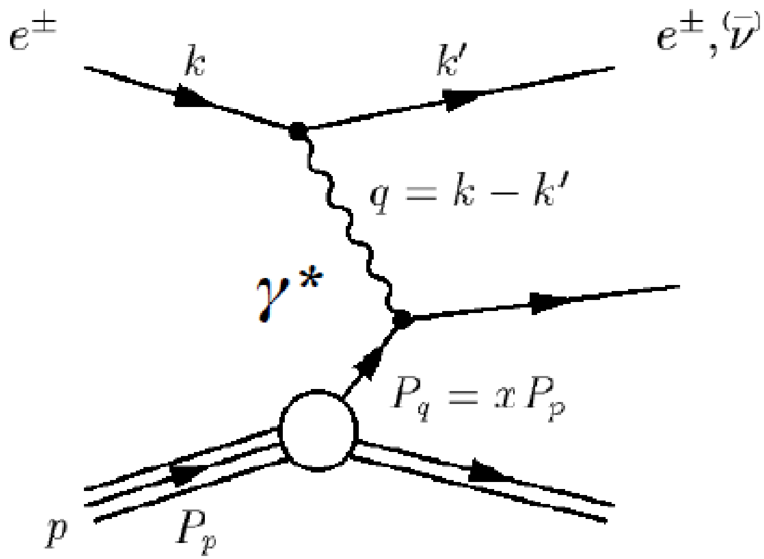
→ Input for all calculations: **Structure of proton**



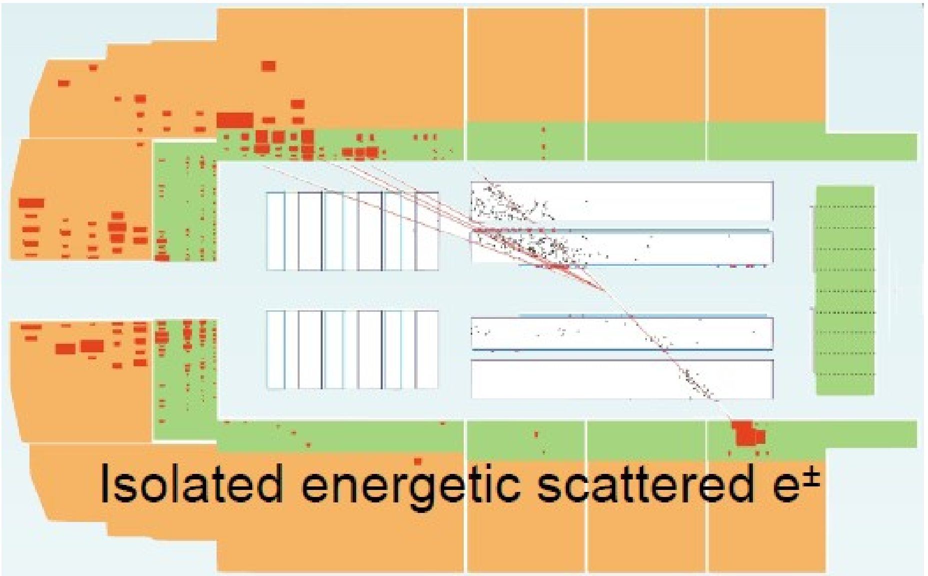
ep Collisions

- Most energetic and precise measurements done at HERA
- Kinematics:
  - Photon virtuality: $\mathbf{Q^2 = -q^2}$
  - Bjorken scaling: $\mathbf{x = -q^2/2P_pq}$
  - Photon energy fraction: $\mathbf{y = qP_p/kP_p}$

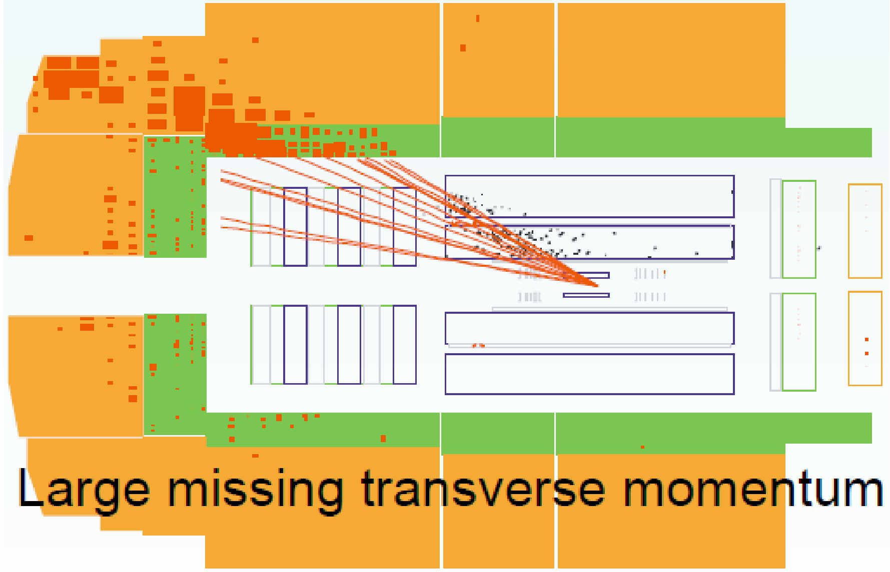
Diff. cross section measurements
$\rightarrow$ structure function of proton



γ*,*Z* (neutral current) *e* + *p* → *e* + *X



W*± (charged current) *e* + *p* → *ν* + *X



PDF Measurements

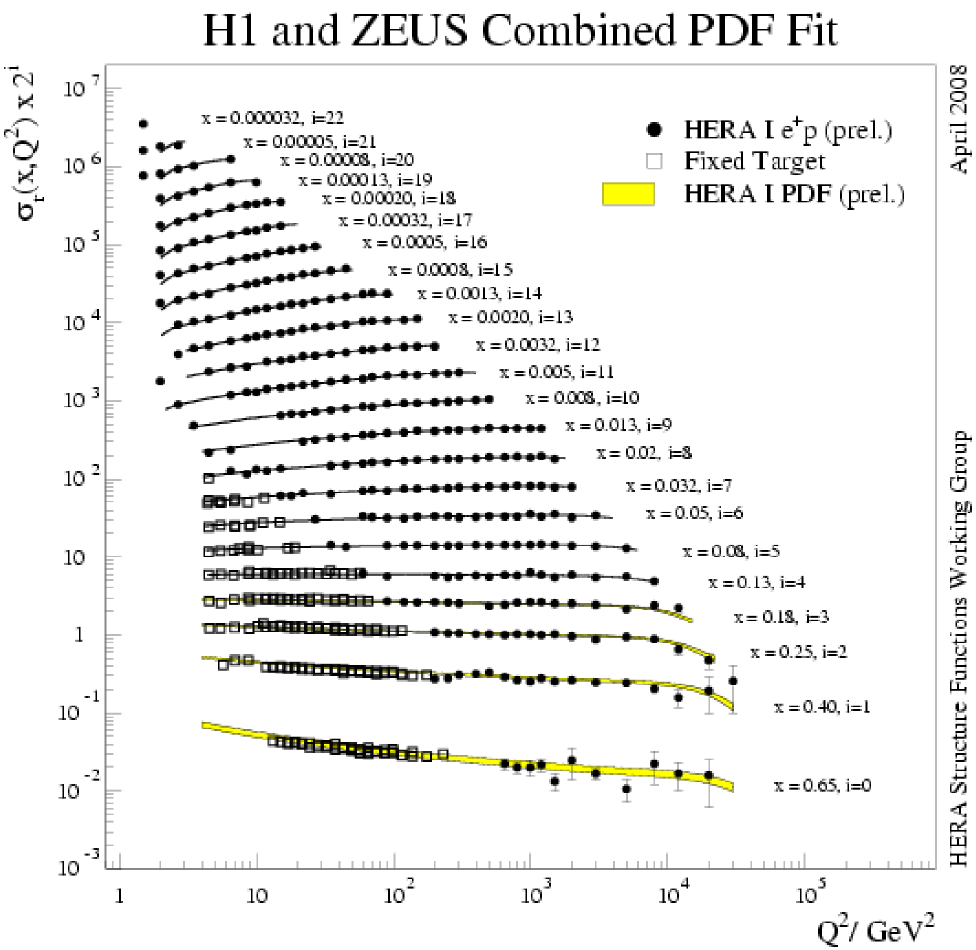
- E.g. neutral current:

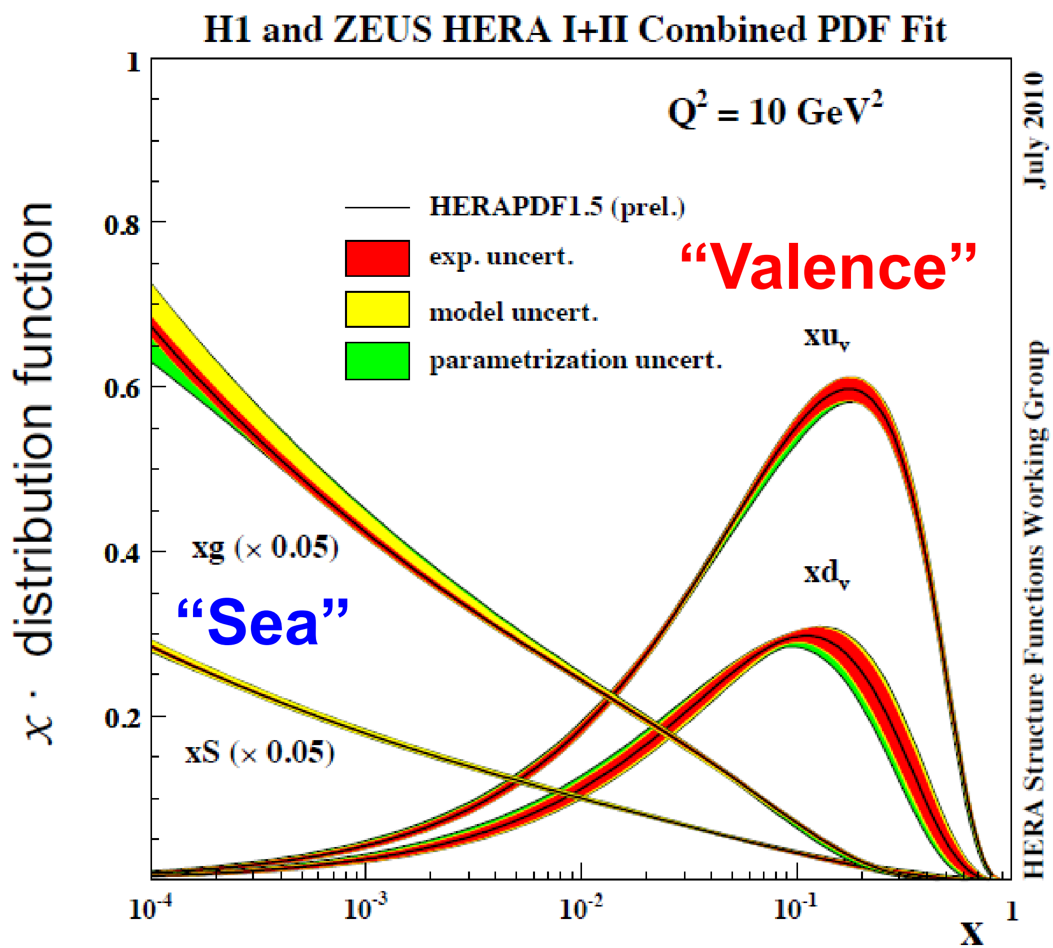
$$\frac{d^2\sigma^{ep}}{dxdQ^2} \propto \frac{2\pi\alpha^2}{xQ^4}\left[\underbrace{(1+(1-y)^2)F_2}_{\text{Dominant contribution}} - y^2F_L \mp xF_3\right]$$

- **Quark-parton model:** $F_2 \propto \sum_f \left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$

- **Parton distribution functions (PDFs):** $q_f/\bar{q}_f(x,Q^2)$
  - Probability density to find quark of flavor **f** with a momentum fraction **x**
  - **Bjorken scaling:** If partons do not interact: $\mathbf{q_f(x)}$ and $\mathbf{F_2(x)}$
  - PDF dependence on **x** not calculable in perturbative QCD

- **Combination from H1 and ZEUS data provide most precise PDFs**
- **At low x:** dominating gluon density (→ LHC)
- Dependence on $\mathbf{Q^2}$ → **Scaling violation**





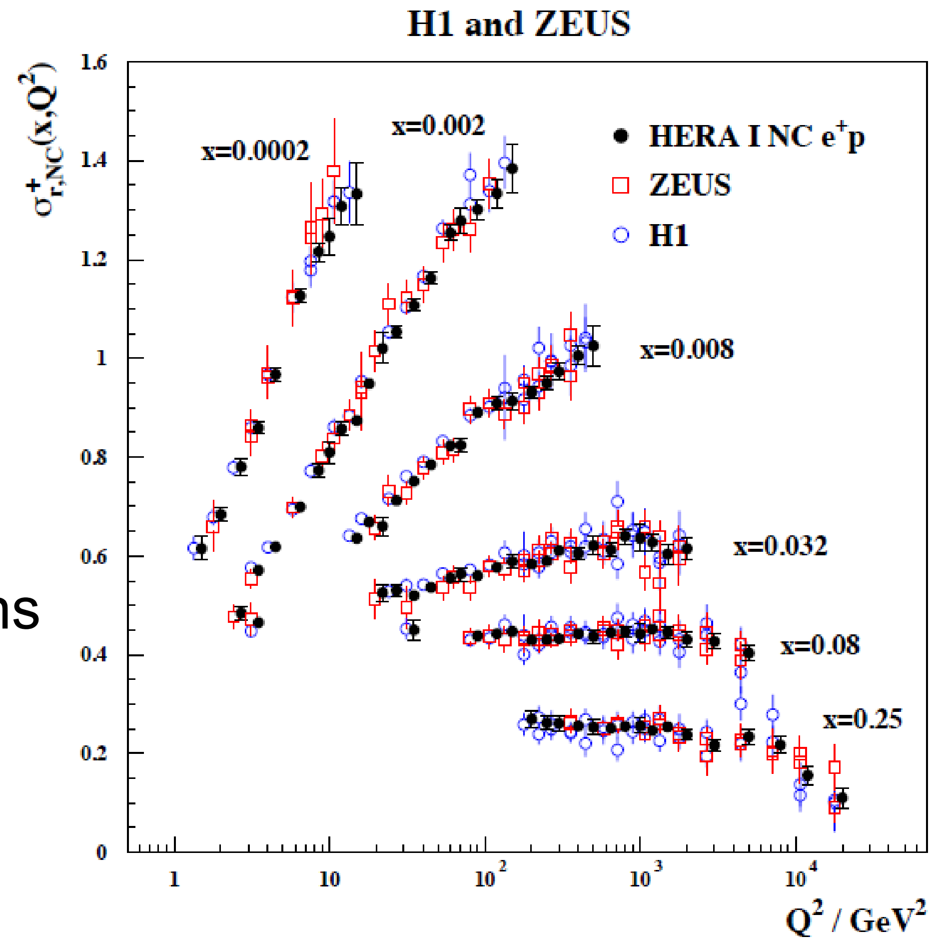
Scaling Violation / DGLAP

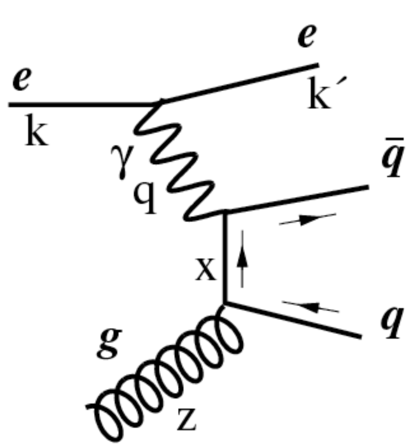
- Quarks do interact via gluon exchange
- **Interpretation of PDFs:** probability density of partons with momentum fraction **x**, as resolved at $\mathbf{Q^2}$:

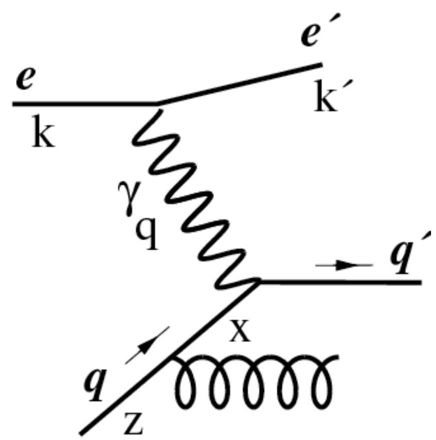
$$F_2(x) \rightarrow F_2(x,Q^2),\ q(x) \rightarrow q(x,Q^2)$$

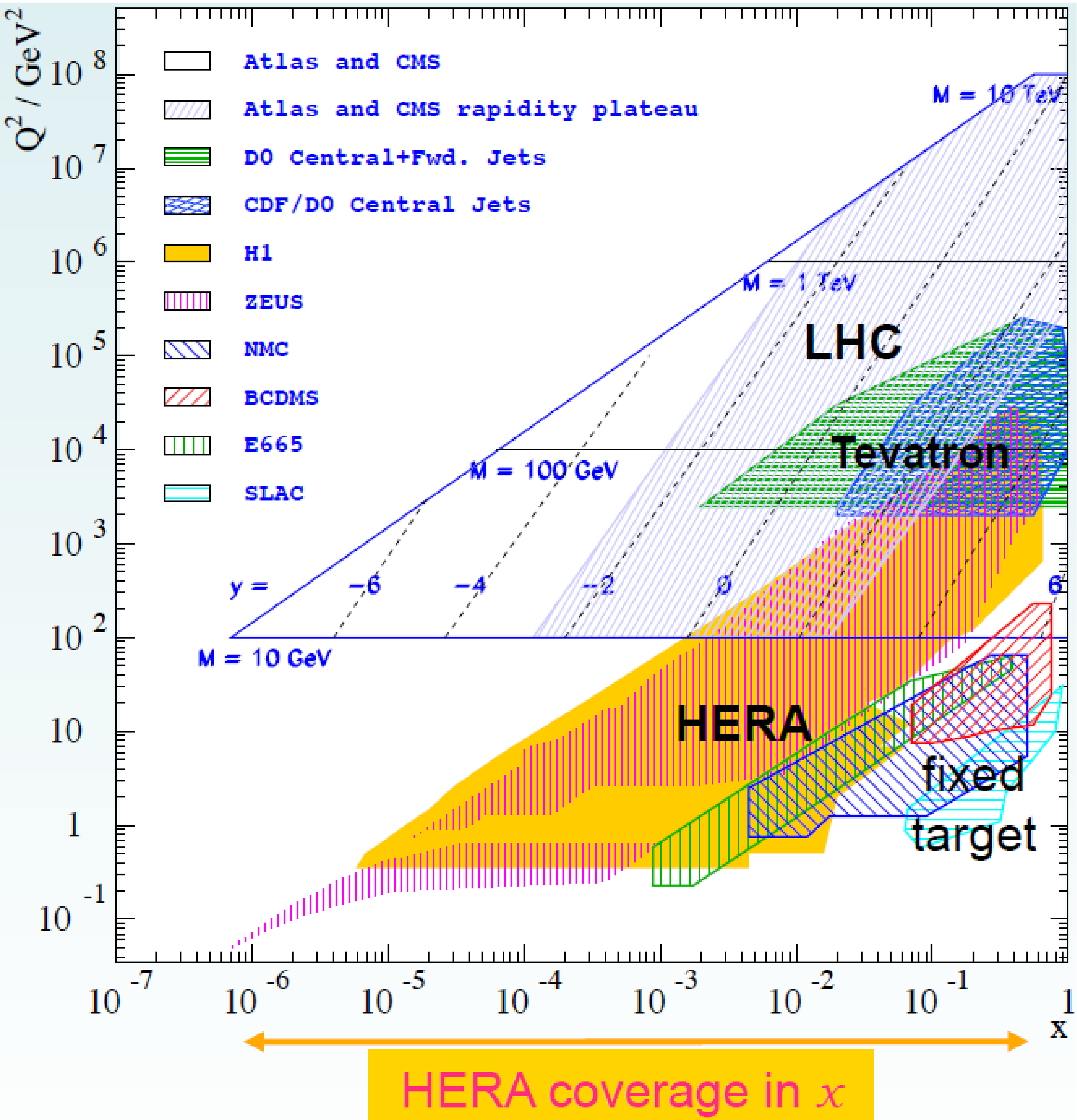
- Dependence on $\mathbf{Q^2}$ described in perturbative QCD via **D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi (DGLAP) equations

→ **Quark and gluon densities coupled**

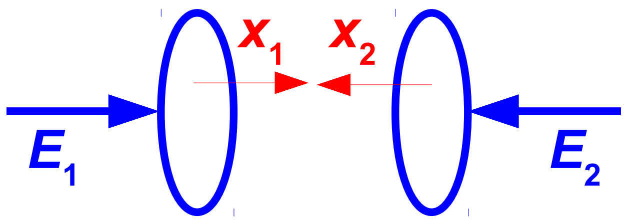








Kinematics in *pp* collisions



Center-of-mass energy:

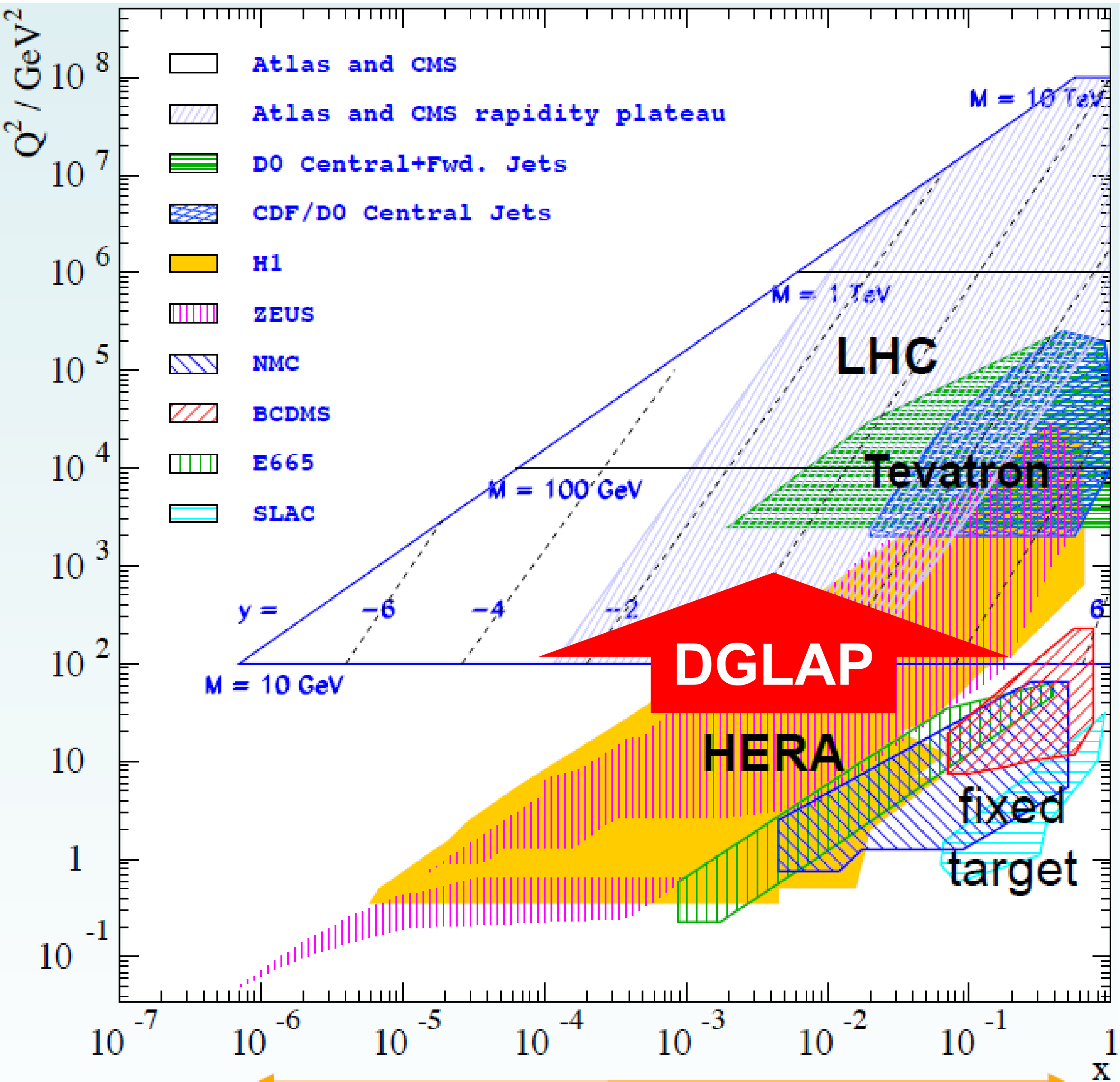
$$s = 4 \cdot E_1 \cdot E_2$$

2-parton interaction:

$$\hat{s} = x_1 \cdot x_2 \cdot s \geq M$$

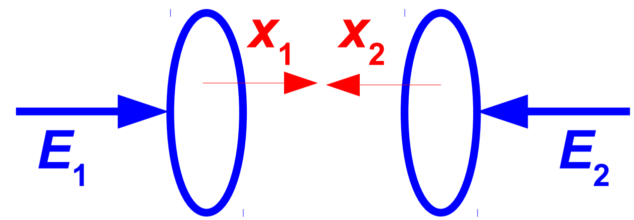
Energy scale $M = Q$

$$x_{1,2} = \frac{M}{\sqrt{s}} \cdot \exp(\pm y)$$



HERA coverage in x

Kinematics in *pp* collisions



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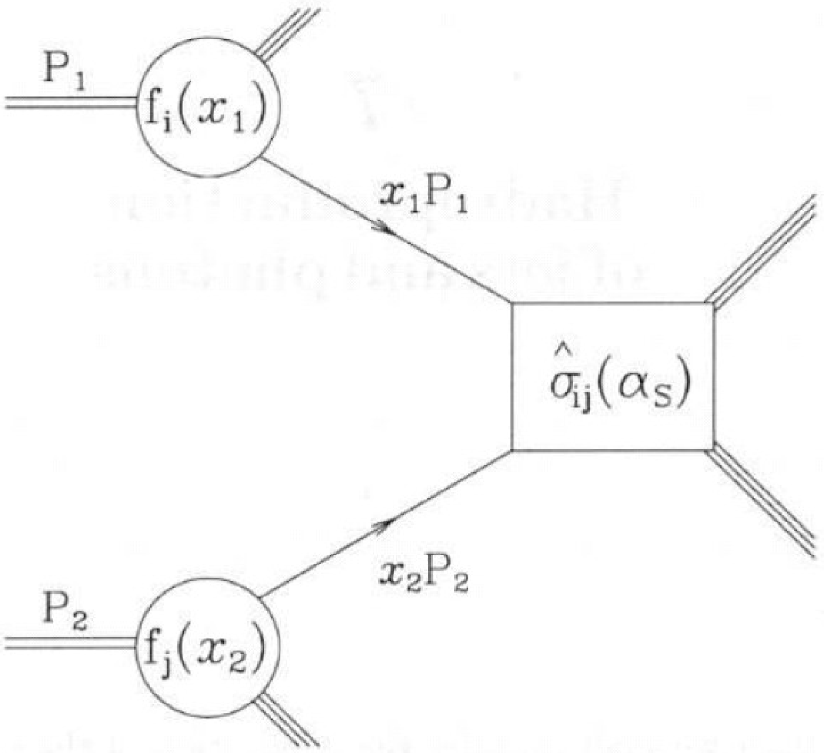
Factorization

Main statement:

Cross sections can be calculated by a product of

- Parton distribution functions (PDFs)
- Perturbative XS of the hard process
- **If needed:** Description of final state via parton shower …



At the LHC:

$$\sigma(\mathbf{pp} \to \mathbf{Y} + \mathbf{X}) = \sum_{\mathbf{q_i},\mathbf{q_j}} \int \mathbf{dx_1} \int \mathbf{dx_2}\ \mathbf{q_i}(\mathbf{x_1}, \mathbf{Q^2}) \otimes \mathbf{q_j}(\mathbf{x_2}, \mathbf{Q^2}) \otimes \hat{\sigma}_{\mathbf{q_i q_j} \to \mathbf{Y}}(\mathbf{x_1}, \mathbf{x_2}, \mathbf{Q^2})$$

Also important for PDF measurements itself

Factorization is often only an approximation: soft gluon interaction between hadrons, interactions of initial and final states …

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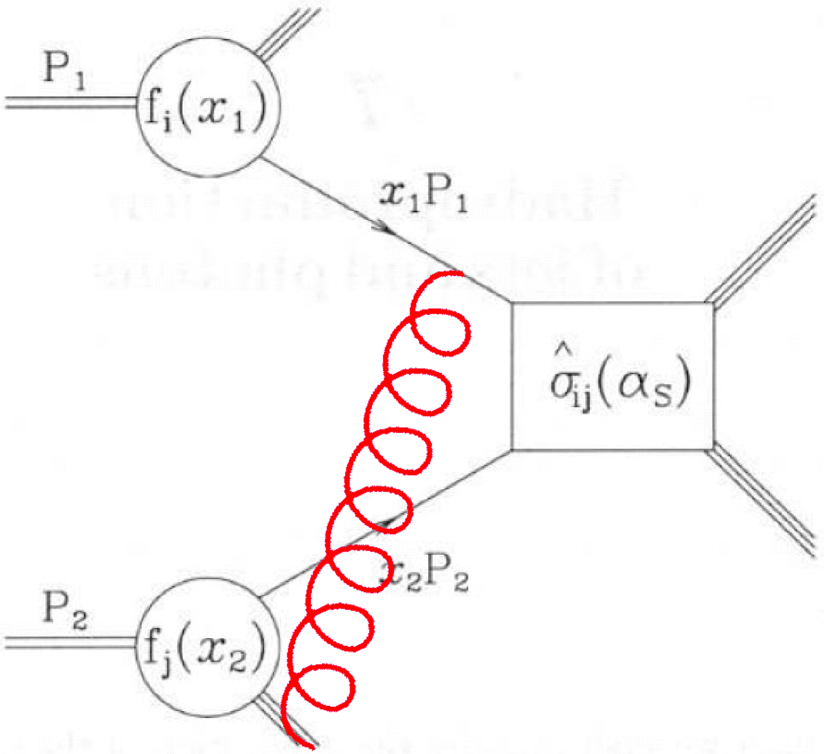


At the LHC:

$$\sigma(pp \rightarrow Y + X) = \sum_{q_i, q_j} \int dx_1 \int dx_2 \; q_i(x_1, Q^2) \otimes q_j(x_2, Q^2) \otimes \hat{\sigma}_{q_i q_j \rightarrow Y}(x_1, x_2, Q^2)$$

Also important for PDF measurements itself

Factorization is often only an approximation: soft gluon interaction between hadrons, interactions of initial and final states …

At fixed $\sqrt{\hat{s}}$ a smaller $\sqrt{s}$ requires larger $\mathbf{x_1}$ and $\mathbf{x_2}$

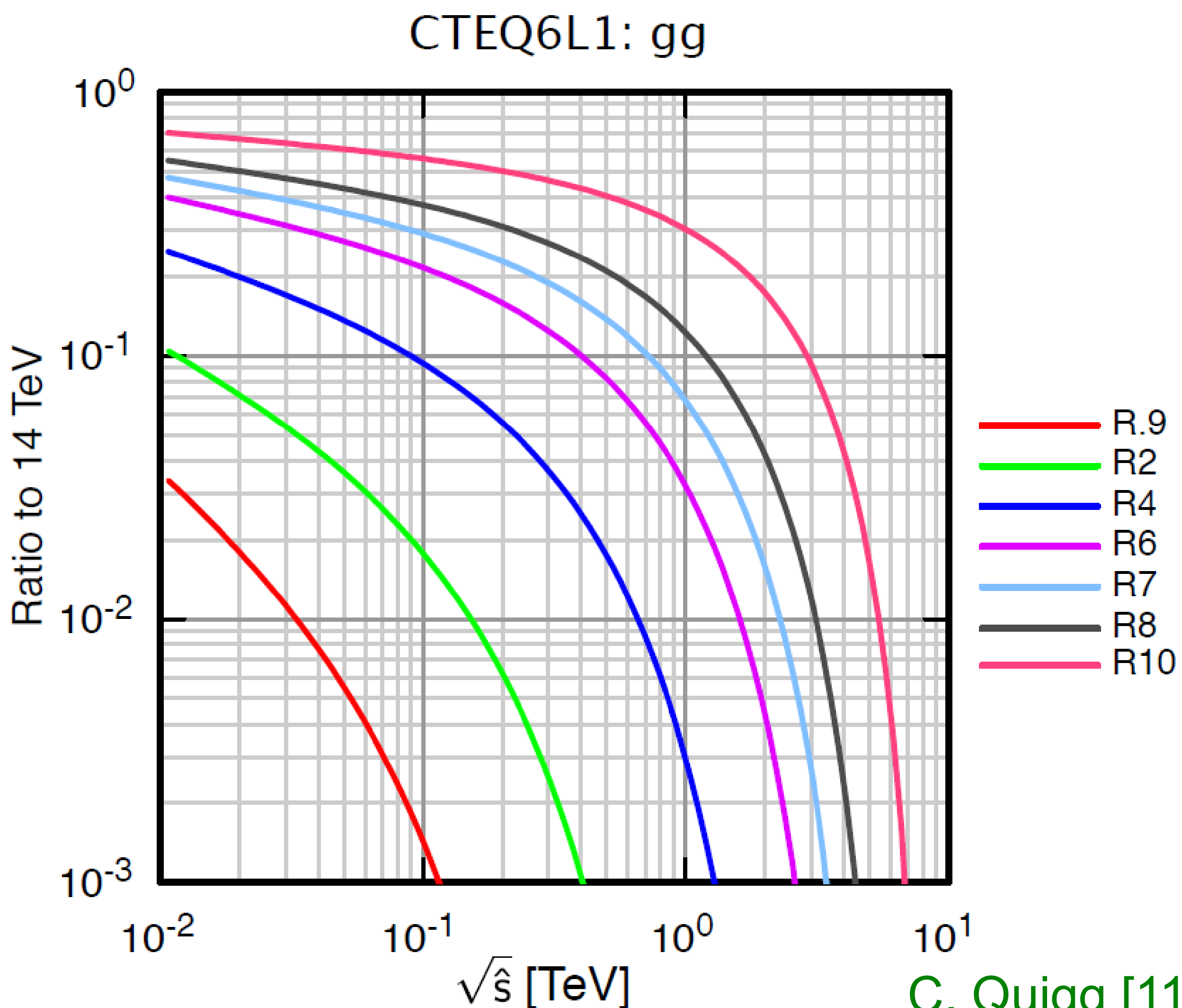
Steeply falling PDFs of “sea” quarks and gluons →
Decreasing cross section

Example: 14 TeV → 7 TeV (gluon-gluon processes)

$\sqrt{\hat{s}}$ = 300 GeV

→ Cross section drops by factor ~5

Ratio of parton luminosities (here: gluon-gluon) w.r.t. 14 TeV



C. Quigg [11]

Data Taking

2009: Data taking at $\sqrt{s}$=900 GeV and 2.36 TeV

Since 30th March 10: $\sqrt{s}$=7 TeV

Peak Luminosity: 1.3×10^{32} cm^{-2} s^{-1}

Plan for 2011: 6.4×10^{32} … 2.2×10^{33}

Design: 10^{34}

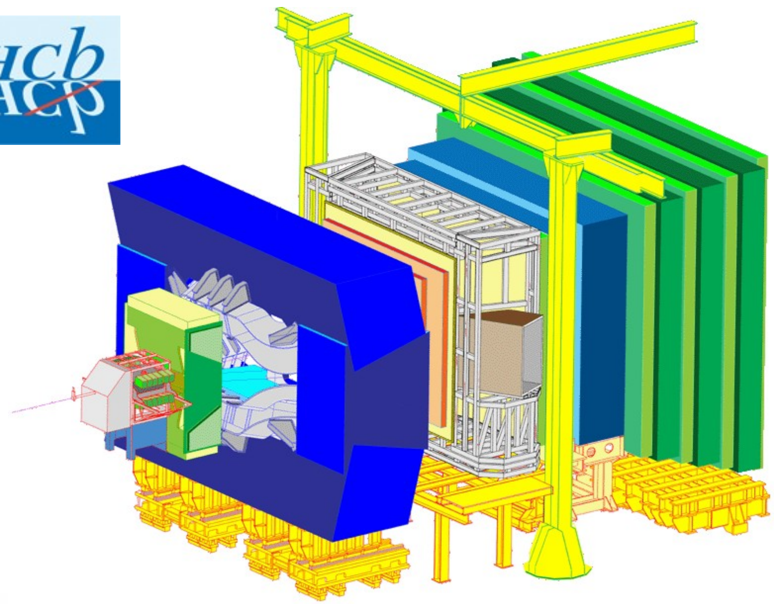
Delivered int. Lumi at CMS: 47/pb

Plan for 2011: 2.2/fb … 7.6/fb

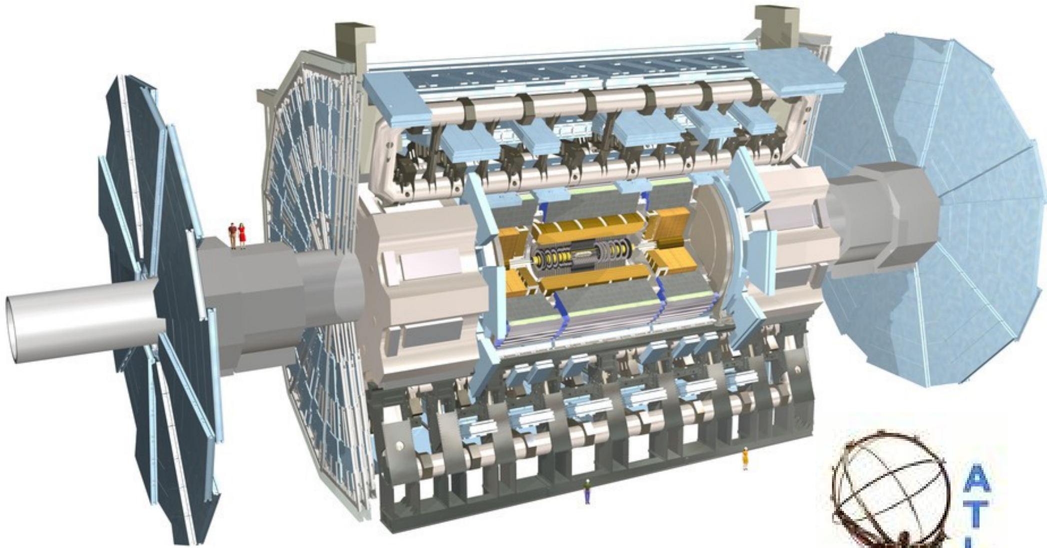
+ ~3 weeks of Heavy Ion

(PbPb at $\sqrt{s}$=2.76 TeV/n; int. Lumi ~7/μb)

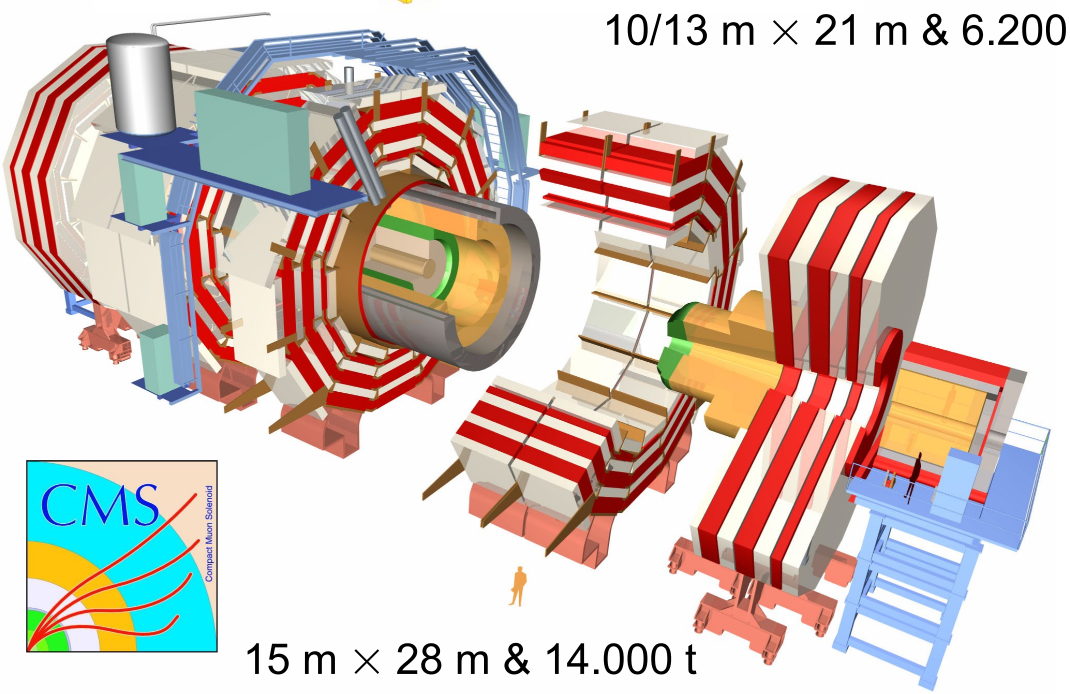
The Experiments



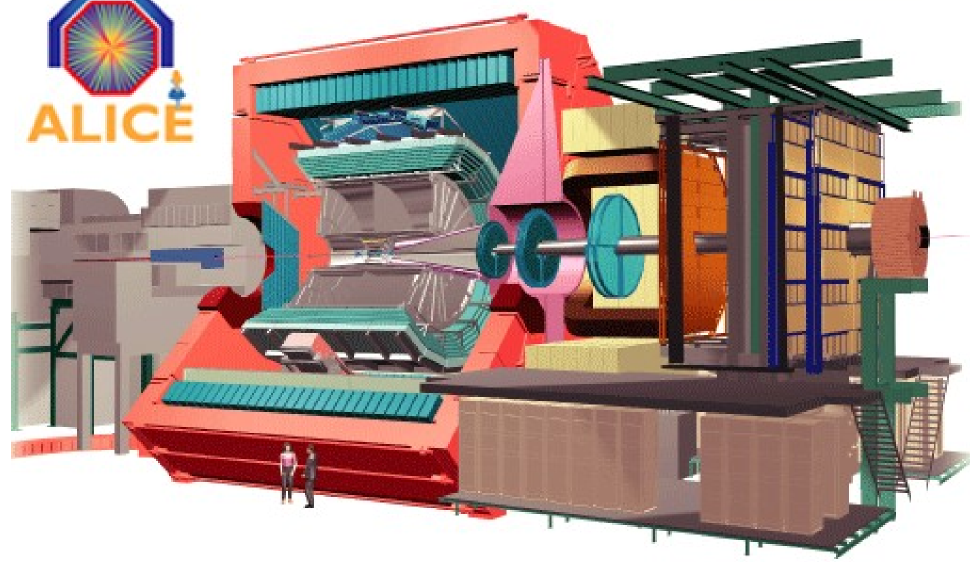
10/13 m × 21 m & 6.200 t



22 m × 44 m & 7.000 t



15 m × 28 m & 14.000 t



16 m × 25 m & 10.000 t

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Particle Identification at ATLAS

Toroidal magnet

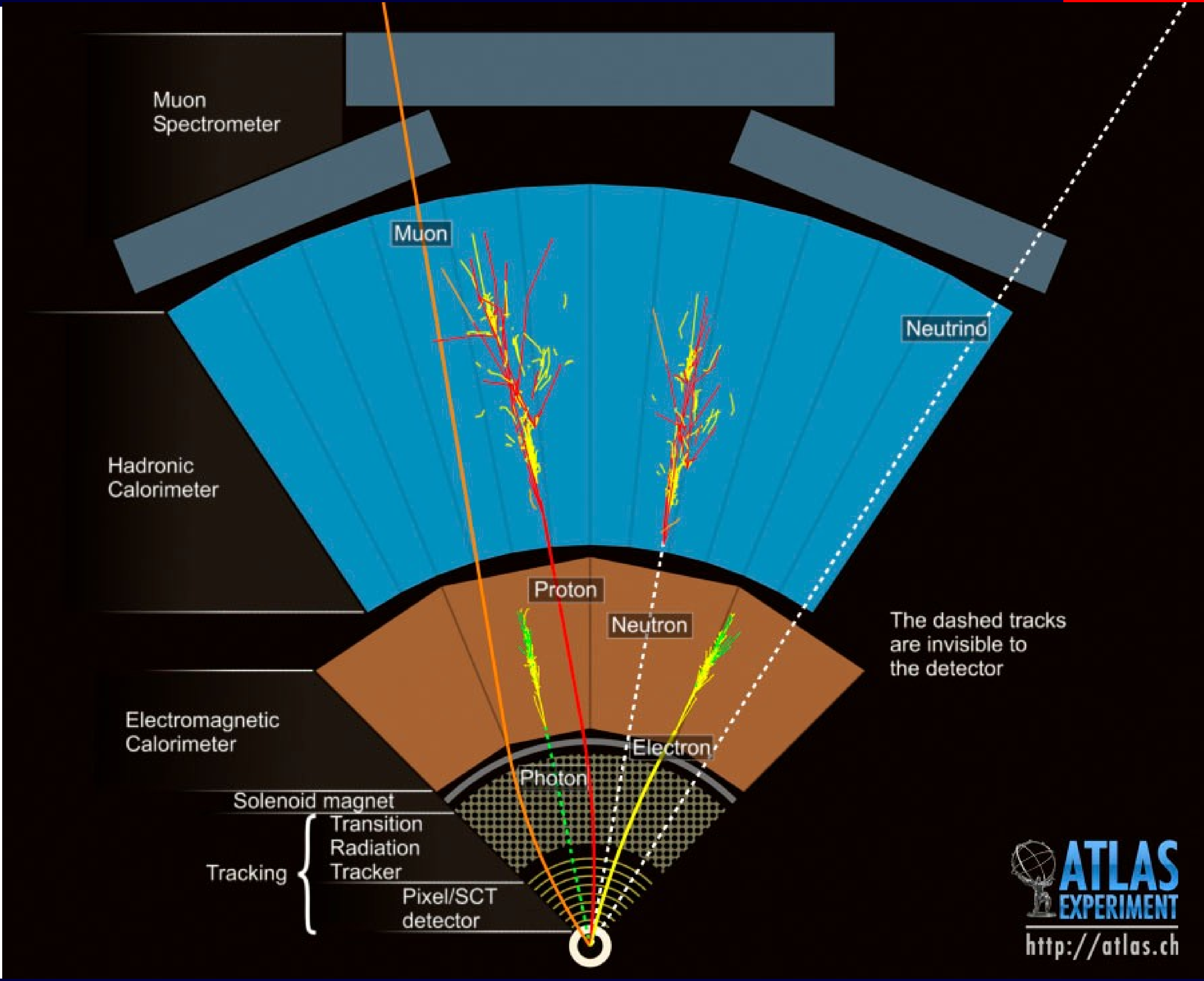
Muon chambers

HCAL
Outer: scintillator
Inner: liquid Argon

ECAL
liquid Argon

Solenoid ~2T

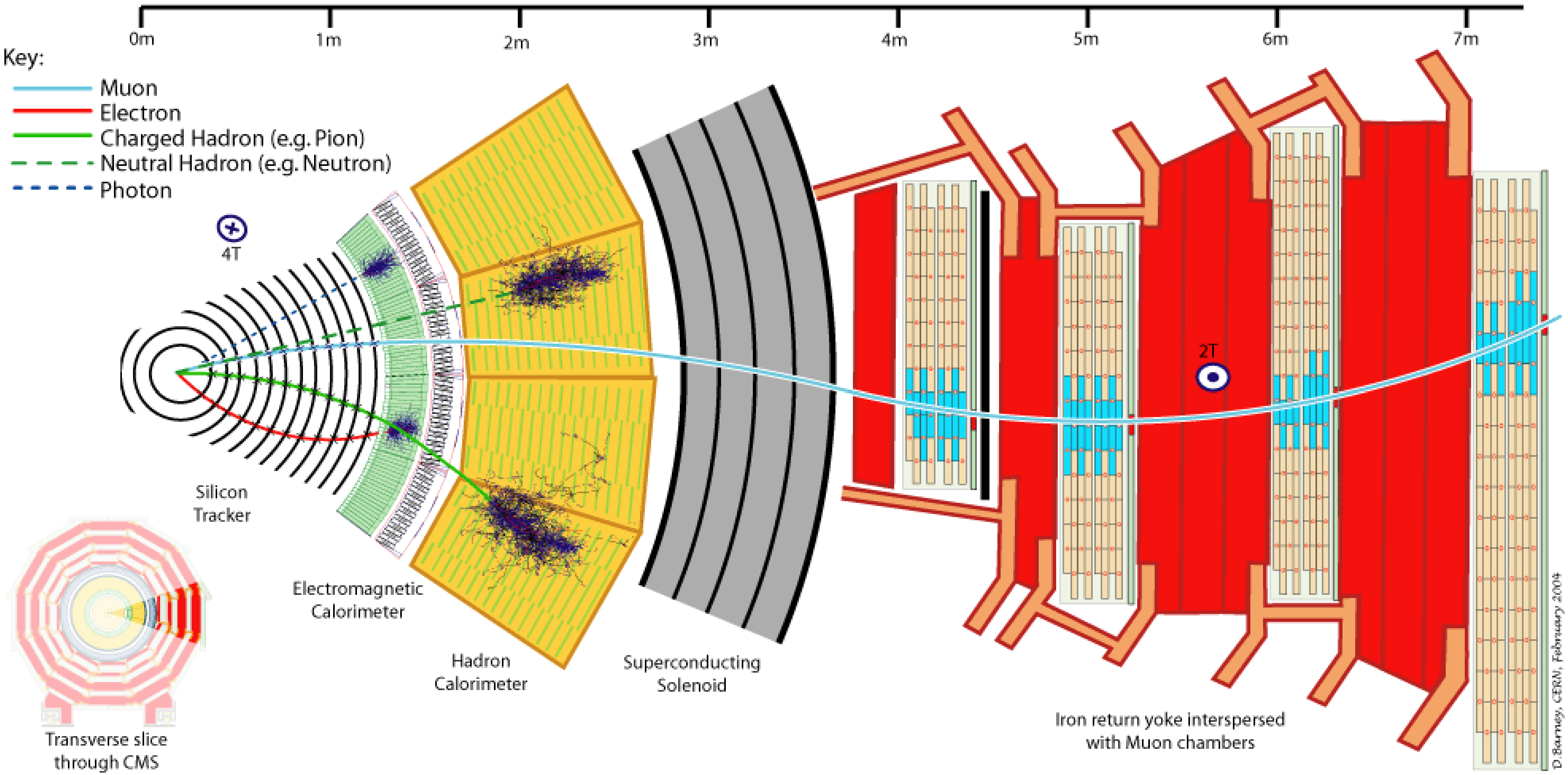
Tracking
Transion radiation
Si-Strip
Si-Pixel



Particle Identification at CMS

Main difference to ATLAS:

- All silicon tracker
- ECAL and HCAL mostly inside solenoid magnet (~4T)
- No toroidal magnet for muon bending

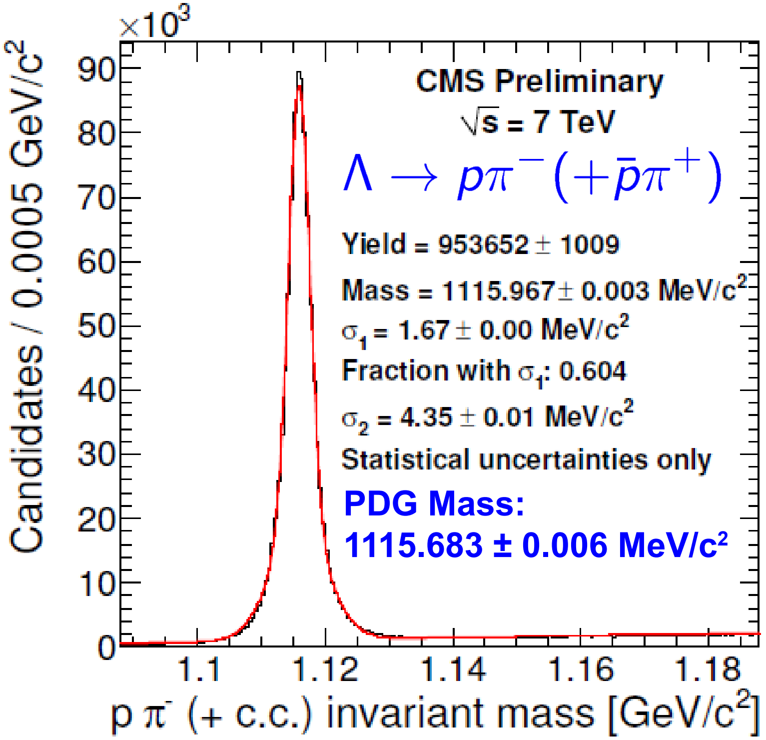


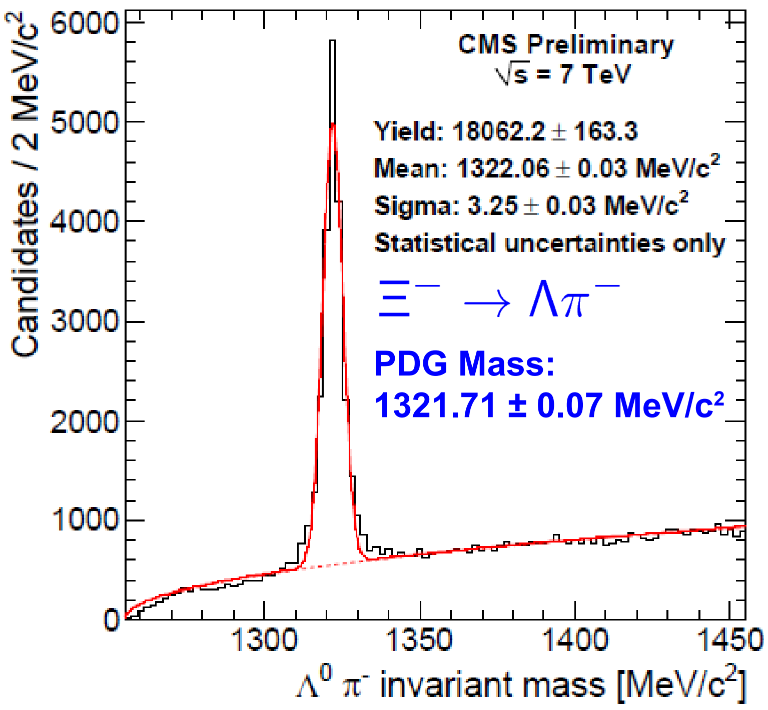
Detector Performance – Tracker

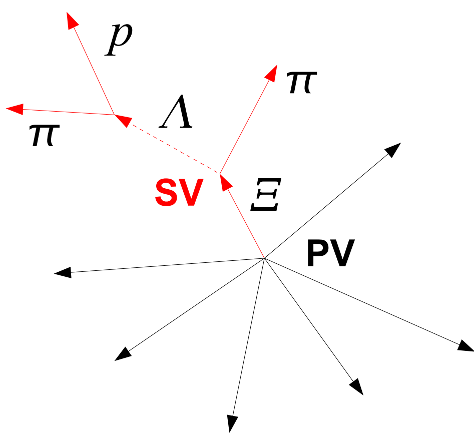
Measurement of strange particle mass resonances:

CMS PAS QCD-10/007

- Λ **baryon candidate:** Two tracks of opposite charge; assign lower p_T to m_π; secondary vertex
- Ξ **baryon candidate:** Λ candidate combined with 3rd negative secondary track; SV of Ξ separated from PV; points back to PV







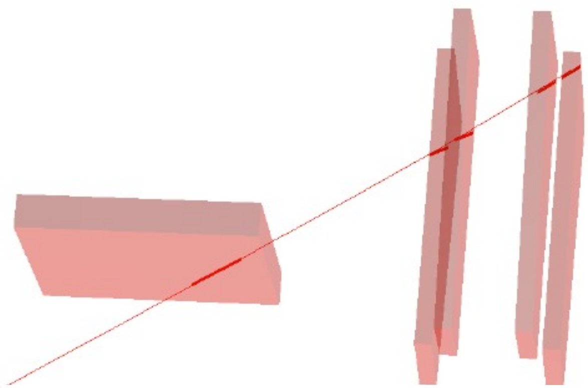
Systematic uncertainties neglected

Mass accuracy at the level 10^{-4} → Very well aligned Si-strip and pixel tracker

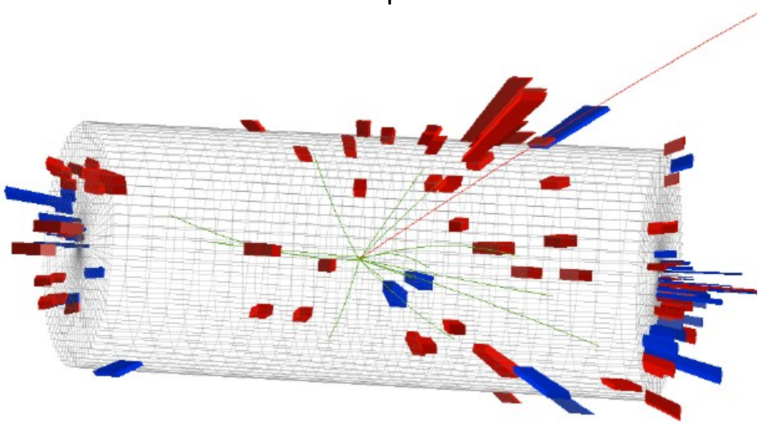
CMS PAS MUO-10/002

CMS Experiment at LHC, CERN
Data recorded: Mon May 17 06:14:28 2010 CDT
Run/Event: 135575 / 156337837
Lumi section: 943
Orbit/Crossing: 247039184 / 401

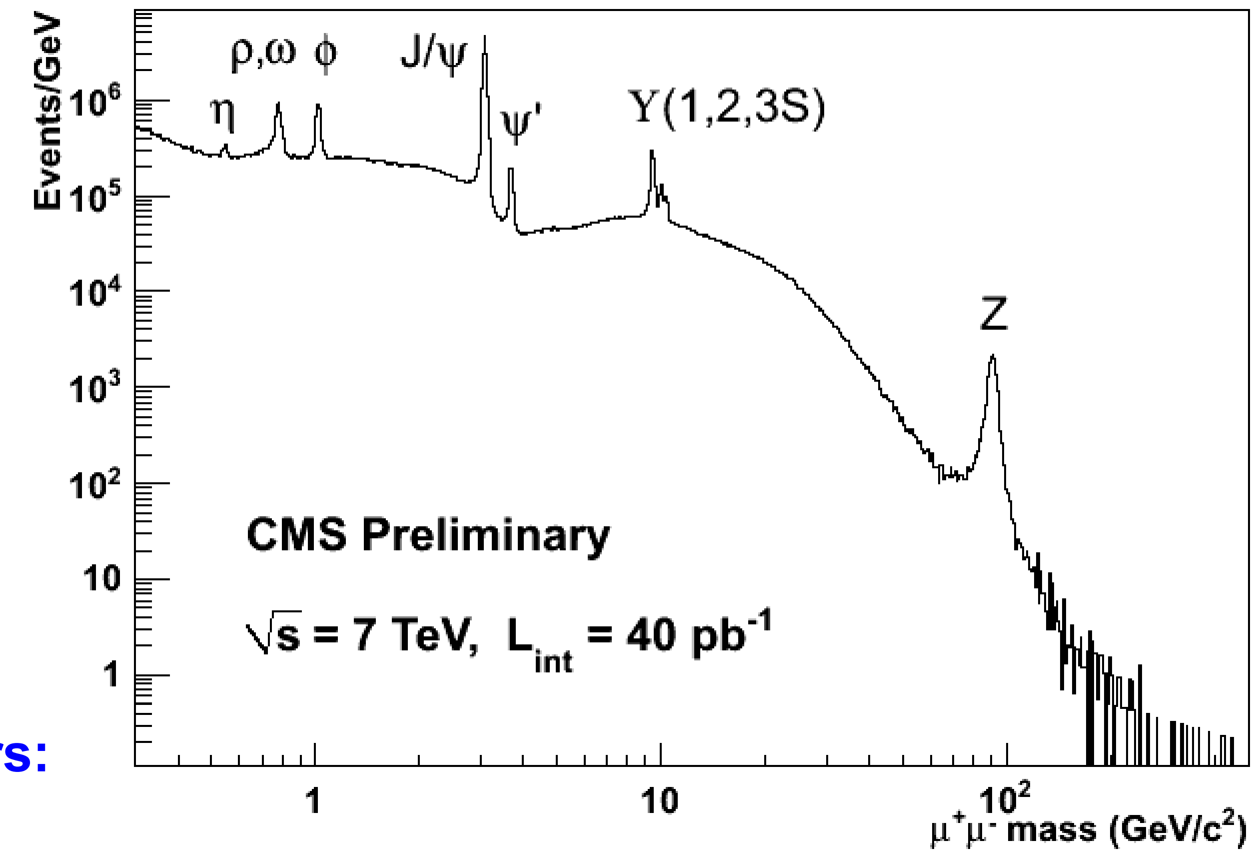
Event display of a μ candidate:
Hits in the muon system
matched to track



p_T = 7.4 GeV/c



Full invariant mass spectrum of opposite charge muon pairs:



Jet Algorithms

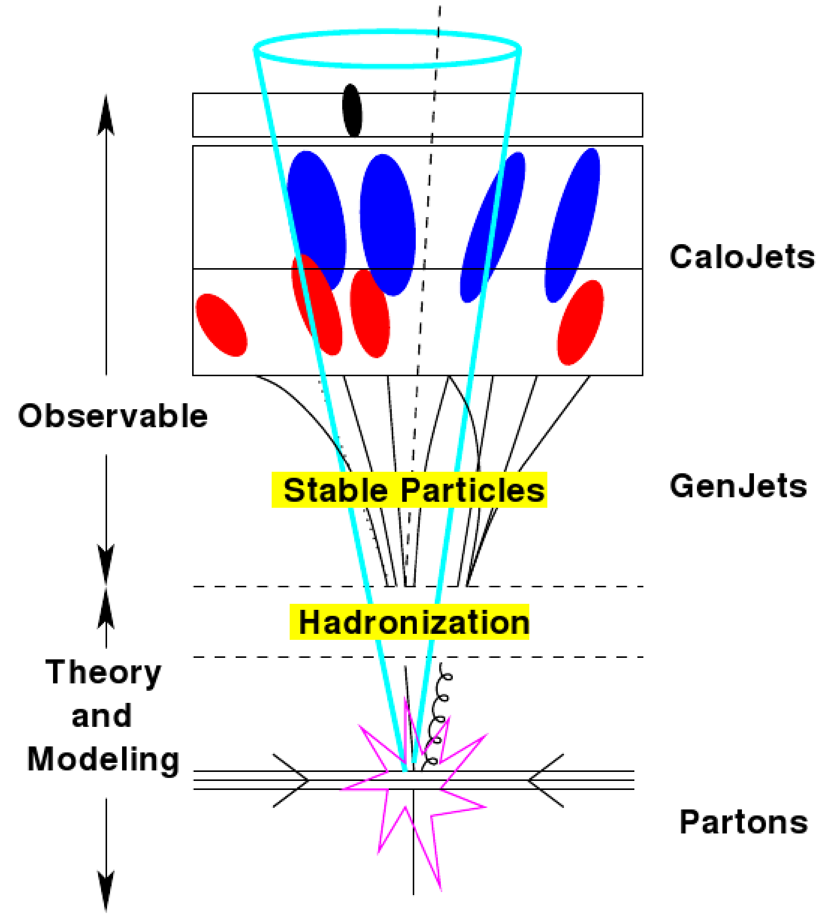
- Jet algorithm should provide good correspondence (multiplicity, position, energy) between

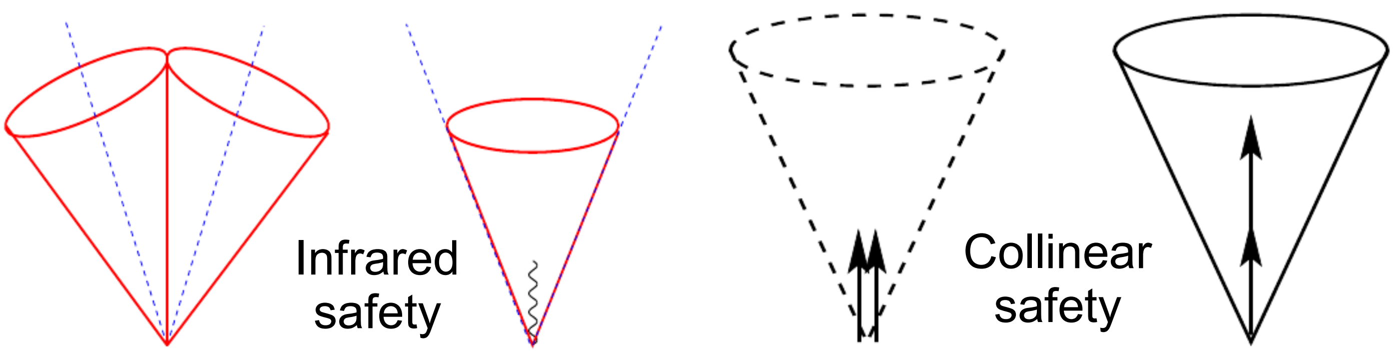
  Calorimeter jet ↔ Particle jet / parton

- Jet algorithms should be:

  Collinear safe, infrared safe, fast ...

- **Challenges:**
  - Thresholds and zero suppression
  - Noise, pileup, and underlying event
  - Response calibration
  - Out-of-cone showering





Sequential Clustering Algorithms

For each input object **i** calculate the "distance to the beam line"

$$\mathbf{d_{iB} = p_{T,i}^{2p}}$$

and the "distance" to the other particles **j**

$$\mathbf{d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right) \cdot \frac{\Delta R_{i,j}^2}{D^2}}$$

$\Delta\phi^2 + \Delta\eta^2$

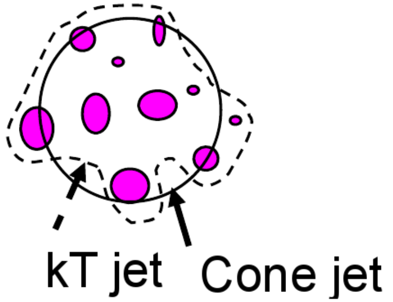
"Cone size" parameter

Find for each **i** smallest $\mathbf{d_{ij}}$

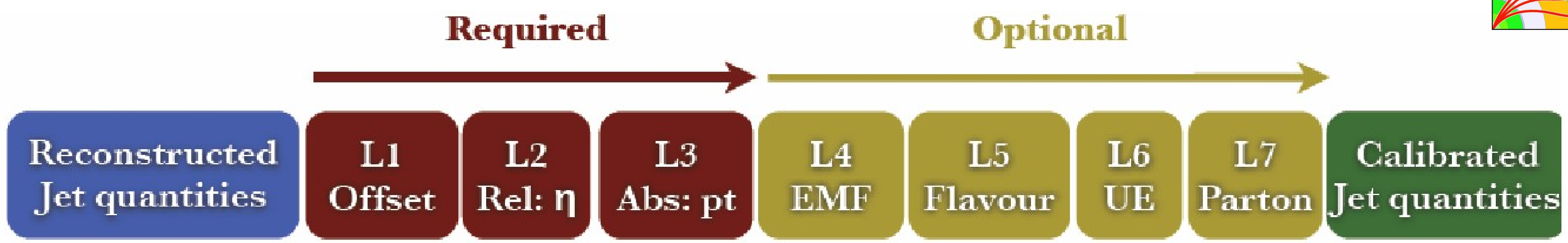
If $\mathbf{d_{iB}} < \mathbf{d_{ij}}$ move object **i** to the list of final jets, else merge **i** and **j**

Infrared and collinear safe for **p = -1, 0, +1**

- **p = +1 (k_T algorithm):** no fixed cone
- **p = 0 (Cambridge-Aachen algorithm):** no fixed cone, well suited for subjet structure studies
- **p = -1 (anti-k_T algorithm):** almost fixed cone



Jet Calibration



- **Factorization by residual corrections** facilitates use of data driven corrections
  - **L1:** Pile-up and noise measured in zero-bias events
  - **L2:** Jet response vs. η relative to barrel using diJet balance
  - **L3:** Jet response vs. p_T found in barrel using γ/Z + jets, top etc.
- **With current statistics:** Usage of MC truth with residual corrections from data/MC comparison
- Allows data-driven corrections as they emerge to easily replace MC truth

MC Truth Calibration

Match genJets to reconstructed jets, with $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.25$

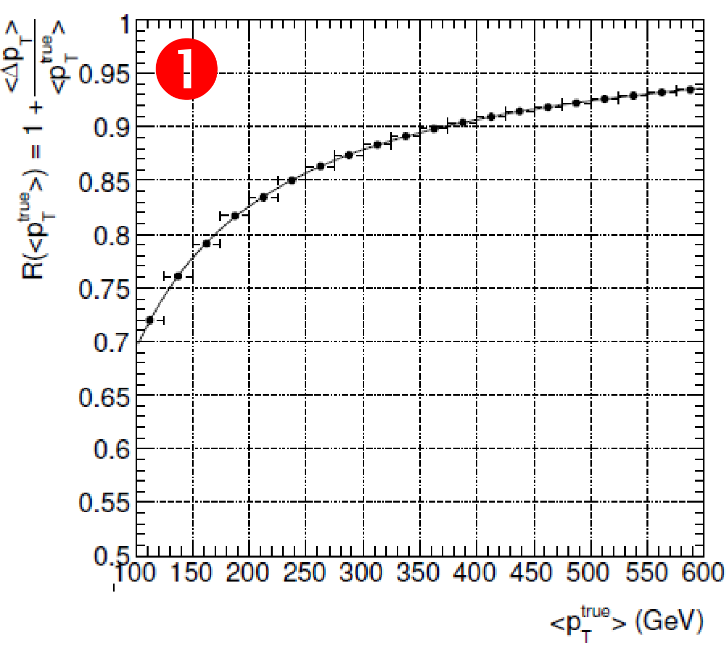
❶ Mean of response distribution: $\mathbf{R}(\mathbf{p}_\mathbf{T}^\mathbf{true}) = \langle \mathbf{p}_\mathbf{T}^\mathbf{reco} / \mathbf{p}_\mathbf{T}^\mathbf{true} \rangle$

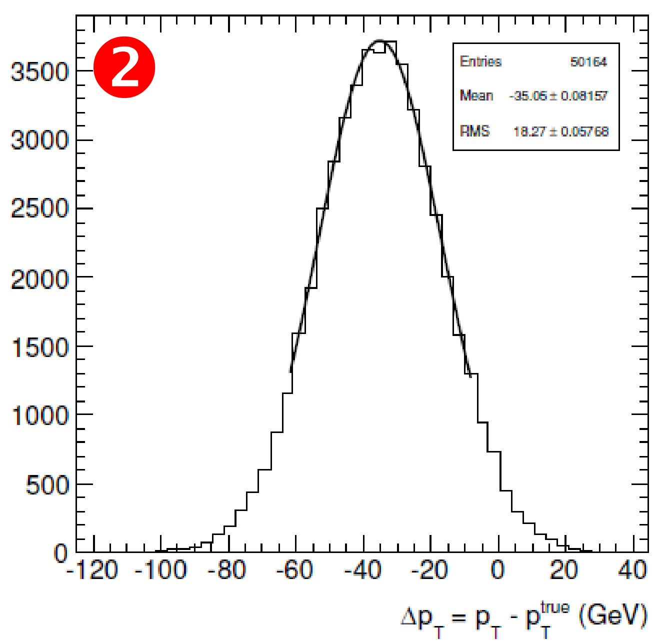
$\rightarrow$ Fit analytic function

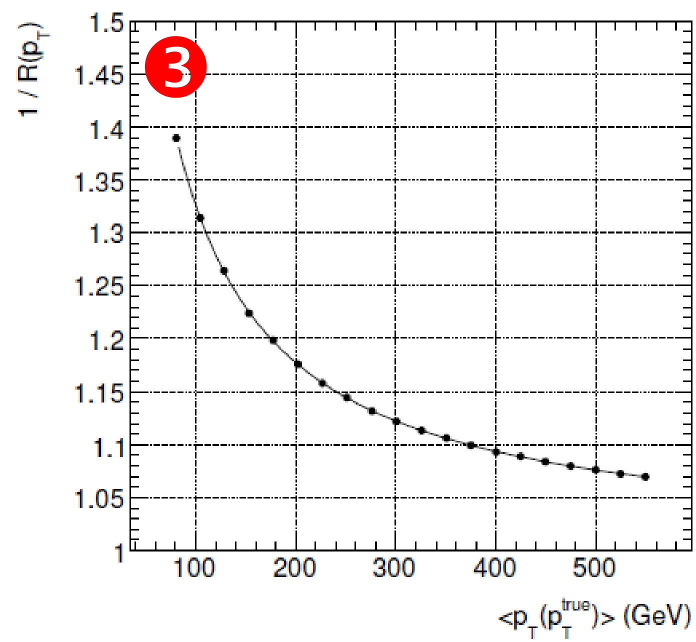
❷ Mapping of recoJet p_T to genJet p_T: $\mathbf{p}_\mathbf{T}^\mathbf{true} \leftrightarrow \langle \mathbf{p}_\mathbf{T}^\mathbf{reco} \rangle$

❸ **Inversion:** $\mathbf{C}(\mathbf{p}_\mathbf{T}^\mathbf{reco}) = \mathbf{1}/\mathbf{R}(\mathbf{p}_\mathbf{T}^\mathbf{true}(\mathbf{p}_\mathbf{T}^\mathbf{reco}))$ $\rightarrow \mathbf{p}_\mathbf{T}^\mathbf{reco,corr} = \mathbf{p}_\mathbf{T}^\mathbf{reco} \cdot \mathbf{C}(\mathbf{p}_\mathbf{T}^\mathbf{reco})$

$\rightarrow$ Fit analytic function







Jet Calibration – Relative Response

- Use diJet balance **B** from central (barrel) jet and probe jet

$$\mathbf{B} = \frac{\mathbf{p}_\mathbf{T}^\mathbf{probe} - \mathbf{p}_\mathbf{T}^\mathbf{barrel}}{\mathbf{p}_\mathbf{T}^\mathbf{diJet}}$$

- Least biased estimator **R** of relative response $\langle \mathbf{p}_\mathbf{T}^\mathbf{probe} \rangle / \langle \mathbf{p}_\mathbf{T}^\mathbf{barrel} \rangle$

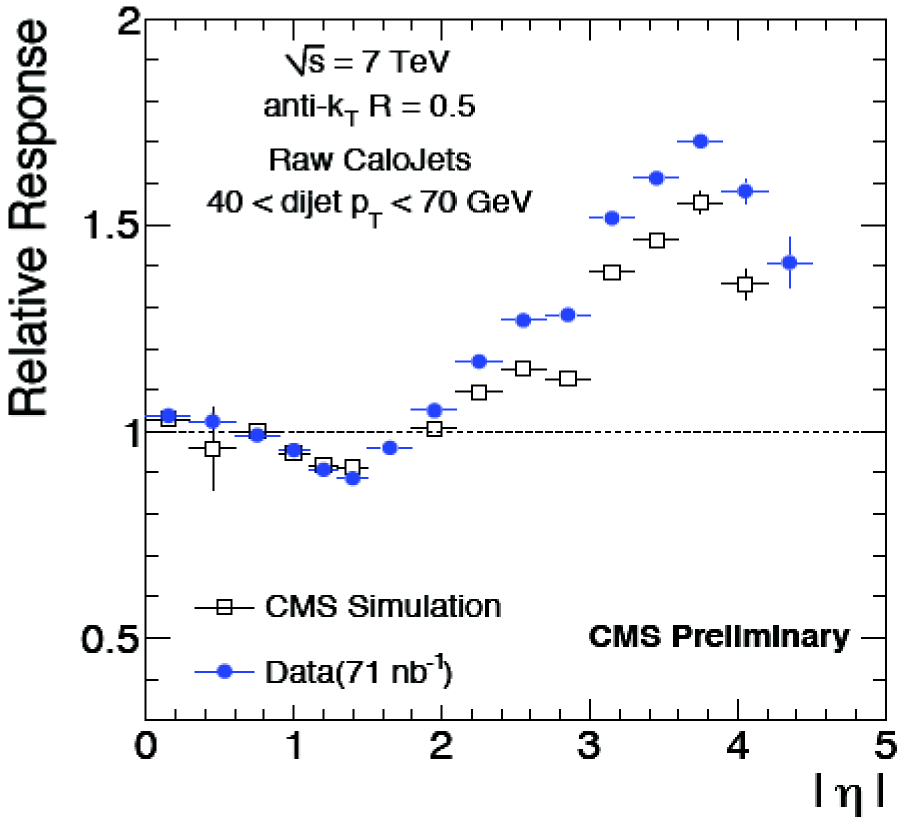
$$\mathbf{R}(\eta^\mathbf{probe}, \mathbf{p}_\mathbf{T}^\mathbf{diJet}) = \frac{2 + \langle \mathbf{B} \rangle}{2 - \langle \mathbf{B} \rangle}$$

- Falling spectrum & finite jet resolution

  → migration to higher p_T bins

  → measured response is systematically biased to higher values

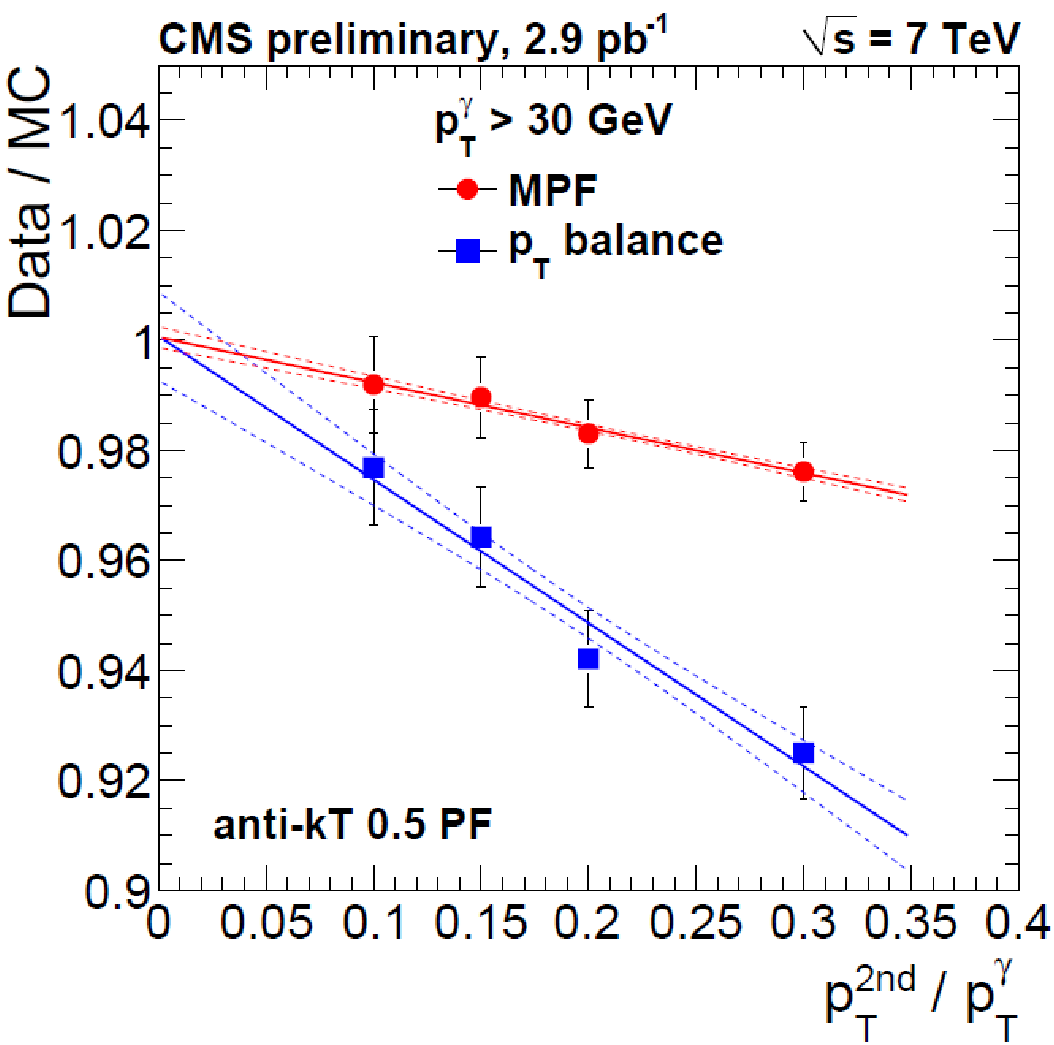
  → binning in diJet p_T minimizes bias
- Residual corrections for MC vs. data difference needed



CMS PAS JME-10/003

Use γ+jet events for absolute jet energy response; two approaches:

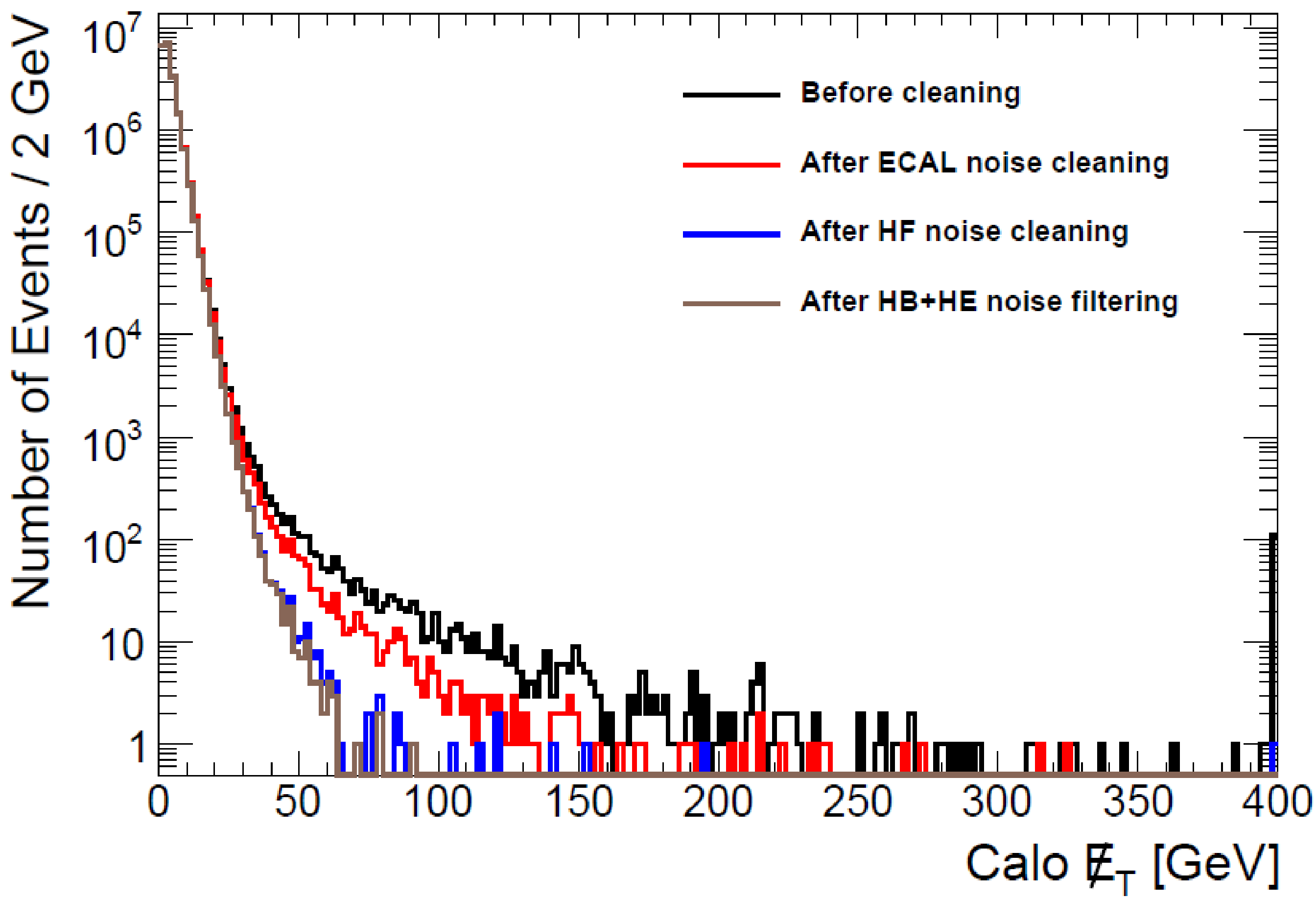
- Transverse momentum balance
- Missing E_T projection fraction (MPF):
  - Only small dependence on jet algorithm
  - Calibration of total recoil → less dependence on further jet activity
  - Dominant uncertainties:
    - flavor difference
    - parton corrections
    - QCD bg
    - proton fragments
    - 2^{nd} jet extrapolation



CMS PAS JME-10/010

MET

- **Missing transverse momentum** is defined as vectorial momentum imbalance in the transverse plain (with magnitude **MET**)
- Three major algorithms to reconstruct MET at CMS
  - **Calo MET:** based on calorimeter energy deposits
  - **Track corrected MET:** Replacing calorimeter deposits from charged hadrons by matched tracks
  - **Particle Flow MET:** identify stable particles using all subdetectors prior to MET calculation (or jet clustering)

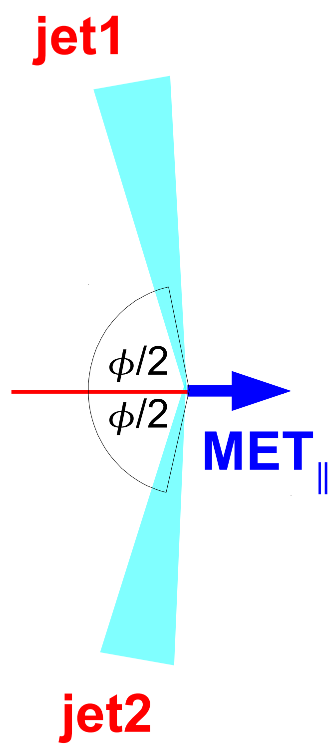


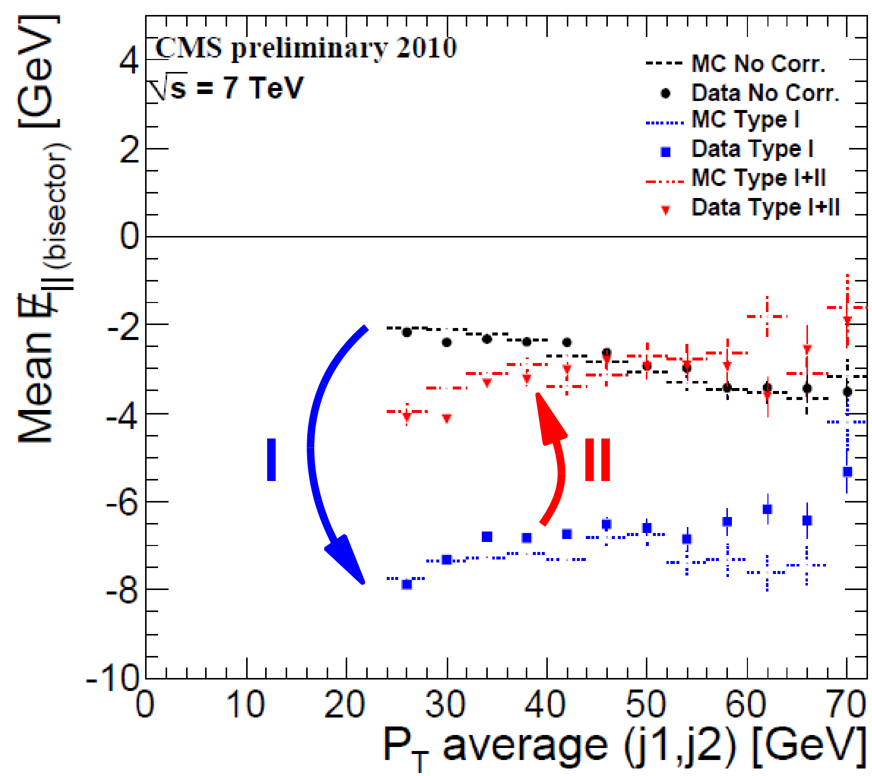
CMS PAS JME-10/004

→ **Careful noise cleaning of MET tails needed**

MET corrections:

- **Type I:** Replace calorimeter deposits clustered in jets by corrected jets; for diJets: introduces bias of MET $\parallel$ to jet bisector axis
- **Type II:** Additional correction from unclustered energy or jets below threshold; determined from MC or from data (e.g. $Z \rightarrow ll$)

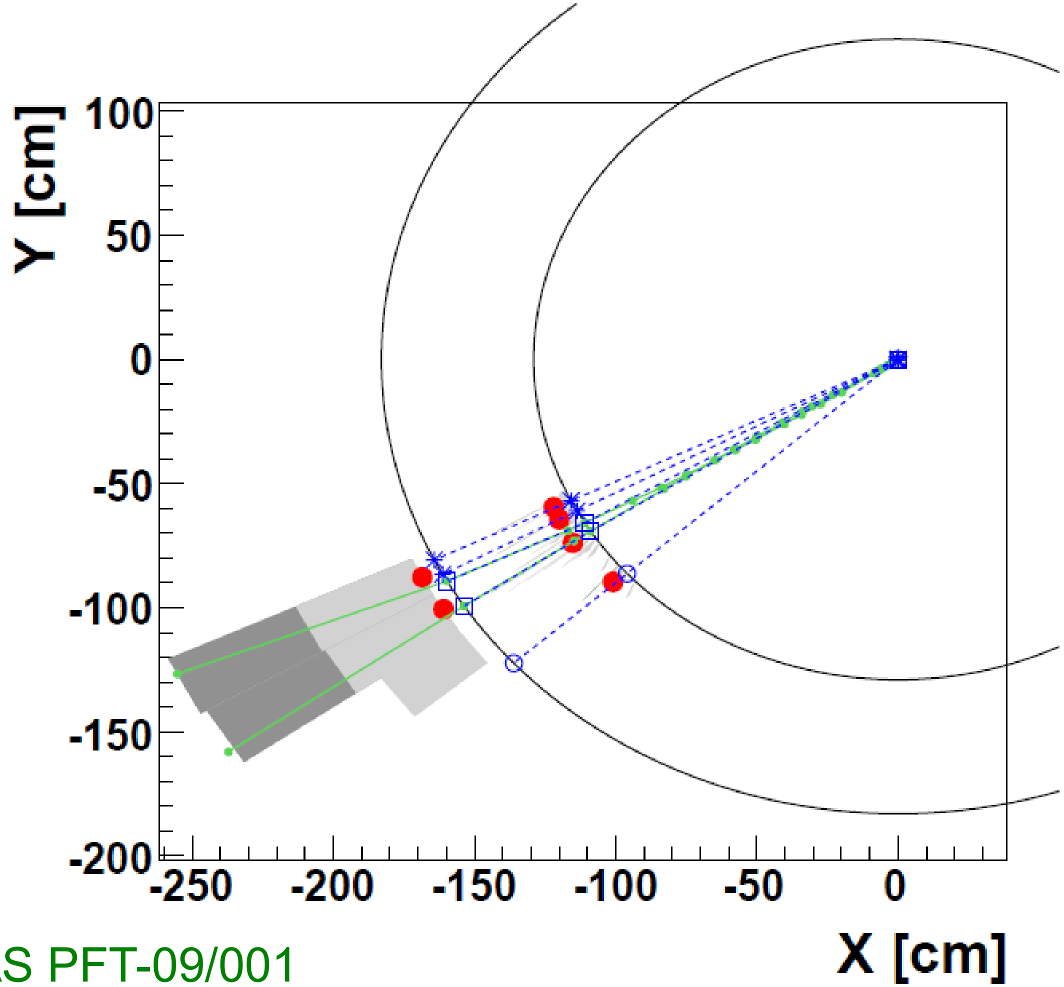


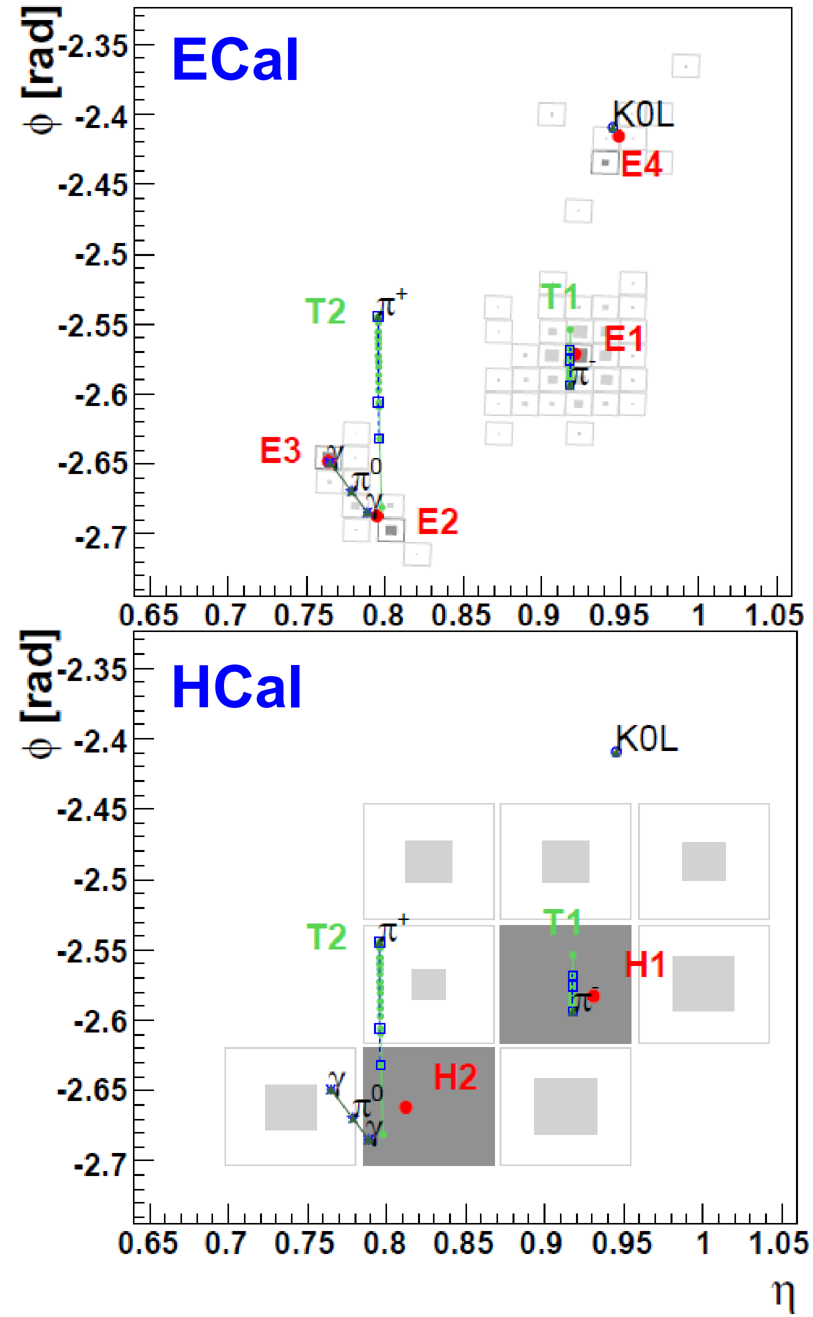


CMS PAS JME-10/004

Particle Flow

Identification of all stable particles (electrons, photons, muons, charged and neutral hadrons) **by combination of all subdetectors** prior to jet clustering

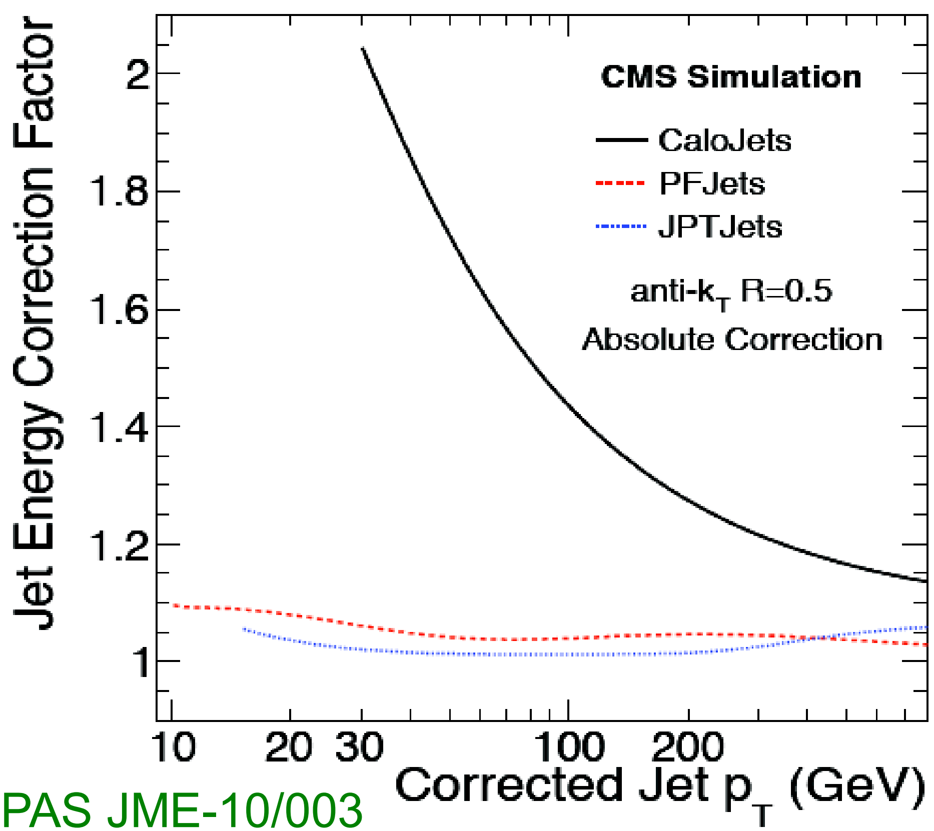


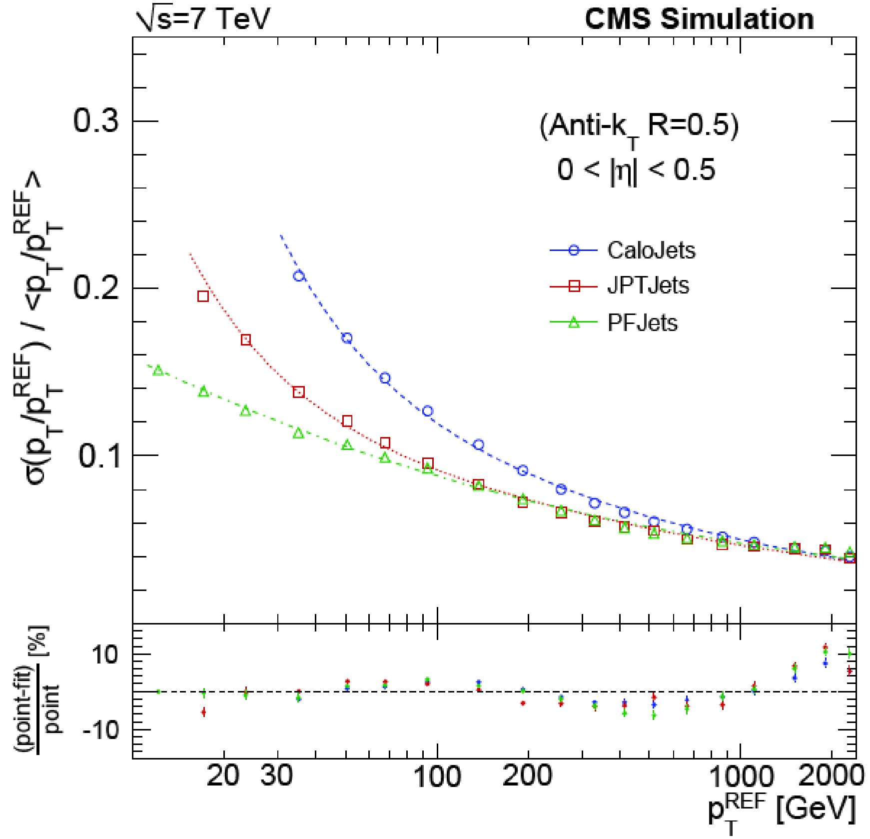


CMS PAS PFT-09/001

Particle Flow – Jets

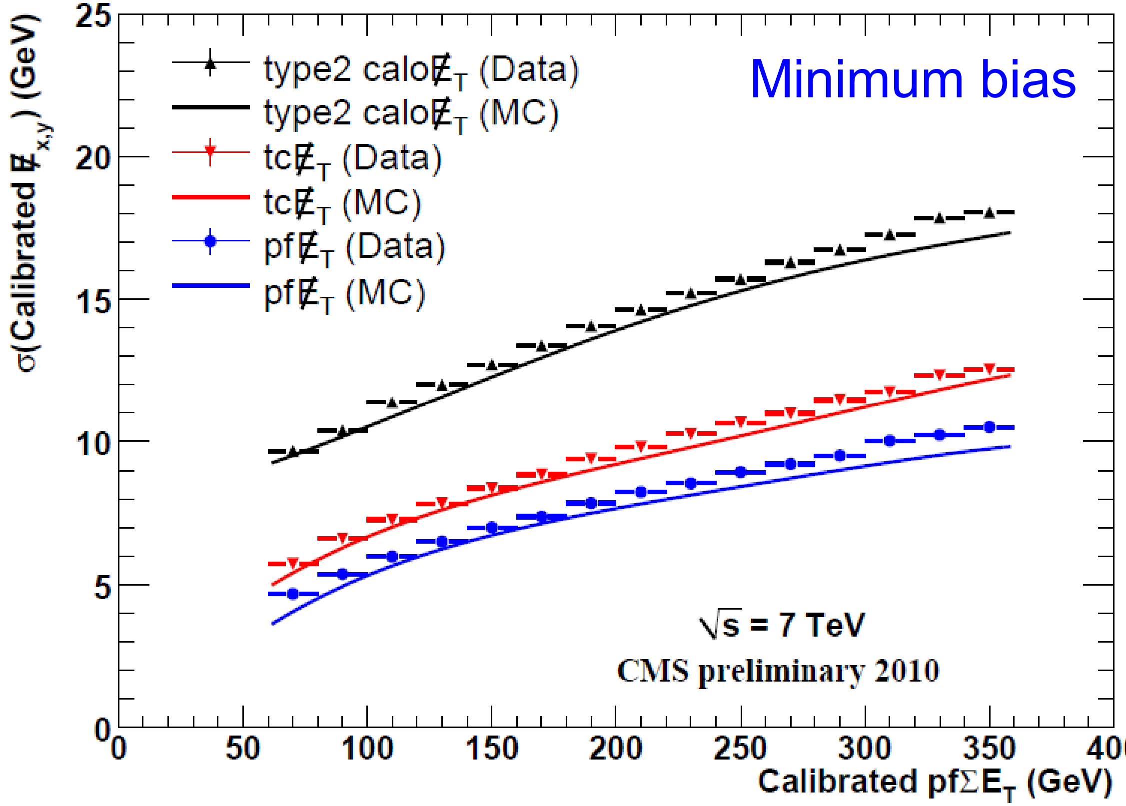
- Cluster PF candidates in anti-k_T jets
- Reduced absolute scale dependence due to an extra cluster calibration applied during the PF algorithm
- Improvement of p_T resolution due to precise tracker measurements → no improvement in the very forward region

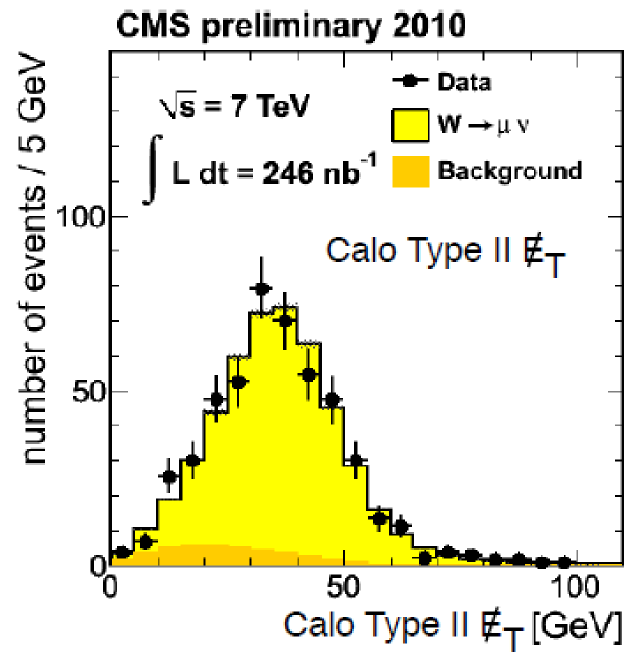


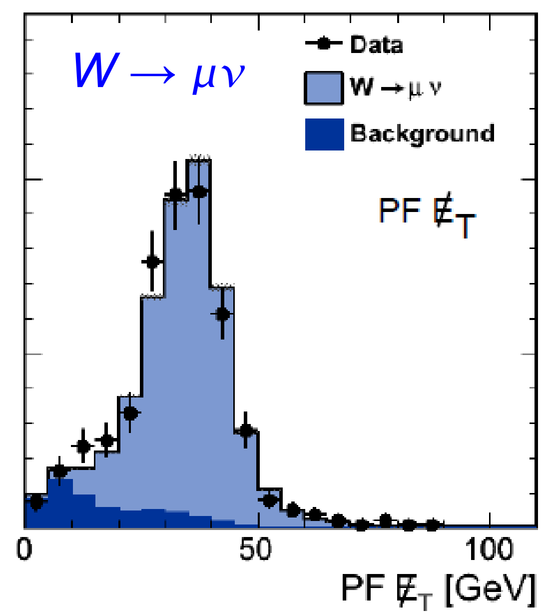


CMS PAS JME-10/003

Particle Flow – MET



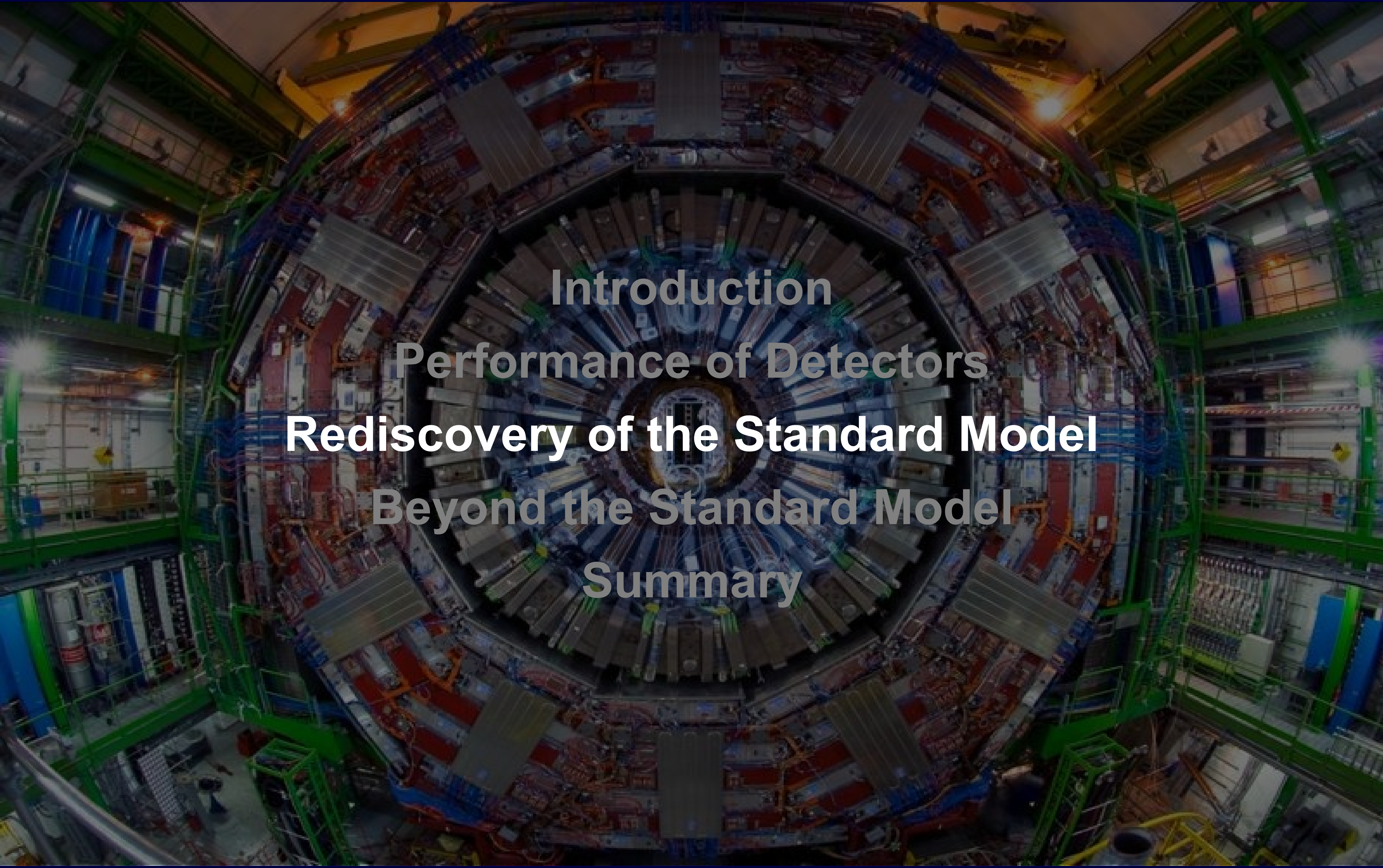




MET from all PF candidates shows superior resolution with respect to calorimeter MET

CMS PAS JME-10/004 & JME-10/005

Outline



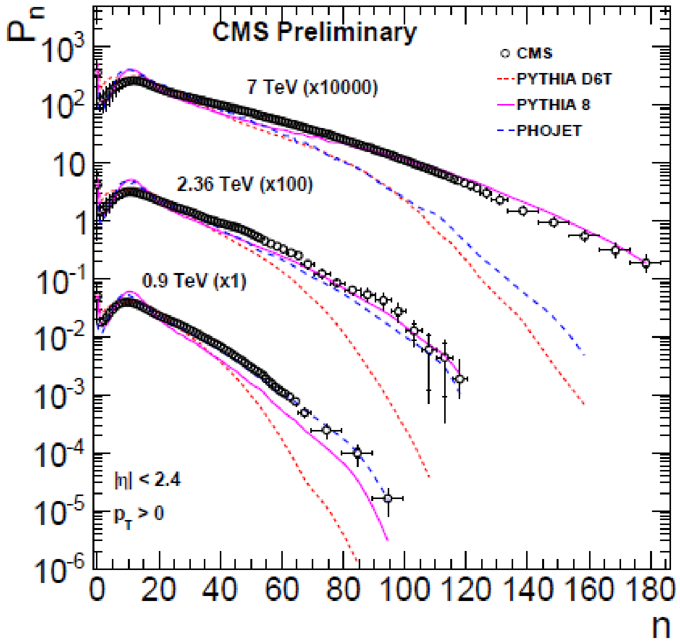
Introduction

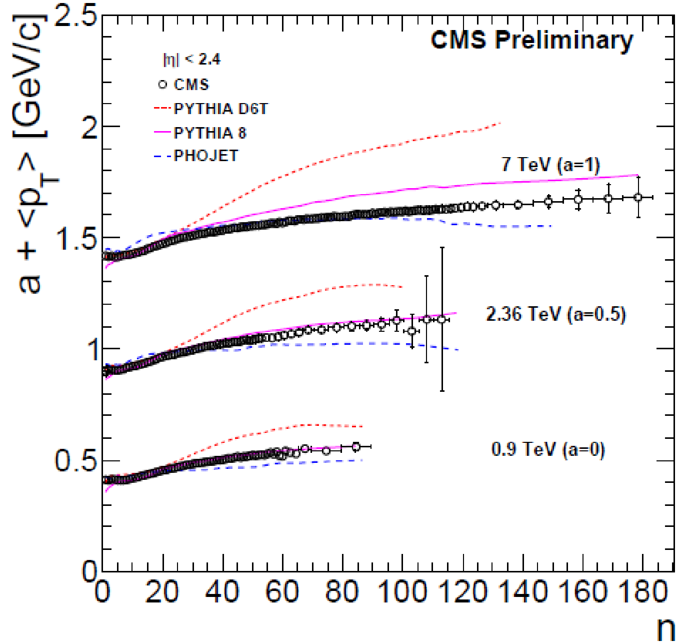
Performance of Detectors

Rediscovery of the Standard Model

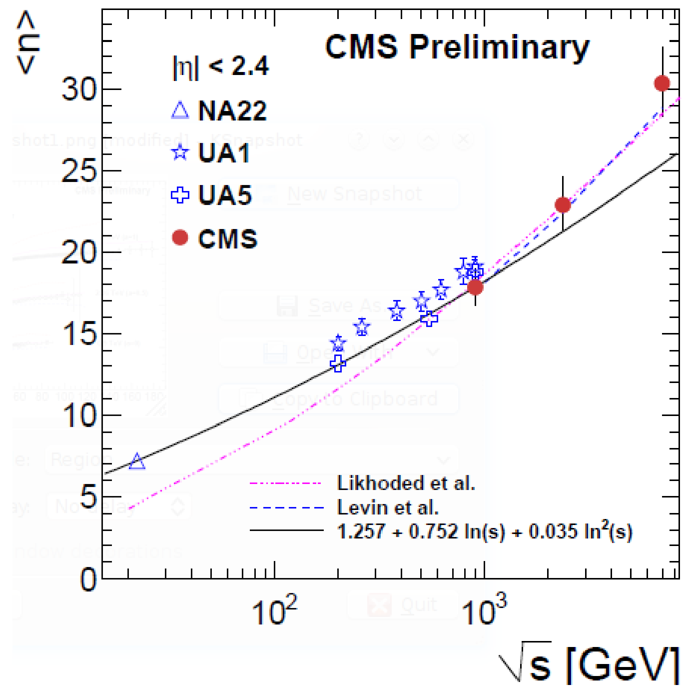
Beyond the Standard Model

Summary





- Rise of particle density in data stronger than in model predictions
- Reduced impact on high p_T physics



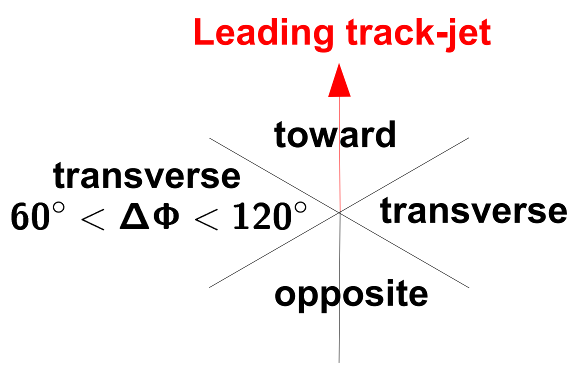
Measurement at 900 GeV, 2.36 TeV and 7 TeV:

- Scaling of particle multiplicity $\langle n \rangle$ and average momentum $\langle p_T \rangle$ tests soft QCD
- All tested models fail to describe n and $\langle p_T \rangle$ distributions at all $\sqrt{s}$ (too few low momentum particles)

→ MC generator tuning

CMS PAS QCD-10-004

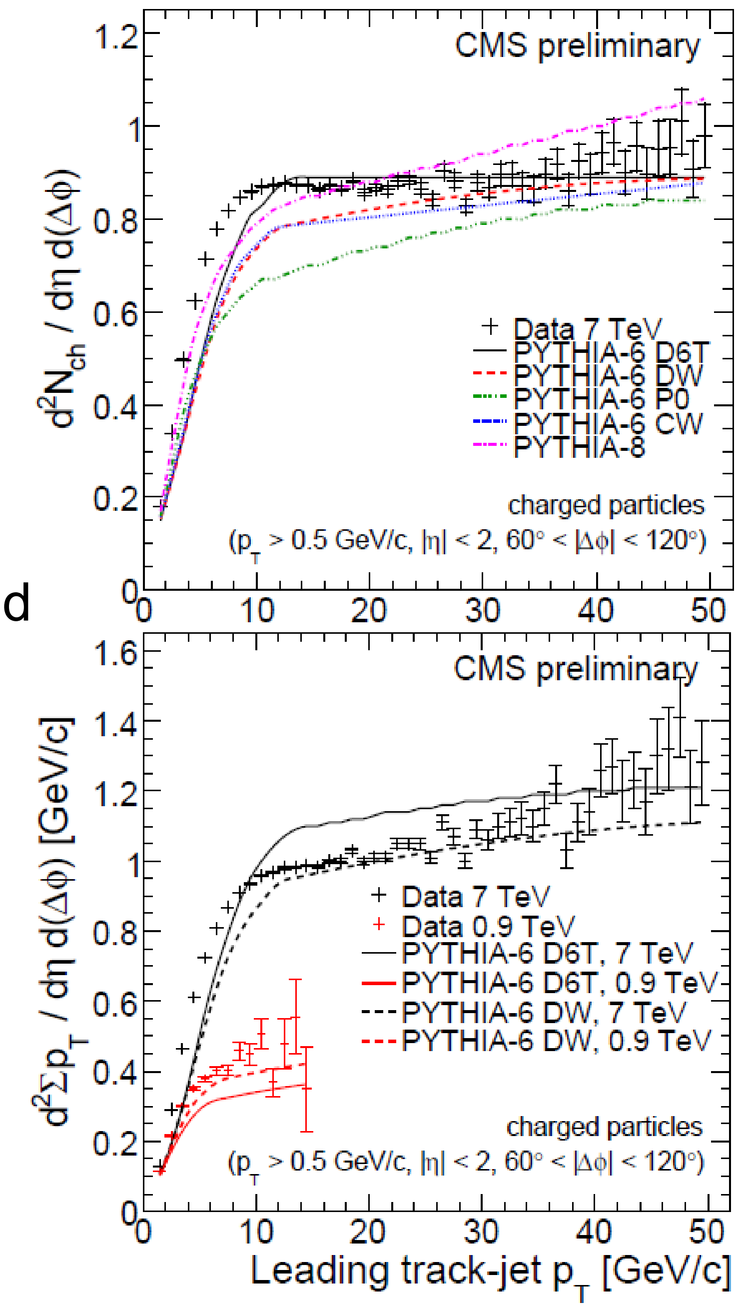
Underlying Event



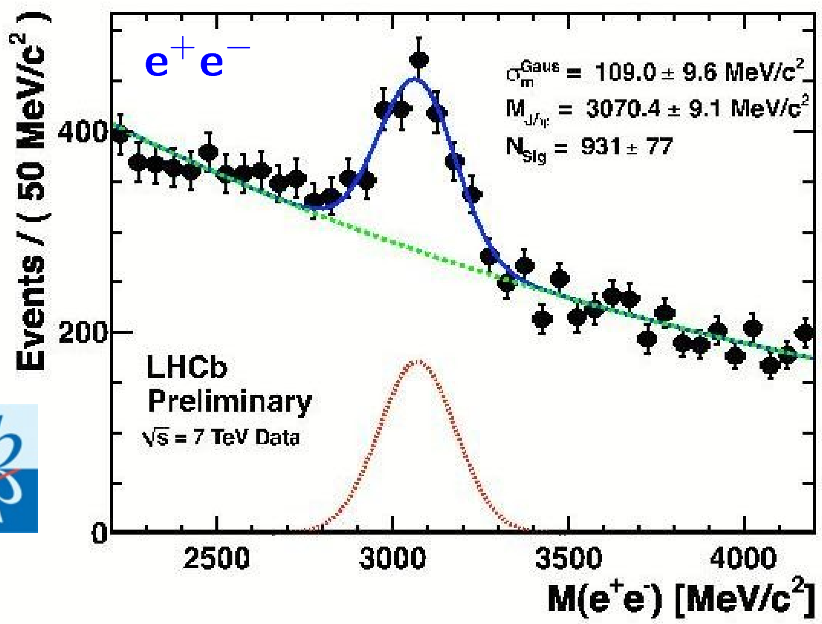
- Underlying event (UE) = multiple particle interaction (MPI) + beam-beam remnants (BBR)
- New 7 TeV data essential for understanding of UE and MPI at high scales (relevant for SM precision measurements and searches)
- UE expected to increase with scale of leading parton (smaller impact angles) and $\sqrt{s}$ (increasing parton densities at given scale)
- Tested models underestimate track multiplicity and Σp_T at low leading jet p_T

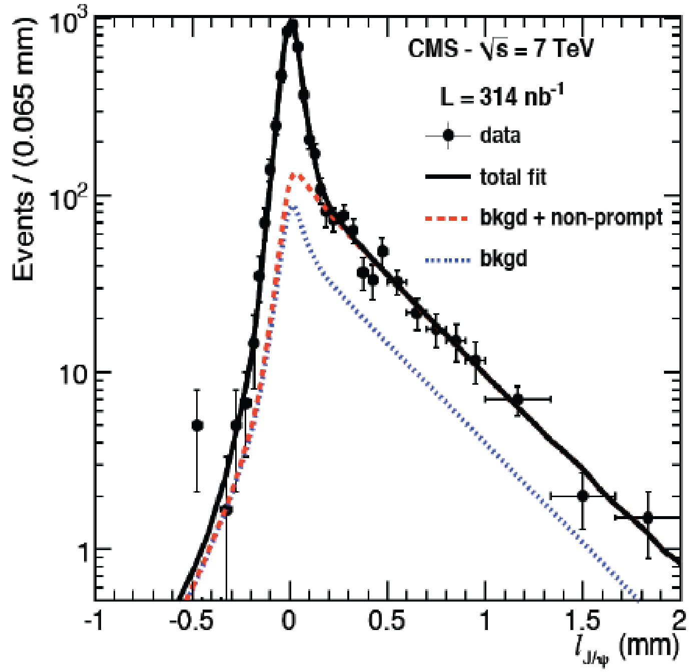
→ MC generator tuning

CMS PAS QCD-10-005



J/ψ Production





$6.5<p_T<10$ GeV/c, $1.6<|y|<2.4$

- J/ψ reconstruction in μ and e channel
- Total cross section for inclusive production in μ channel:

$$\mathbf{Br(J/\Psi \to \mu^+\mu^-) \cdot \sigma(pp \to J/\Psi + X) = (289.1 \pm 16.7(stat) \pm 60.1(syst))\ nb}$$

- Unbinned ML fit to transverse decay length to **disentangle prompt** (direct or decay from heavier charmonium states) **and secondary production** (*B* hadron decays)
- Cross section for non-prompt production in μ channel:

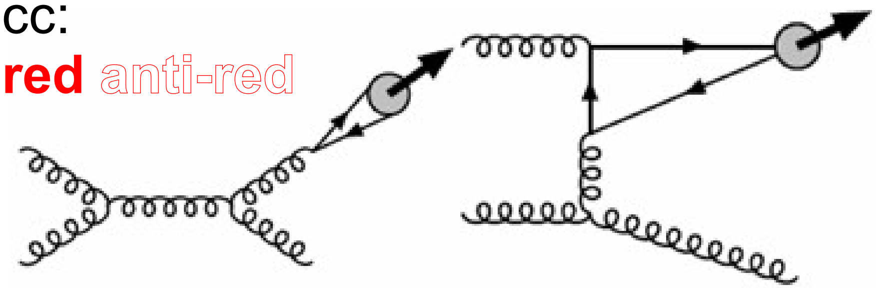
$$\mathbf{Br(J/\Psi \to \mu^+\mu^-) \cdot \sigma(pp \to Y \to J/\Psi) = (56.1 \pm 5.5(stat) \pm 7.2(syst))\ nb}$$

CMS PAS BPH-10/002

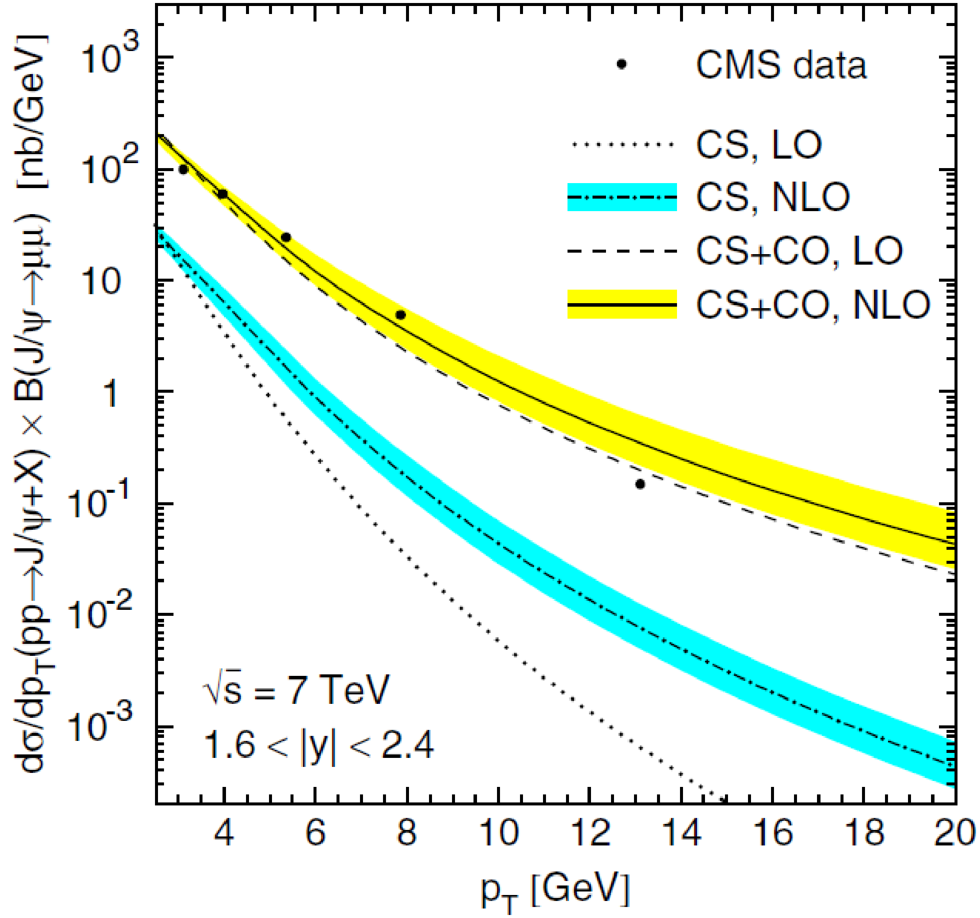
J/ψ Production

Tevatron: J/ψ production cross section larger than predicted by color singlet (CS) processes (confirmed by LHC experiments)

$c\bar{c}$:
red anti-red

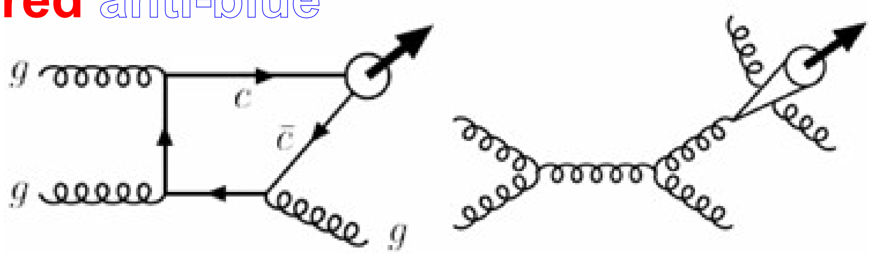


Butenschoen, Kniel 10



Way out: Additional color octet (CO) processes → "splitting out of unwanted color" via soft gluons

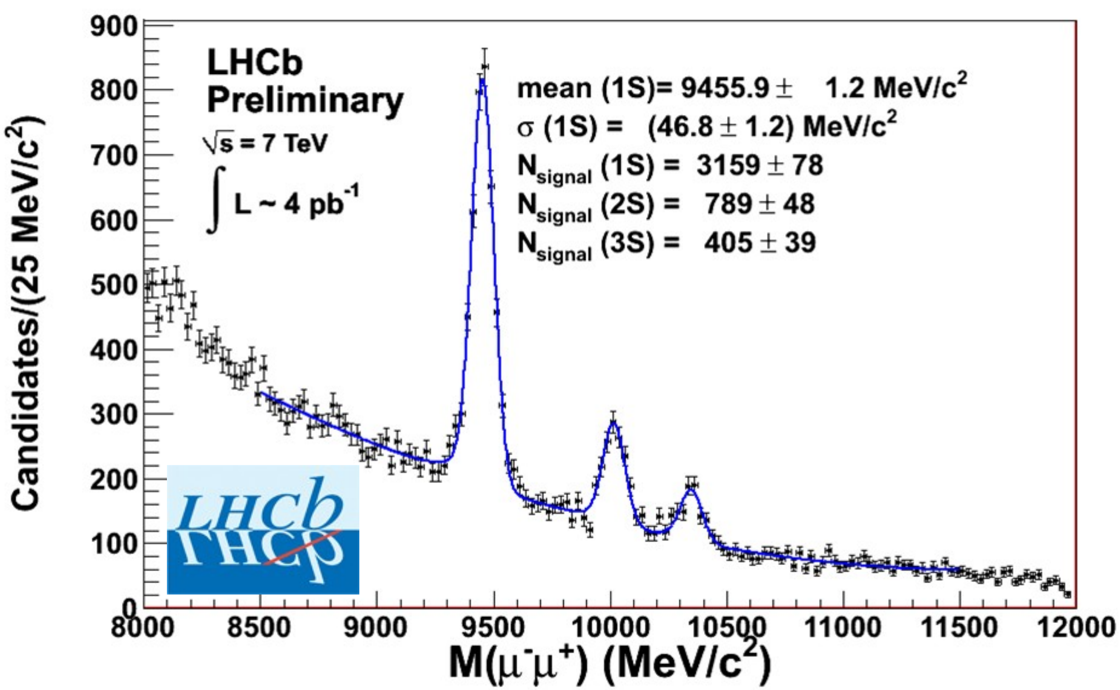
$c\bar{c}$:
red anti-blue

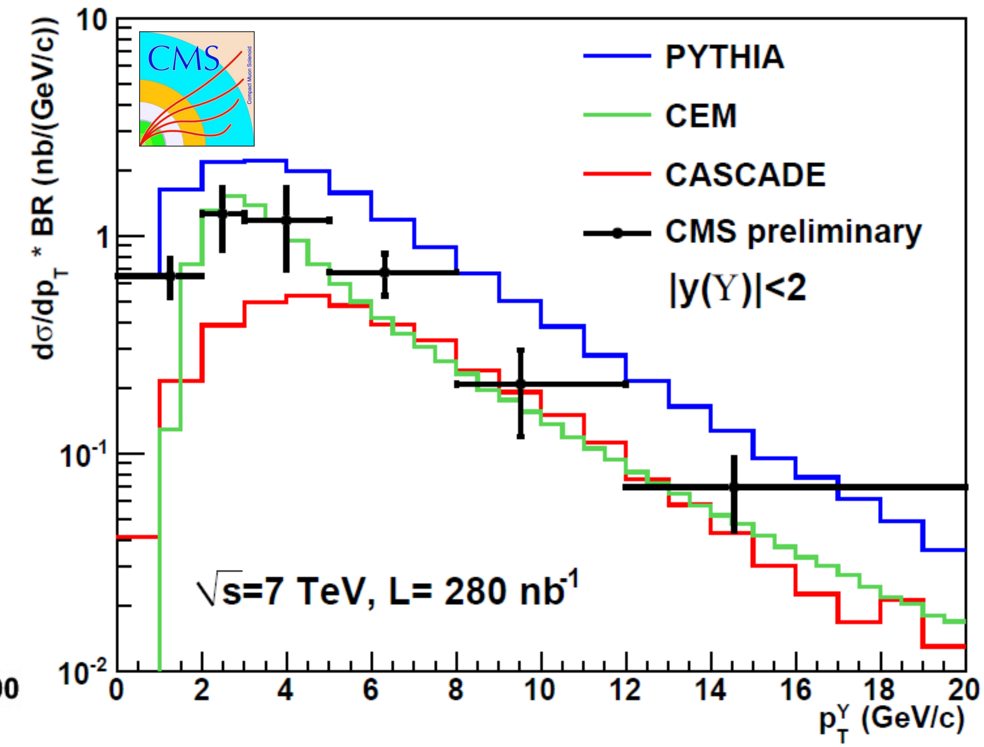


Onia – Υ Production

- Υ(1S), Υ(2S) and Υ(3S) identified and resolved
- Differential cross section measured and compared with theoretical predictions

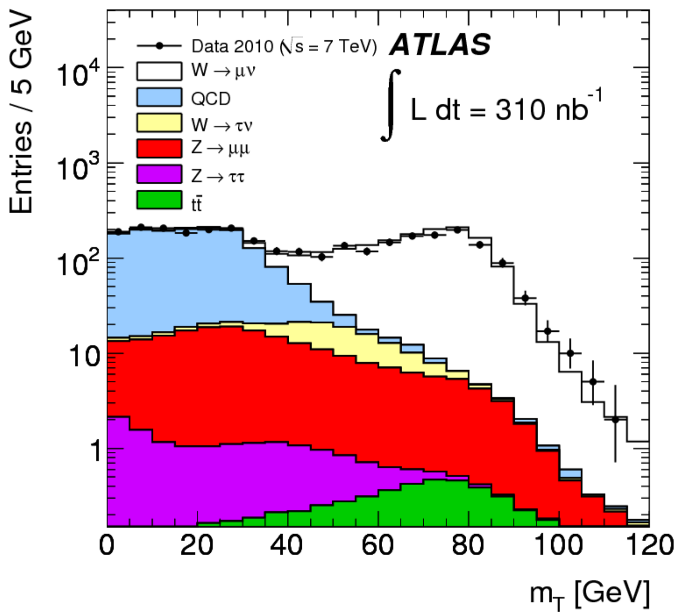
  → Uncertainties large, but some tension between experimental measurement and different models

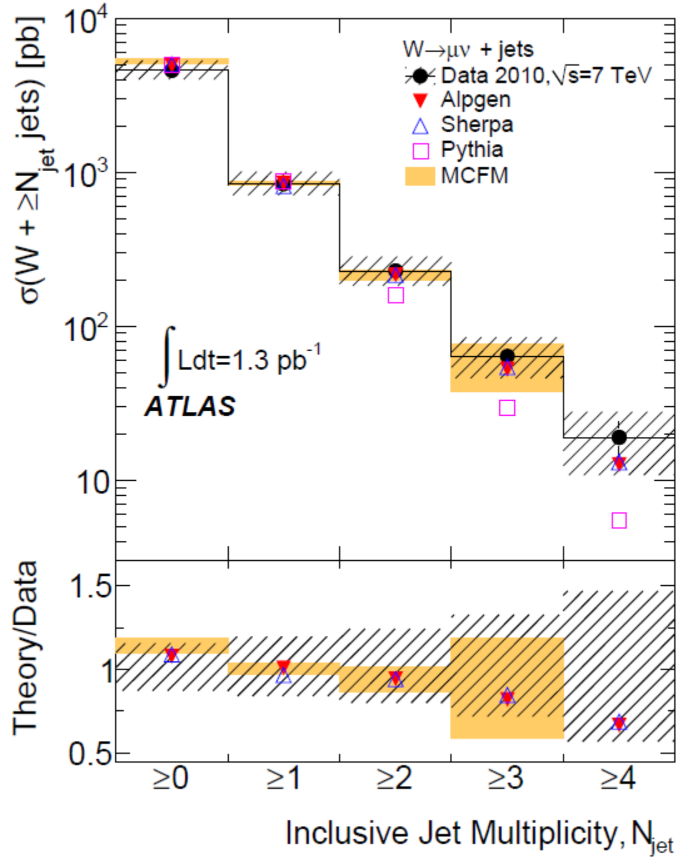


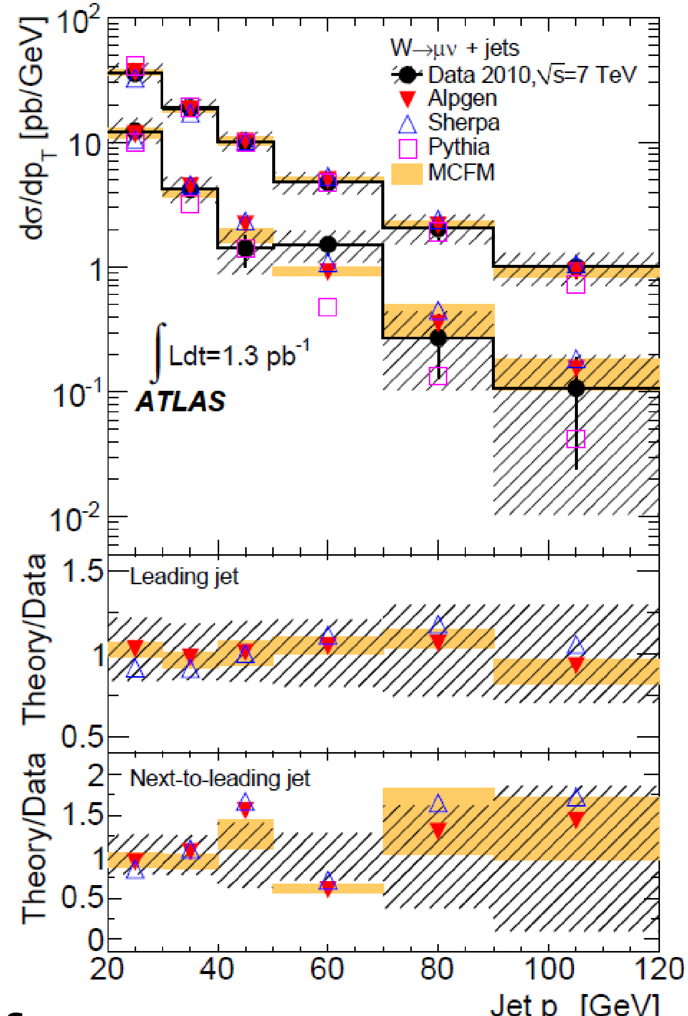


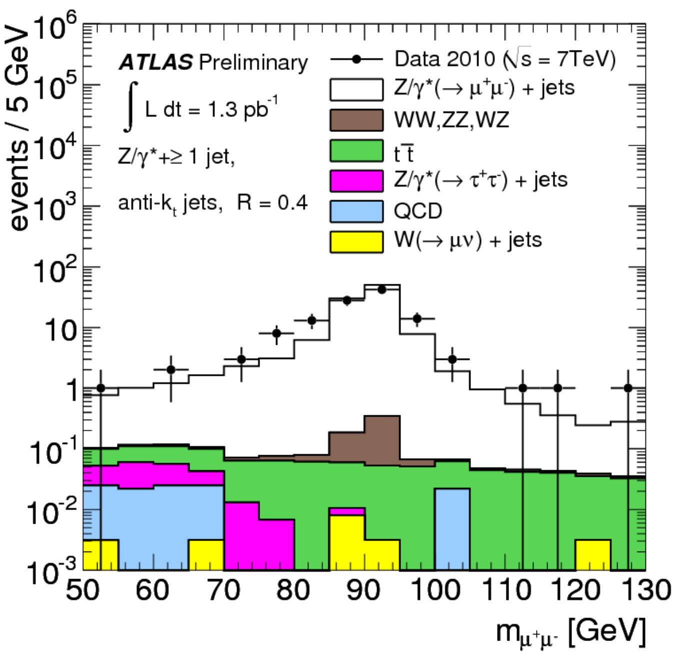
CMS PAS BPH-10-003

Electroweak Physics





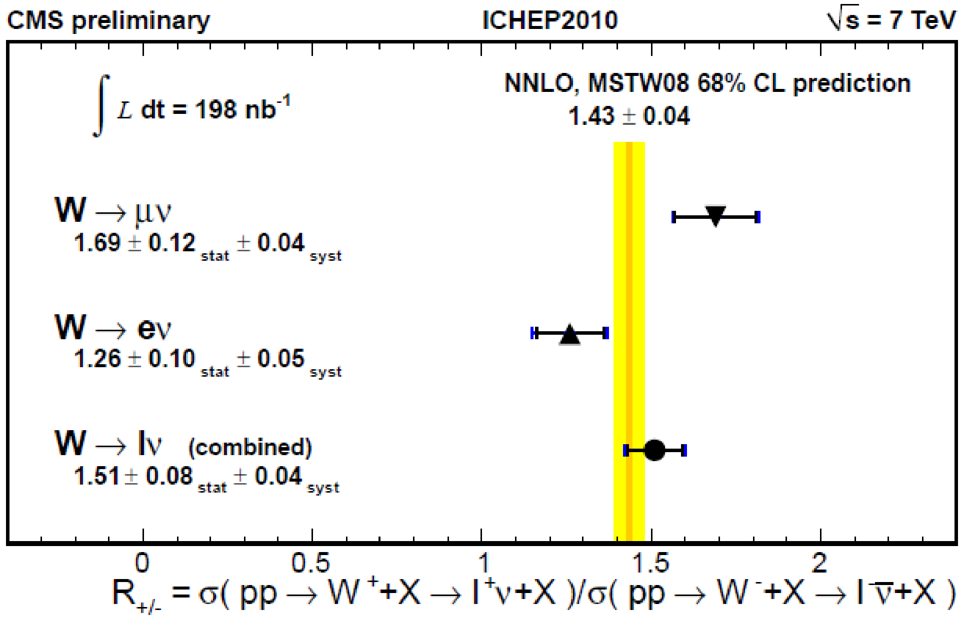


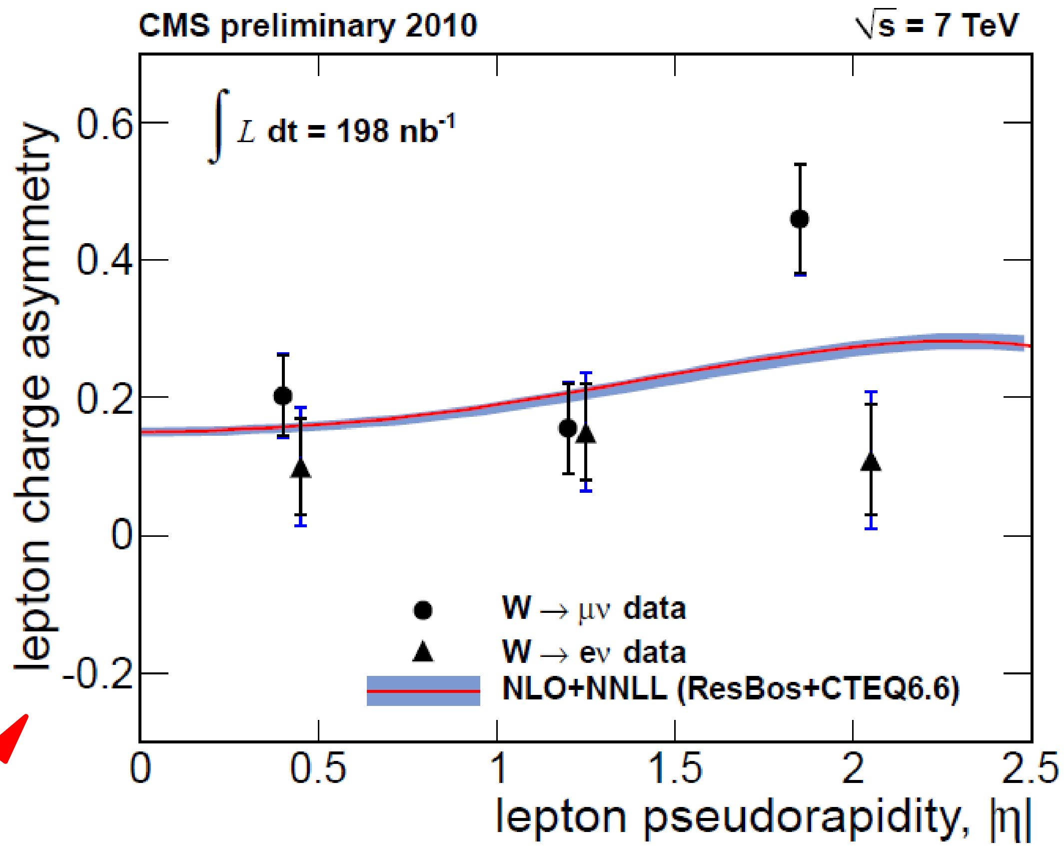


Measurement of *W / Z* cross sections important for:

- Calibration of detectors
- Backgrounds for Top/Higgs/BSM analyses
- Precision measurements of SM parameters

W^+/W^- Charge Asymmetry





$$\mathbf{A}(\eta) = \frac{\mathbf{d}\sigma^{(+)}/\mathbf{d}\eta - \mathbf{d}\sigma^{(-)}/\mathbf{d}\eta}{\mathbf{d}\sigma^{(+)}/\mathbf{d}\eta + \mathbf{d}\sigma^{(-)}/\mathbf{d}\eta}$$

Different parton content in protons (up, down)

- ➔ Charge dependent production cross section
- ➔ Lepton charge asymmetry as function of η
- ➔ **Constraints on pdfs expected with 10 pb^{-1}**

CMS PAS EWK-10-002

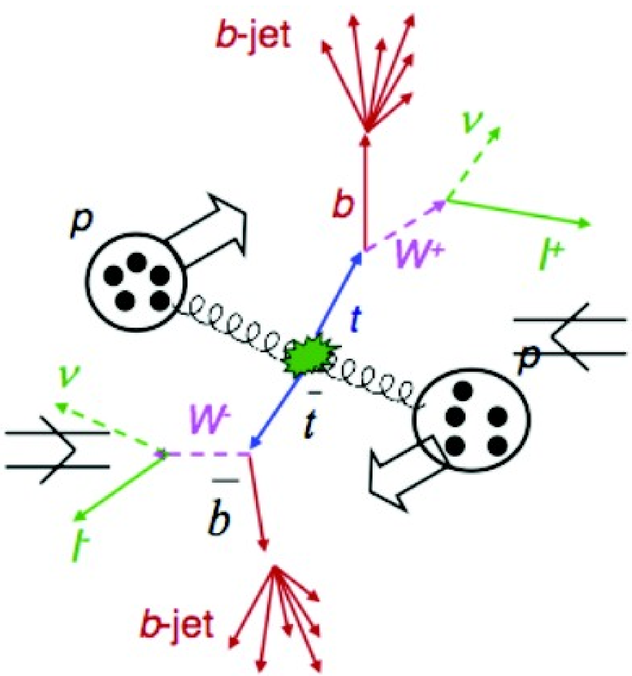
Top

The LHC is a top factory (already >6000 top evts at CMS/ATLAS)

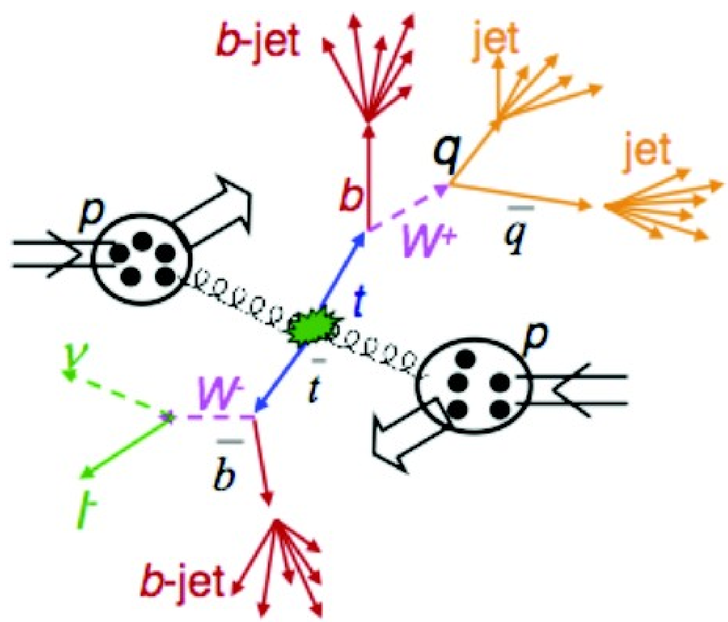
Clear signature: leptons, b-tags, MET

Properties:

- Spin = 1/2, q = +2/3 *e* (?), m = 172.0±2.2 GeV
- Yukawa coupling h_{top}~1 (big contributions to radiative corrections of Higgs mass)
- Short lifetime ($\tau \approx 5 \cdot 10^{-25}$ s); decay before hadronization; polarization of $W^{\pm}$
- …

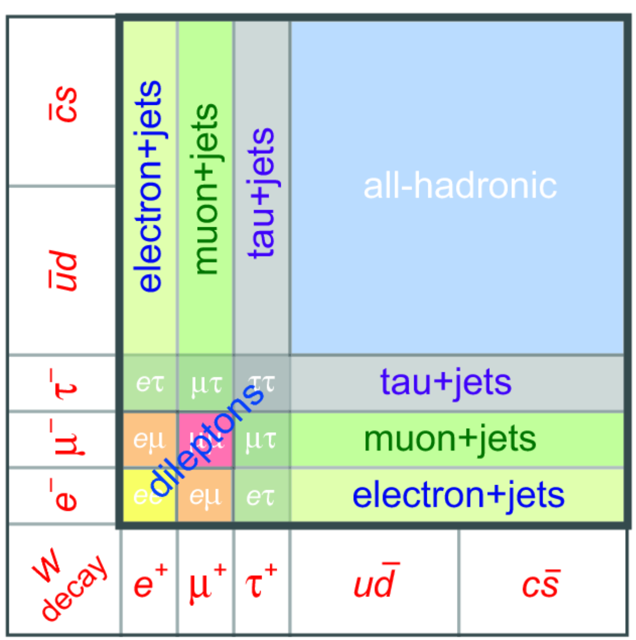


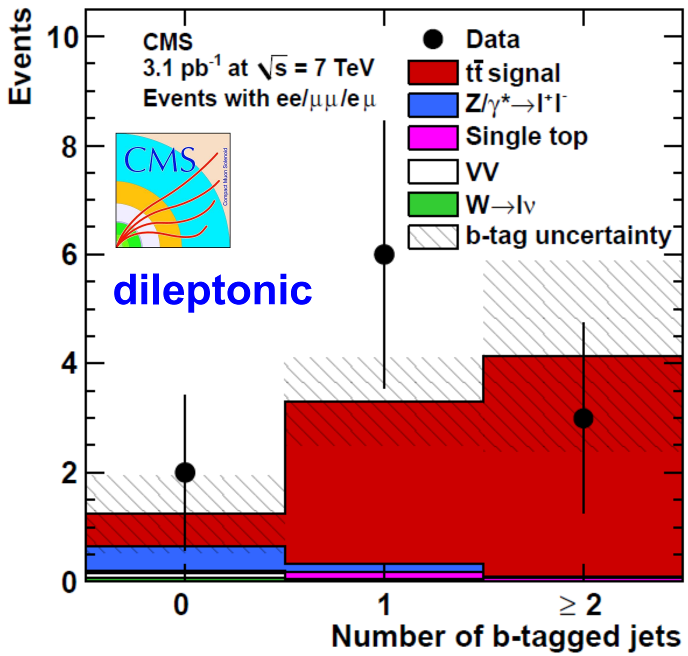
di-leptonic decay

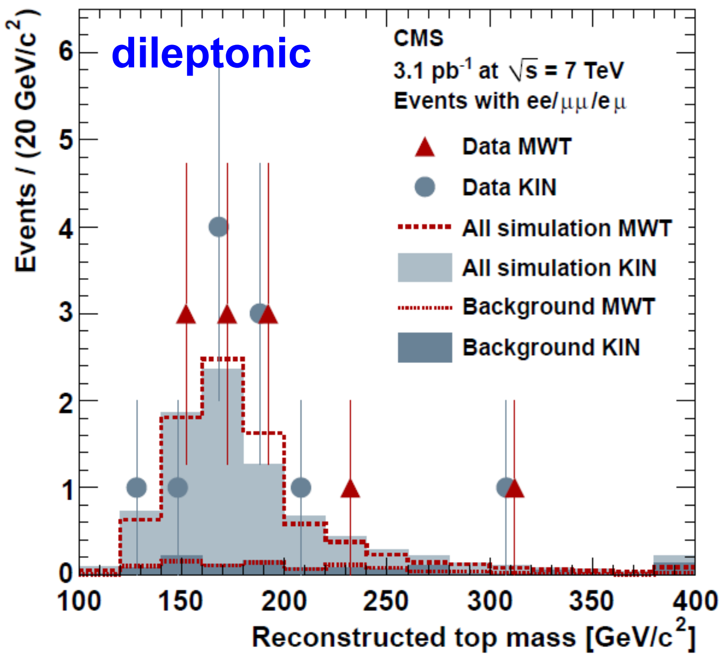


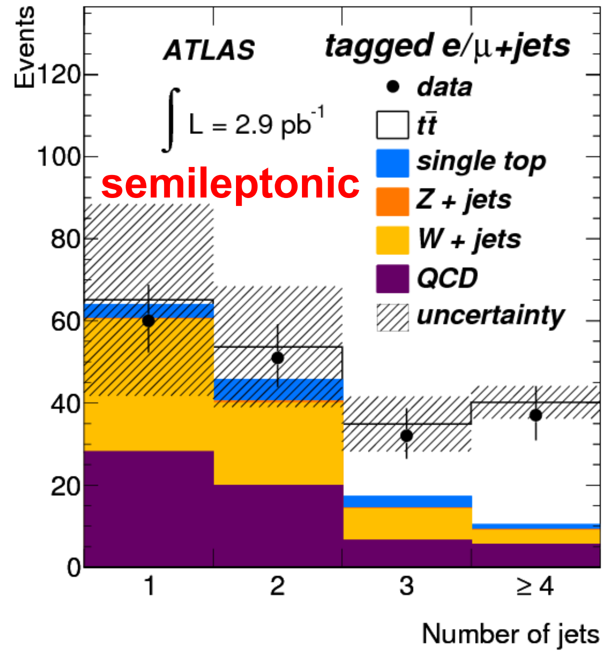
semi-leptonic decay

Top Pair Decay Channels









Cross section measurements

- Dileptonic channel (CMS)

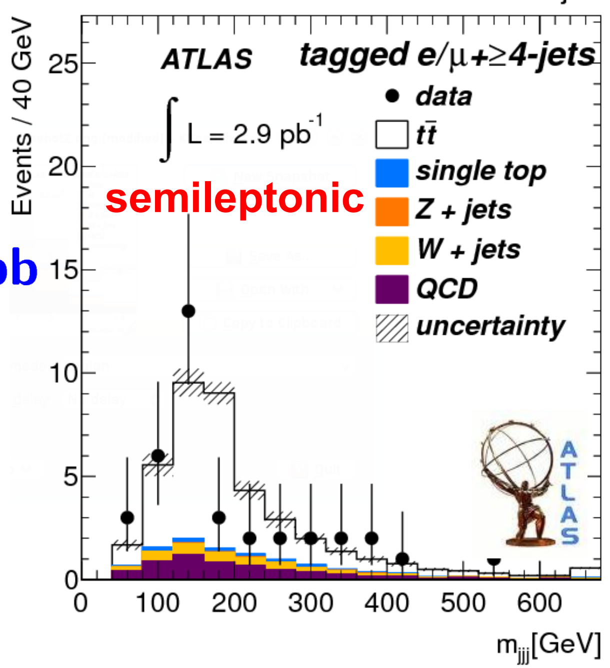
$$\sigma(pp \to t\bar{t} + X) = 194 \pm 72(\text{stat}) \pm 24(\text{syst}) \pm 21(\text{lumi})\ \text{pb}$$

- Semileptonic channel (ATLAS)

$$\sigma(pp \to t\bar{t} + X) = 145 \pm 31(\text{stat})^{+42}_{-27}(\text{syst})\ \text{pb}$$

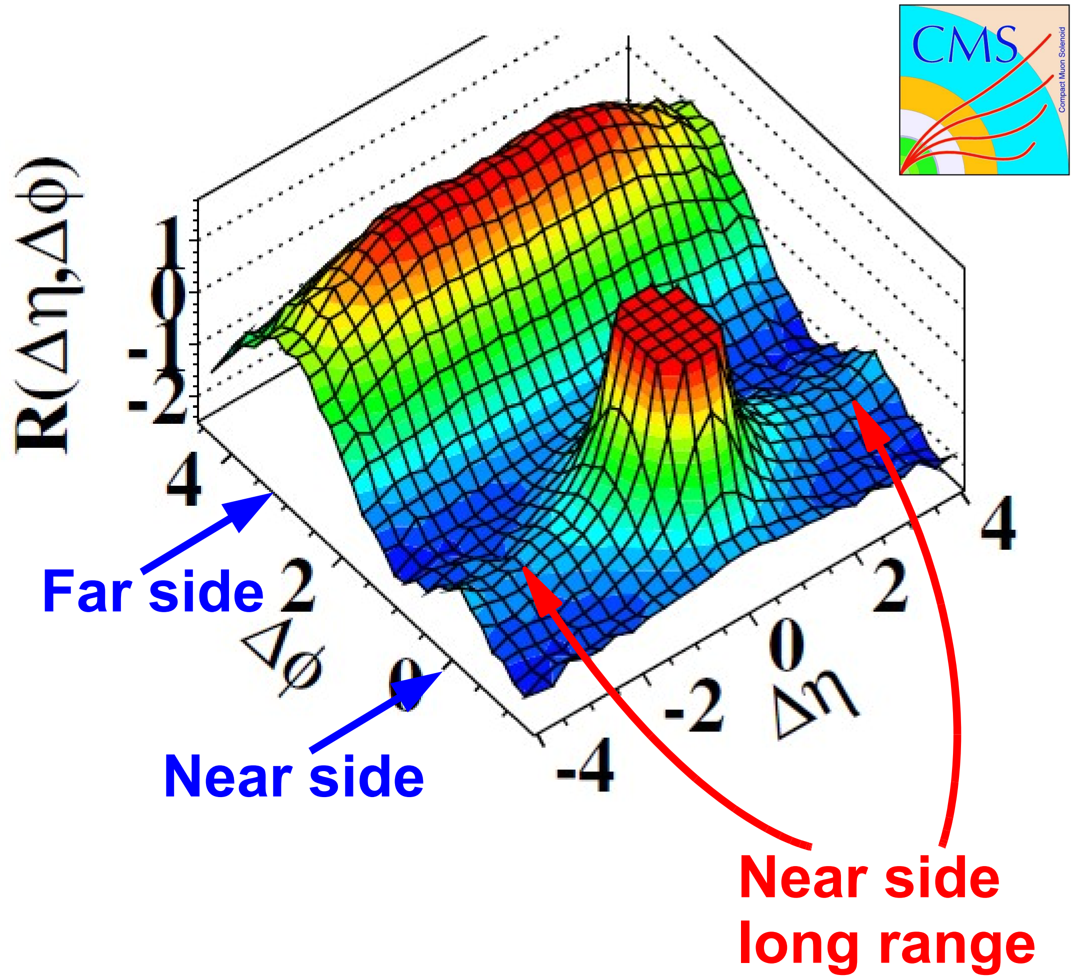
- Compared to theory [Langenfeld, Moch, Uwer 09]

$$\sigma(pp \to t\bar{t} + X) = 164.6^{+11.4}_{-15.7}\ \text{pb}$$



The Ridge

- Angular correlation in pp events at 7 TeV with high track multiplicity
  - 1 GeV < track p_T < 3 GeV
  - N_{tracks} > 110
- Ratio ***R*** of signal (same event pairs) and bg (different event pairs)
- Jet peak and back-to-back structure visible

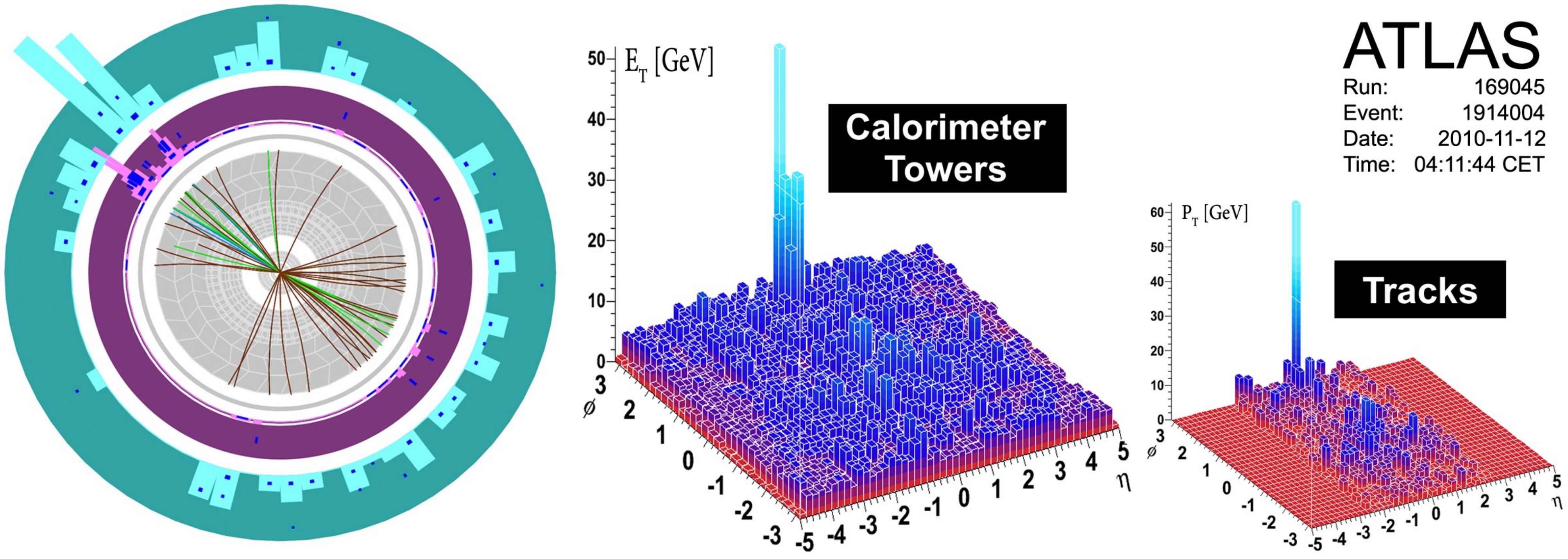


→ Structure at near side long range reassembles Bose-Einstein correlation observed in AuAu collisions at RHIC

JHEP 1009:091 (2010)

Heavy Ions – “Jet Quenching”

- New diJet asymmetry observed (increasing with centrality)
- Not observed in pp collisions



- **Possible interpretation:**

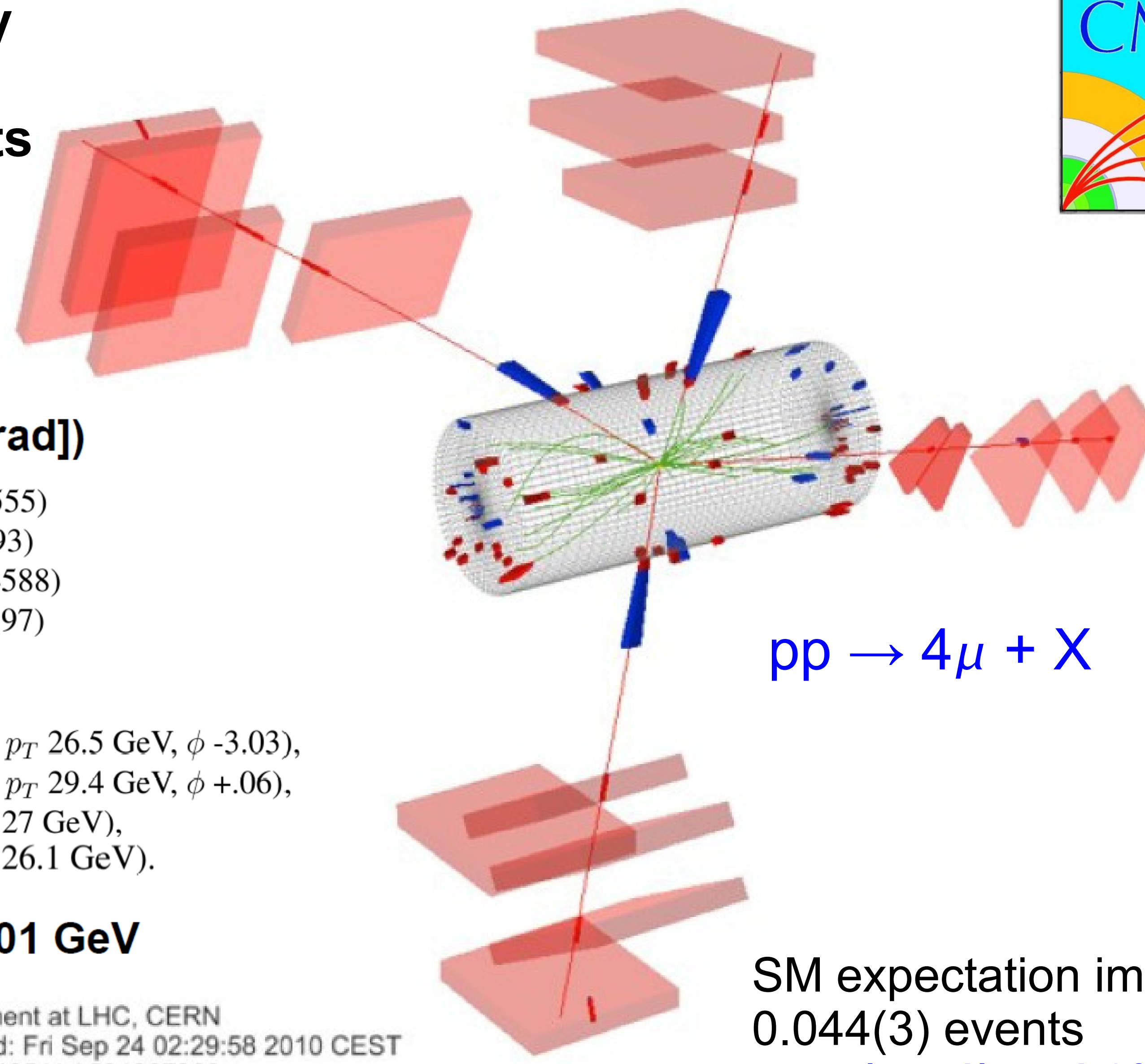
Strong jet energy loss in hot dense medium

CERN-PH-EP-2010-062

WW / *WZ* / *ZZ* or Higgs Physics?

Integrated Luminosity still small for cross section measurements

However, some exciting candidates!



Muons (p_T [GeV], η, φ [rad])

μ_0^-(48.1422, -0.412532,-1.92555)
μ_1^+(43.4421, 0.204654, 1.79493)
μ_2^+(25.8769, -0.782084, 0.774588)
μ_3^-(19.5646, 2.01112, -0.980597)

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

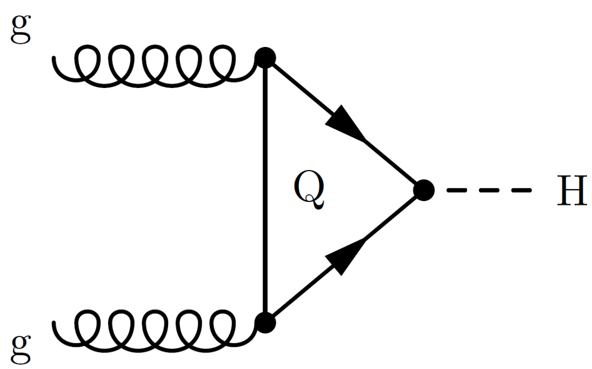
Invariant Mass of 4μ: 201 GeV

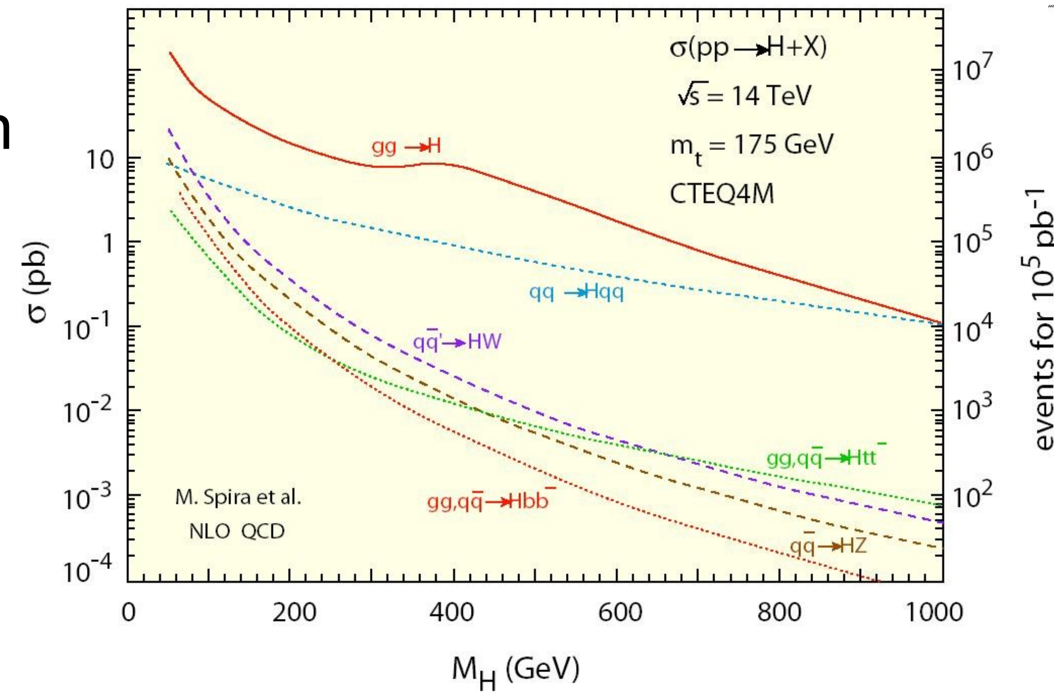
$pp \rightarrow 4\mu + X$

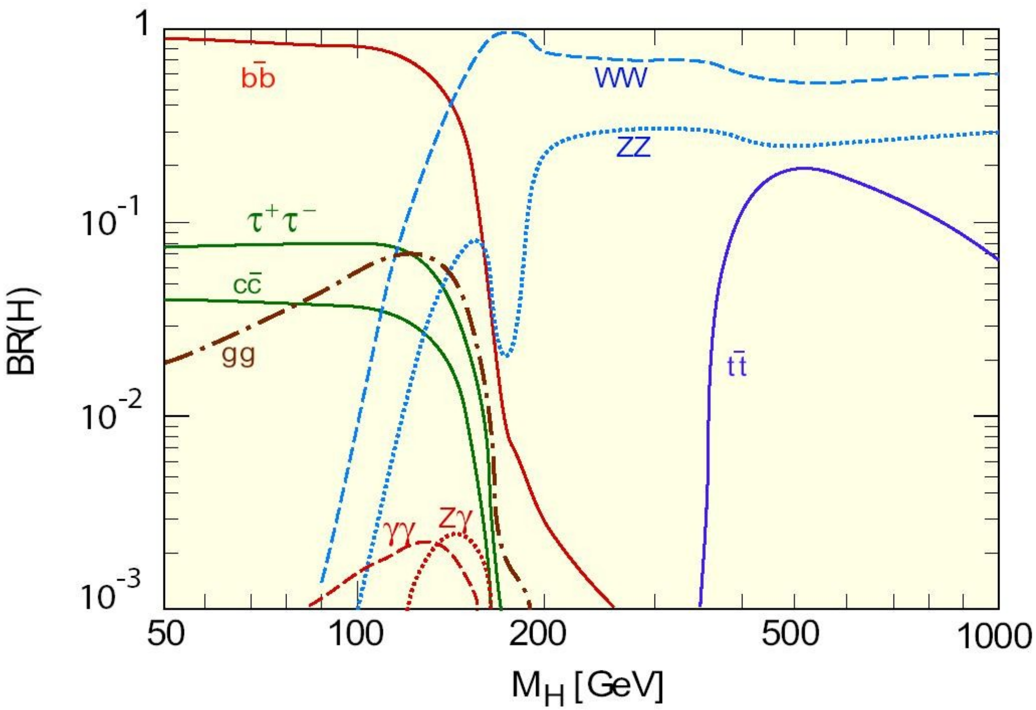
SM expectation im 7/pb:
0.044(3) events
prob(N≥1) ≈ 4.2%

Standard Model Higgs

Dominant production cross section at LHC: gluon-gluon fusion







Branching ratio is fuction of M_H

→ **Many different search channels**

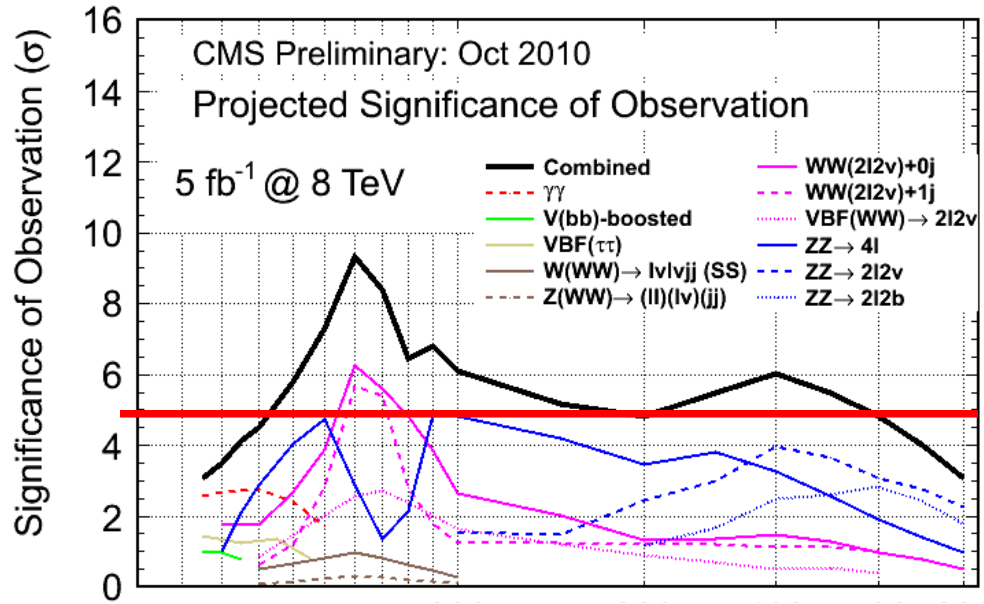
Higgs in 2011/12

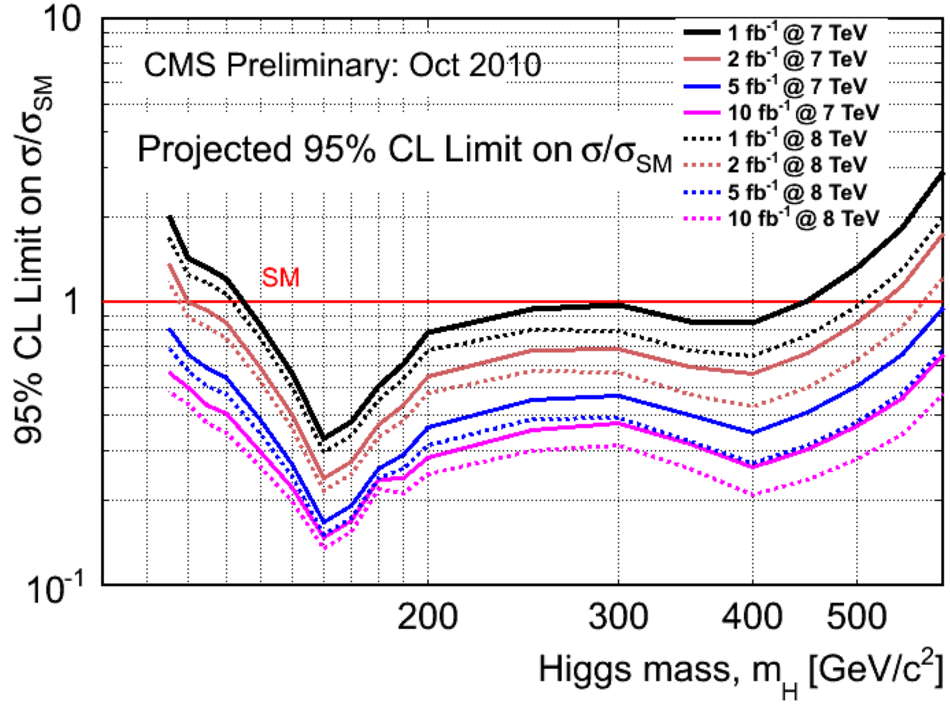
Low m_H region most challenging:

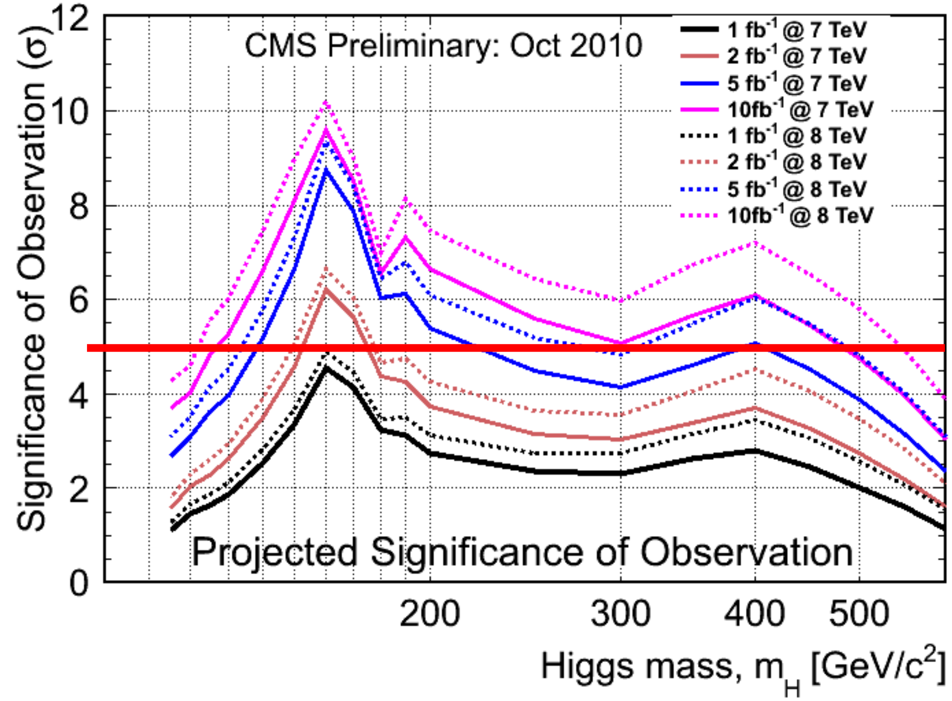
$H \rightarrow \gamma\gamma$: small cross section, but clear signature at CMS

5 fb^{-1}@7 TeV: exclusion at 95% CL over total mass range

10 fb^{-1}@7 TeV: discovery potential down to m_H ~ 130 GeV







Outline

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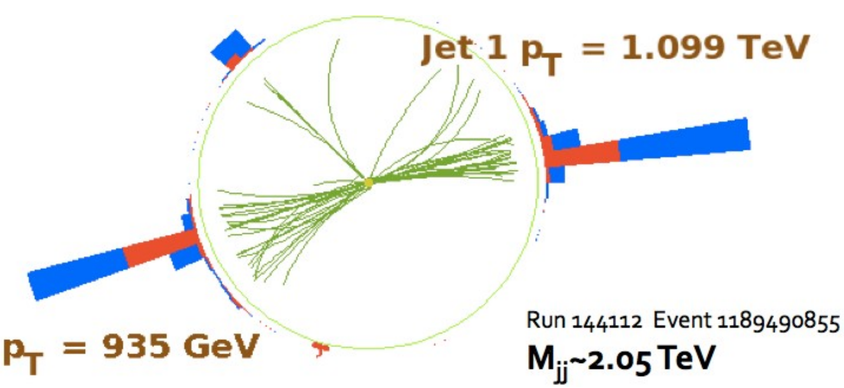
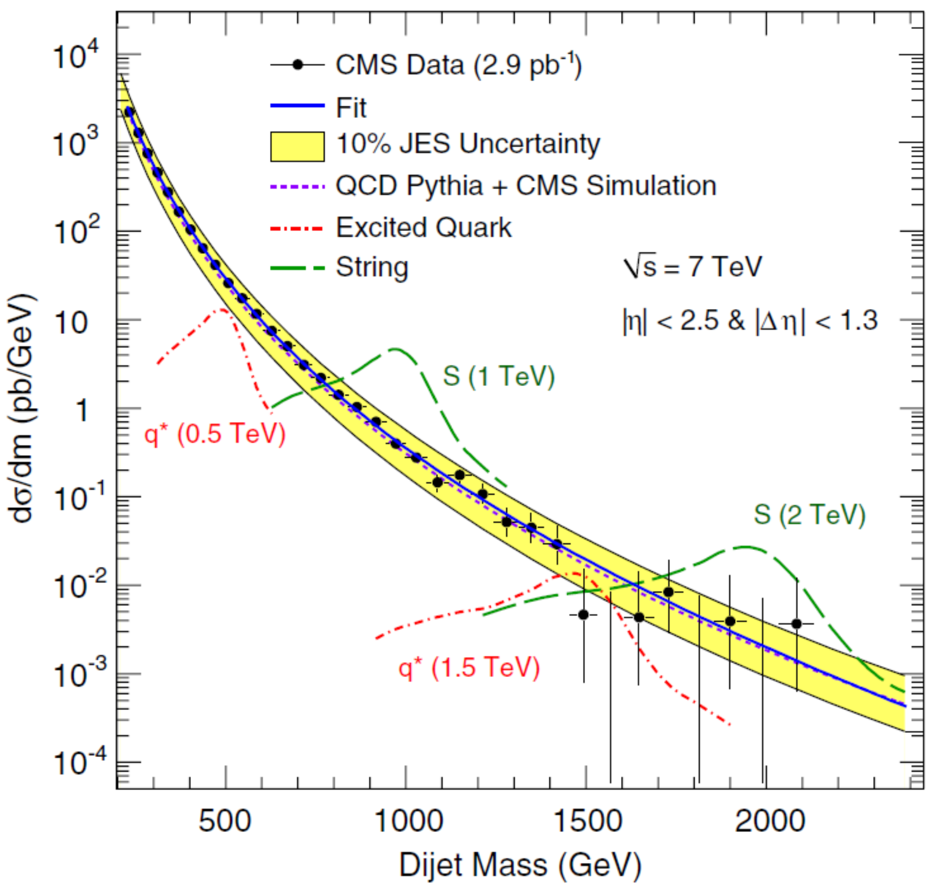
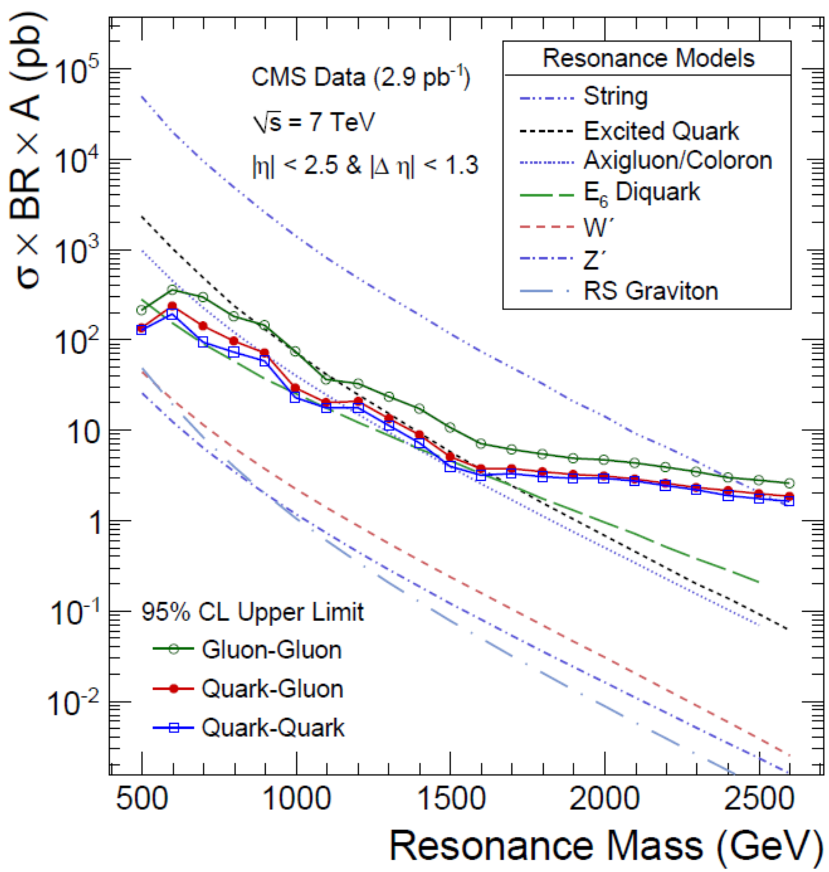
DiJet Resonances

Many extensions of the SM predict heavy particles coupling to quarks or gluons → Resonances in diJet invariant mass spectrum

LHC provides better limits than Tevatron with a few pb^{-1}

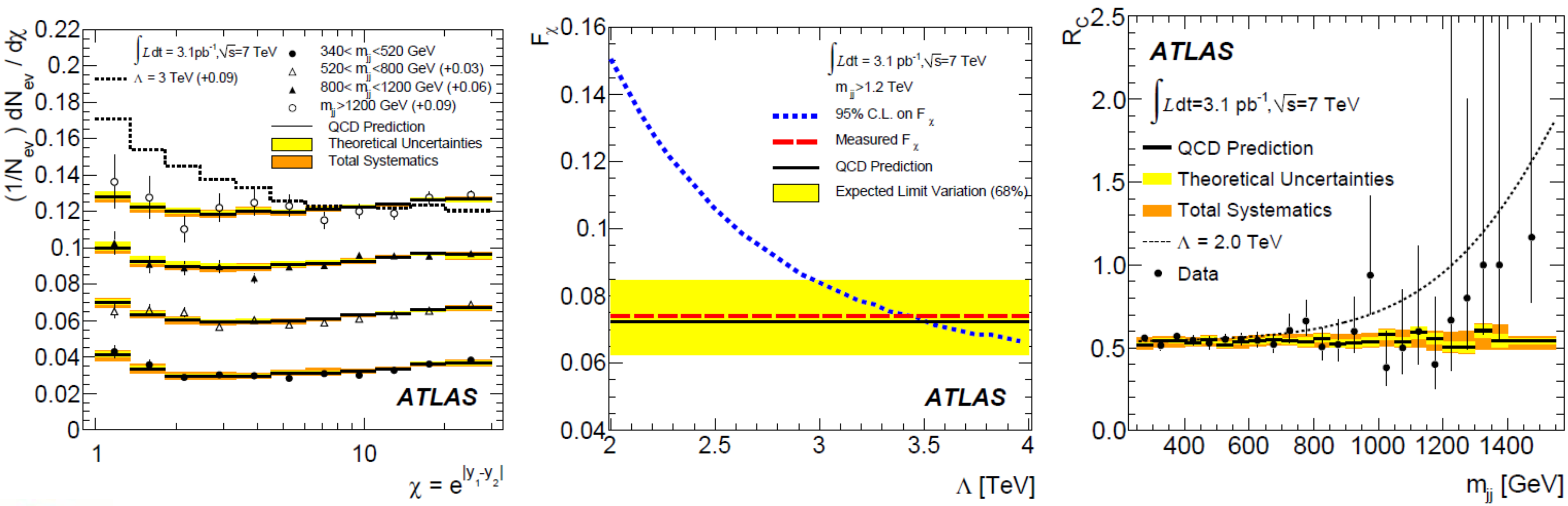






Contact Interactions

- **χ = exp (|y_1-y_2|)** flat for Rutherford scattering dN/dcos $\theta^* \propto 1/\sin^4(\theta^*/2)$; new physics expected at small χ
- **Centrality ratio R_c** of events with both leading jets in central (|η| < 0.7) and non central region (0.7 < |η| < 1.3); new physics expected to produce diJets more central than QCD

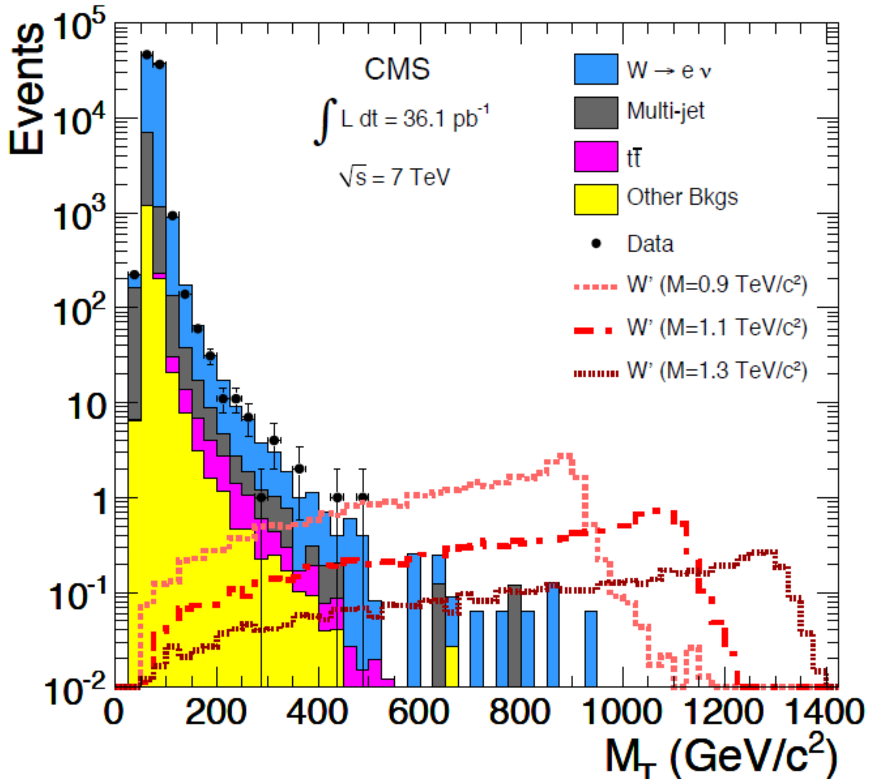


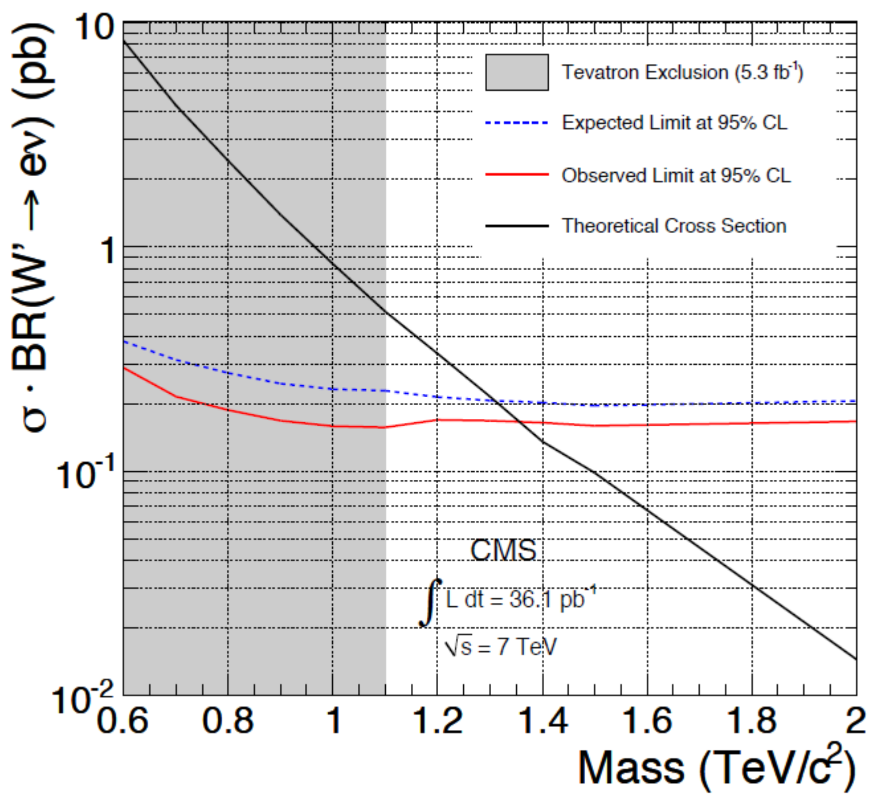
→ No significant deviation from QCD prediction
Best fit for R_c: Λ = 2.9 TeV (no trend seen at CMS)

W' Searches

- Extra heavy gauge bosons predicted by left-right symmetric models or supersymmetric Grand Unified Theories
- **Signature:** lepton (here: *e*) and similar MET $0.4 < E_T^{electron}/MET < 1.5$ in opposite direction ($\Delta\phi$ > 2.5)

→ Better limits on $M_{W'}$ than Tevatron experiments

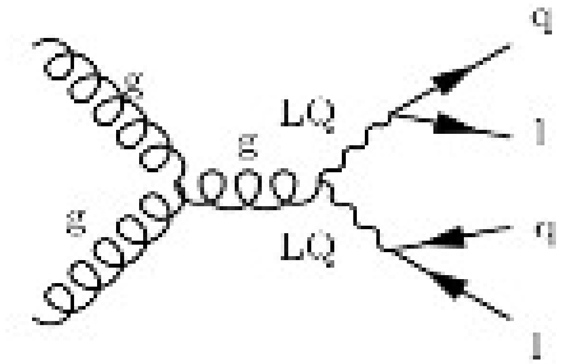




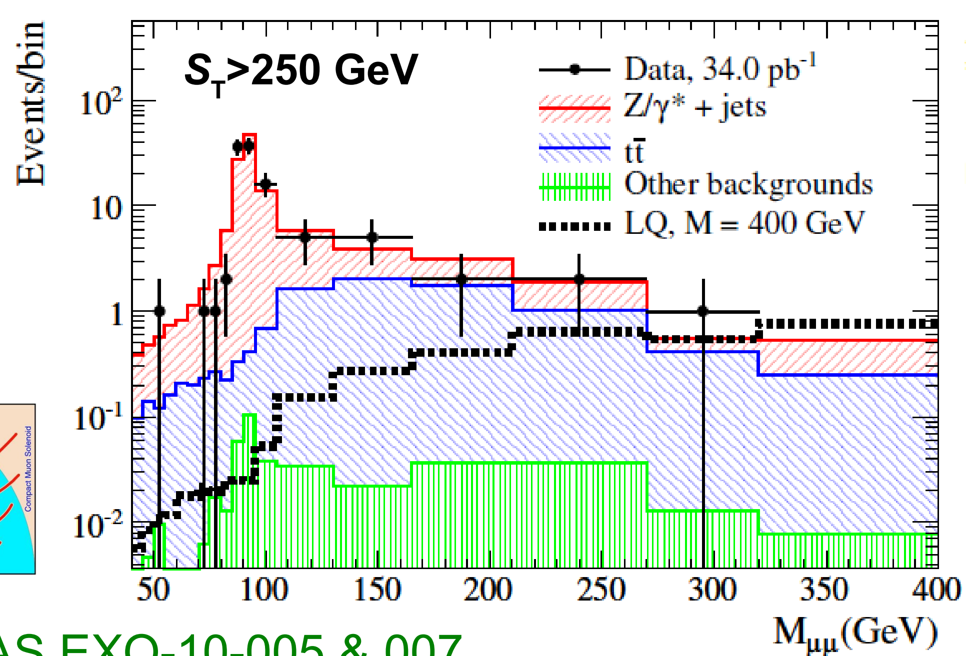
CMS PAS EXO-10-014

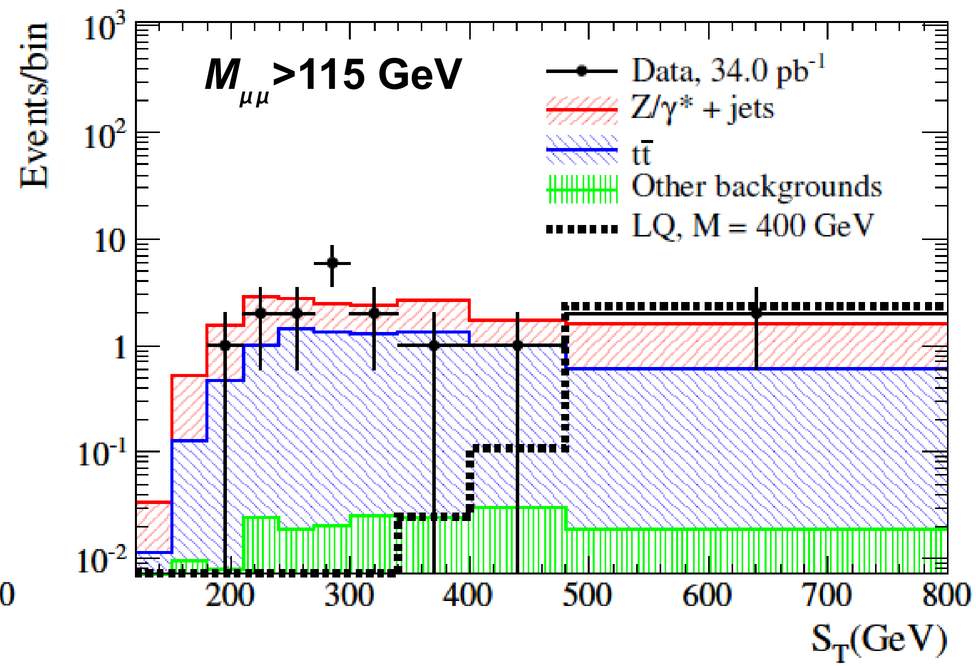
Leptoquarks

- LQ carry lepton and baryon numbers
- Fractionally charged
- Typically constrained to one lepton/quark generation
- LHC: dominant pair production via *gg* fusion or $q\bar{q}$ annihilation



- **Signature:** 2 OSSF leptons + 2 jets with high $M_{\mu\mu}$ and S_T (p_T sum of two leading jets and muons)





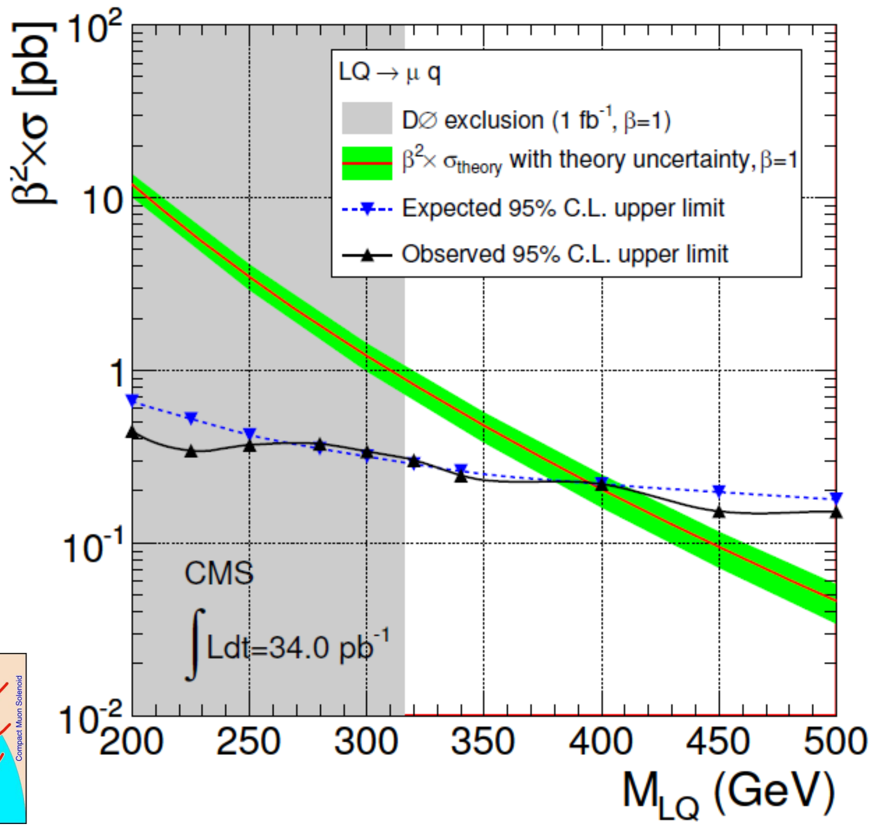
CMS PAS EXO-10-005 & 007

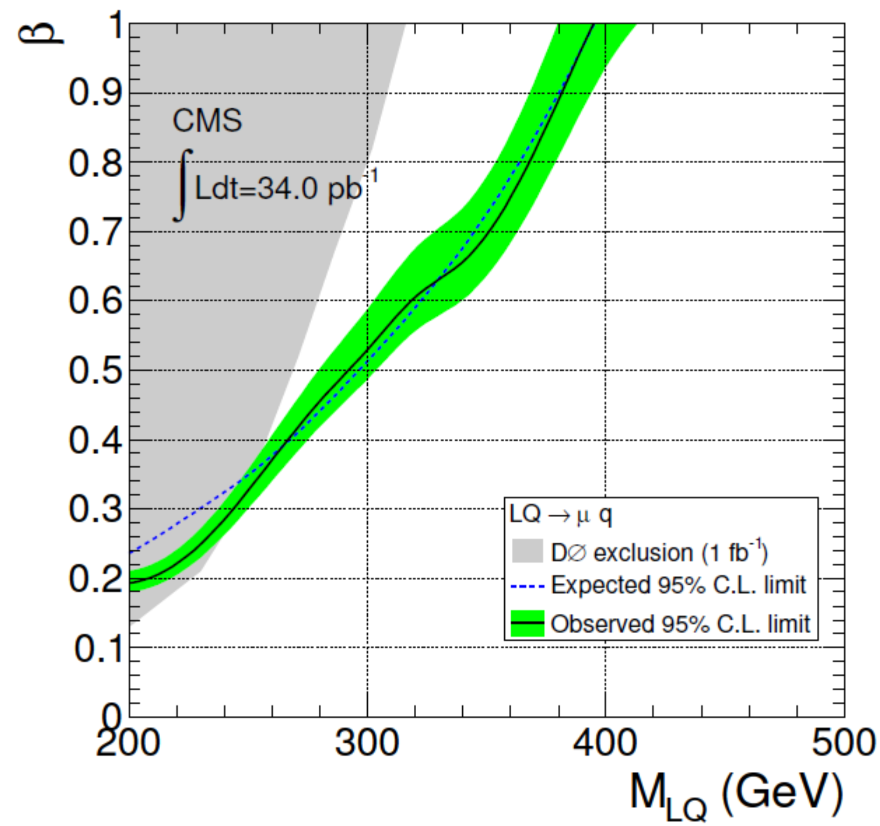
Leptoquarks

No excess of events observed

→ **Exclusion limits on $\beta^2 \times \sigma$** (β: Branching ratio of LQ in corresponding lepton, e.g. second generation LQ → $q\mu$)

(similar limits for first generation LQ)





CMS PAS EXO-10-005 & 007

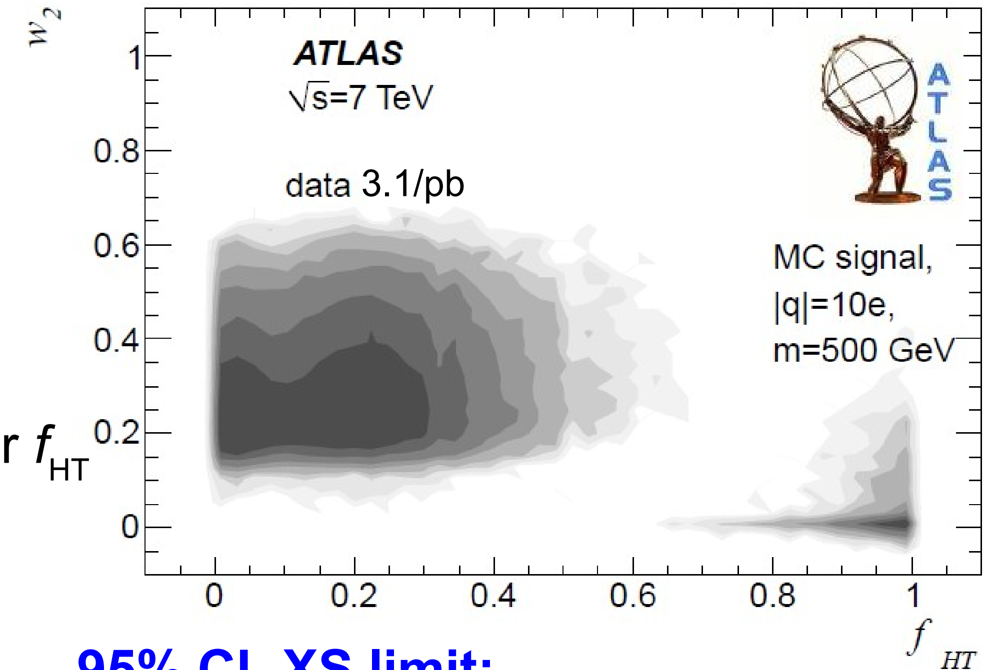
Heavy Ionizing Particles

- Search for heavy particles with large electromagnetic charge ($q \gg e$) like Q-balls, magnetic monopoles, micro BH remnants, dyons …
- **Signature:**
  - Large fraction of high dE/dx hits in tracker f_{HT}
  - Small clusters in Ecal layers w_1 / w_2
- **Data driven background estimation:**
  - Assume no correlation of f_{HT}, w_1 and w_2
  - Bg dominated: !f&!w, f&!w and !f&w → probabilities for bg to pass f or w

$$\mathbf{p_f} = \frac{\mathbf{N_{f\&!w}}}{\mathbf{N_{!w}}}, \ (\mathbf{f} \leftrightarrow \mathbf{w})$$

  - Estimate: $\mathbf{N_{f\&w}} = \mathbf{N_{tot}} \cdot \mathbf{p_f} \cdot \mathbf{p_w}$

arXiv:1102.0459v2 [hep-ex]



95% CL XS limit:

m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	1.4	1.2	2.1
500	1.2	1.2	1.6
1000	2.2	1.2	1.5

95% CL XS limit (pair production):

m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	11.5	5.9	9.1
500	7.2	4.3	5.3
1000	9.3	3.4	4.3

- (Meta-) stable gluinos or squarks can from neutral bound states (R-hadrons) → not visible in muon detectors
- Search based on high dE/dx tracker hits: most probable value of dE/dx estimated by harmonic mean

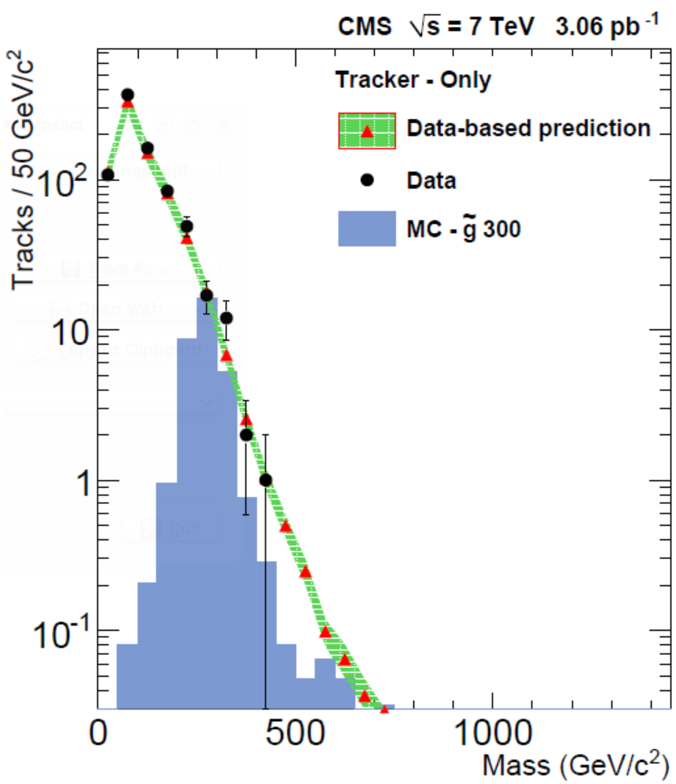
$$I_h = \left(\frac{1}{N}\sum_i (dE/dx)_i^k\right)^{1/k} \quad \text{with} \quad k = -2$$

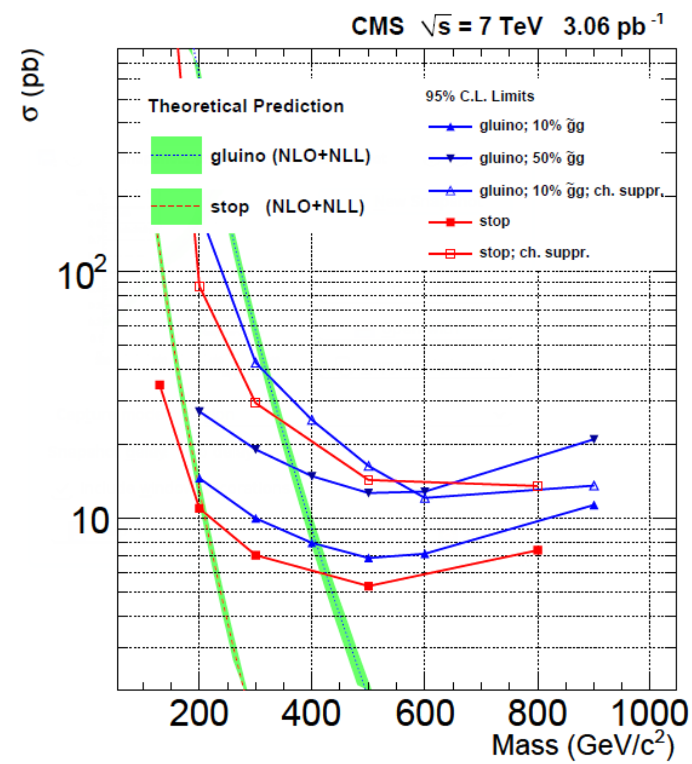
- Relation between I_h, mass m and momentum p

$$I_h = K \cdot \frac{m^2}{p^2} + C$$

with empircal constants K and C from low energy proton data

No excess → limits

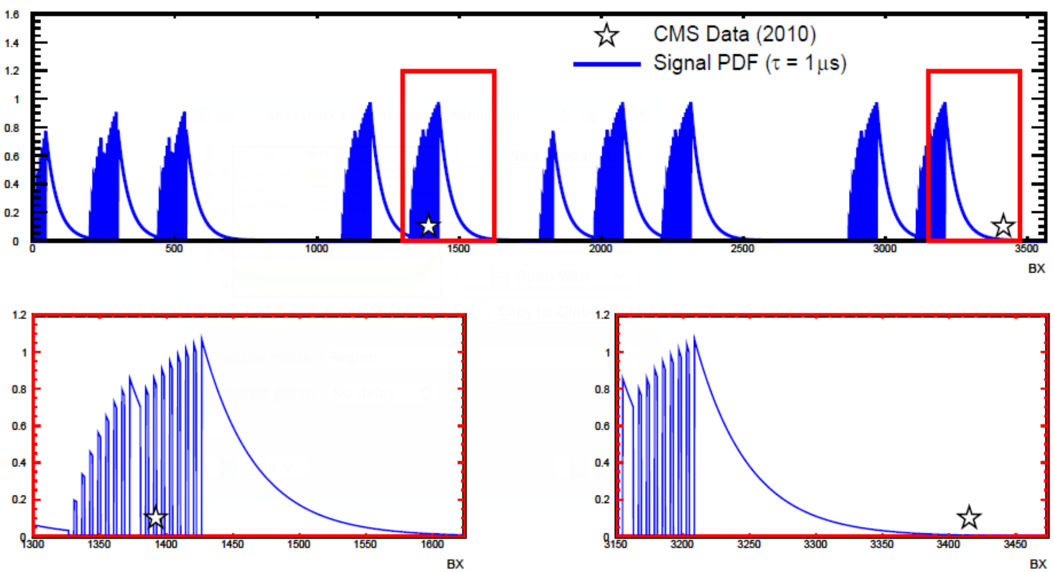


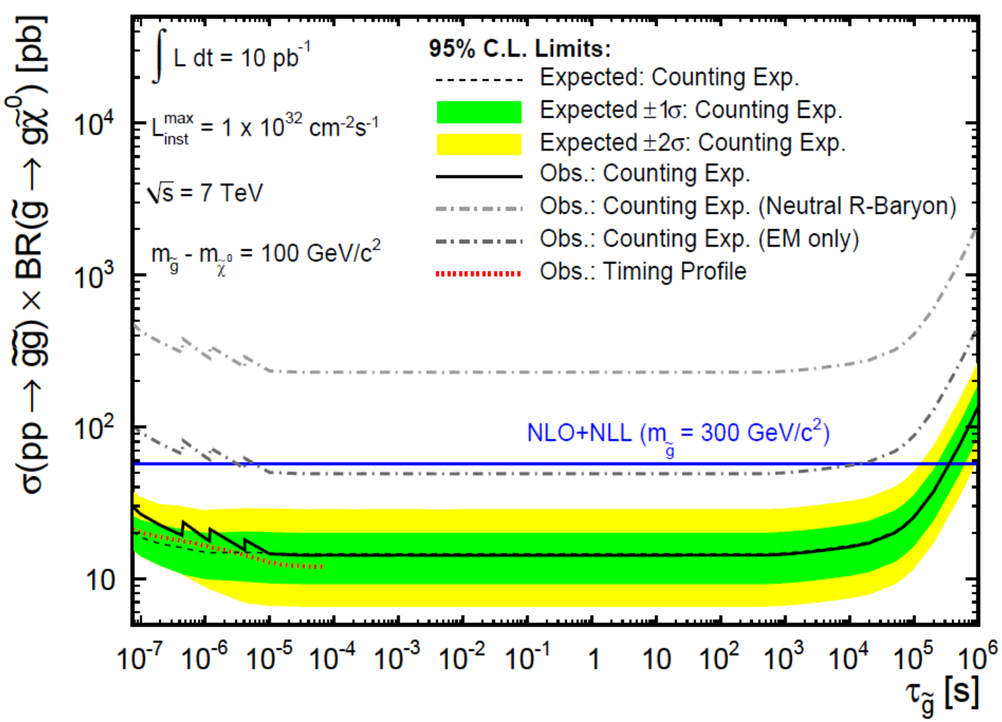


CMS PAS EXO-10-011

Stopped Gluinos

- Probability for *R*-hadron to stop in Hcal: 1% … 20% (model dependent)
  $\rightarrow$ decay: $\tilde{\mathbf{g}} \rightarrow \tilde{\chi}_0 + \mathbf{g}$
- **Signature:** “jets” in triggerable beam gaps
- **Backgrounds:** beam halo, cosmics, and **HCAL noise**
- **No significant excess** $\rightarrow$ limits on $\sigma \times$Br as function of lifetime τ of gluino





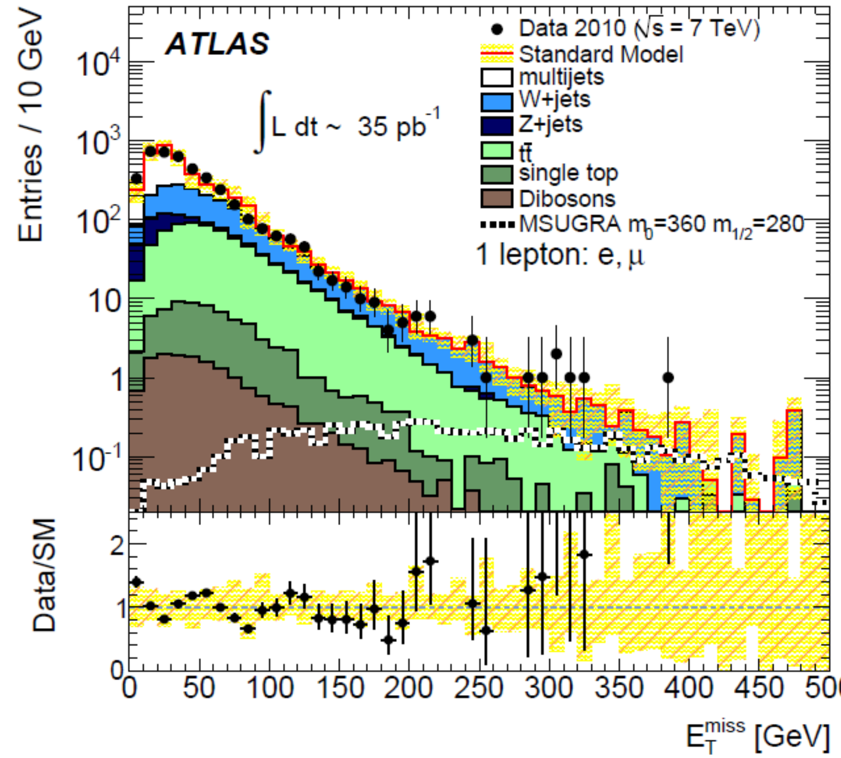
Example: fill with 140 bunches

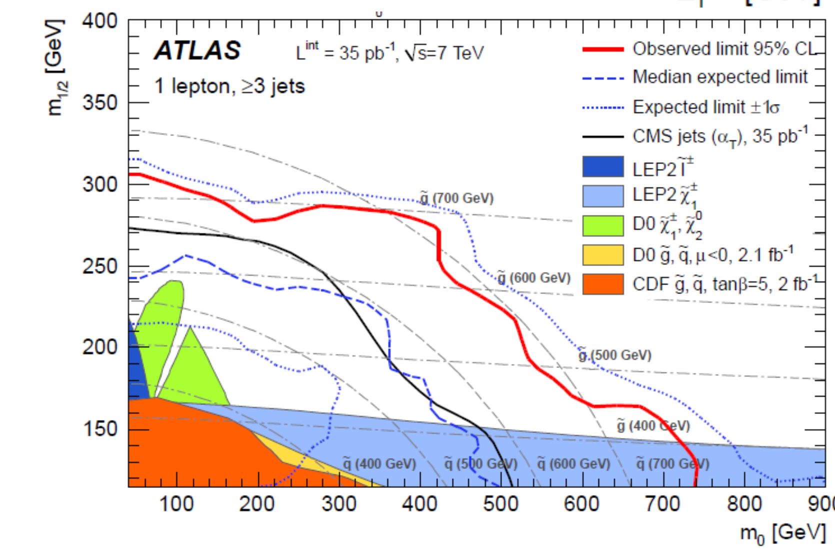
CMS PAS EXO-10-003

Leptonic SUSY Search

- Cascades with sleptons → more than one lepton, e.g. $\tilde{\mathbf{q}} \rightarrow \mathbf{q}\tilde{\chi}_2^0 \rightarrow \mathbf{q}\mathbf{l}\tilde{\mathbf{l}} \rightarrow \mathbf{q}\mathbf{l}\bar{\mathbf{l}}\tilde{\chi}_1^0$
- SUSY cascades with charginos → single leptons, e.g. $\tilde{\mathbf{q}} \rightarrow \mathbf{q}\tilde{\chi}_1^\pm \rightarrow \mathbf{q}\mathbf{l}\nu\tilde{\chi}_1^0$
- **Signature:**
  - exactly one isolated lepton
  - $\geq$3 jets
  - MET > 125 GeV
  - M_T(lepton+MET) >115 GeV
  - M_{eff}(lepton + 3 jets + MET) > 500 GeV
- QCD background from data; other bgs scaled MC simulation (control regions)
- **Observed:** 2 events
- **Expected:** ~4 events

→ **Limits**





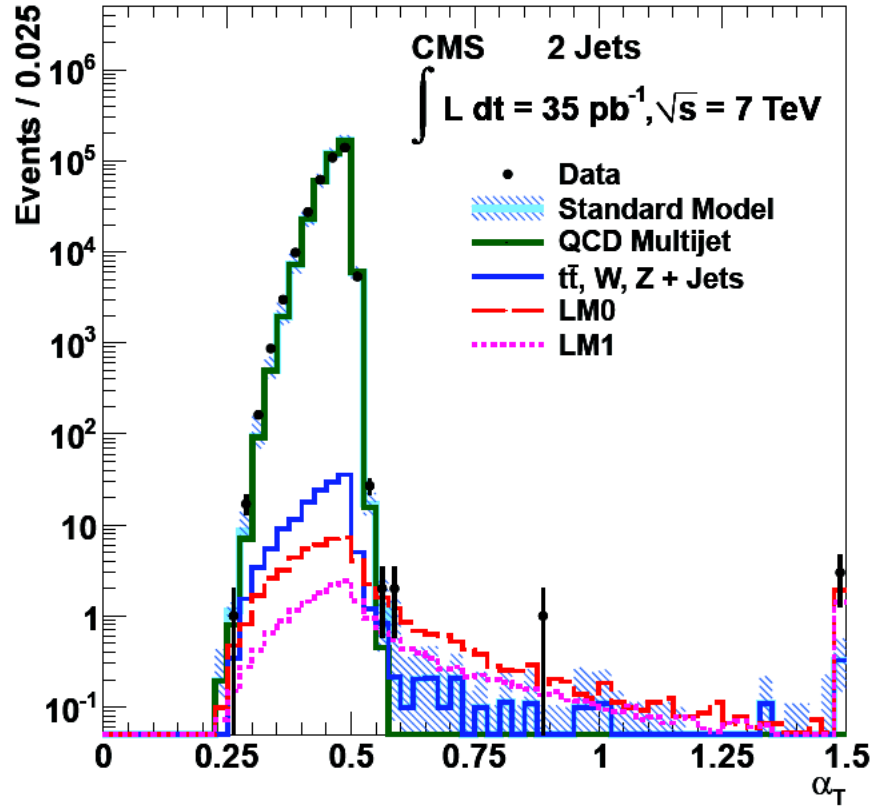
arXiv:1102.2357v2 [hep-ex]

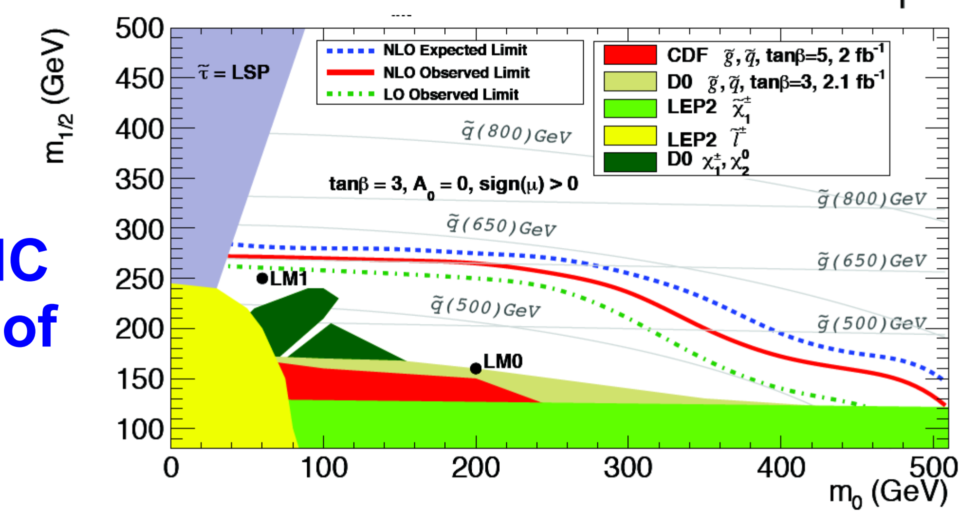
Hadronic SUSY Search with α_T

$$\alpha_T = \frac{E_T^{2nd}}{M_T} = \frac{E_T^{2nd}}{\sqrt{2p_T^{1st}p_T^{2nd}(1-\cos\phi_{12})}}$$

- Perfectly measured diJet events $\alpha_T = 0.5$
- Mismeasurements of p_T: $\alpha_T < 0.5$
- **Selection:** 3rd jet p_T < 50 GeV & $\alpha_T > 0.55$
- $\alpha_T > 0.5$
  - QCD: jets below threshold
  - Events with genuine MET (Top, *W*, *Z*)
- Possible extension on $N_{jet} > 2$ by forming two pseudo jets

→ Already with small statistics the LHC experiments are probing new regions of the SUSY parameter space

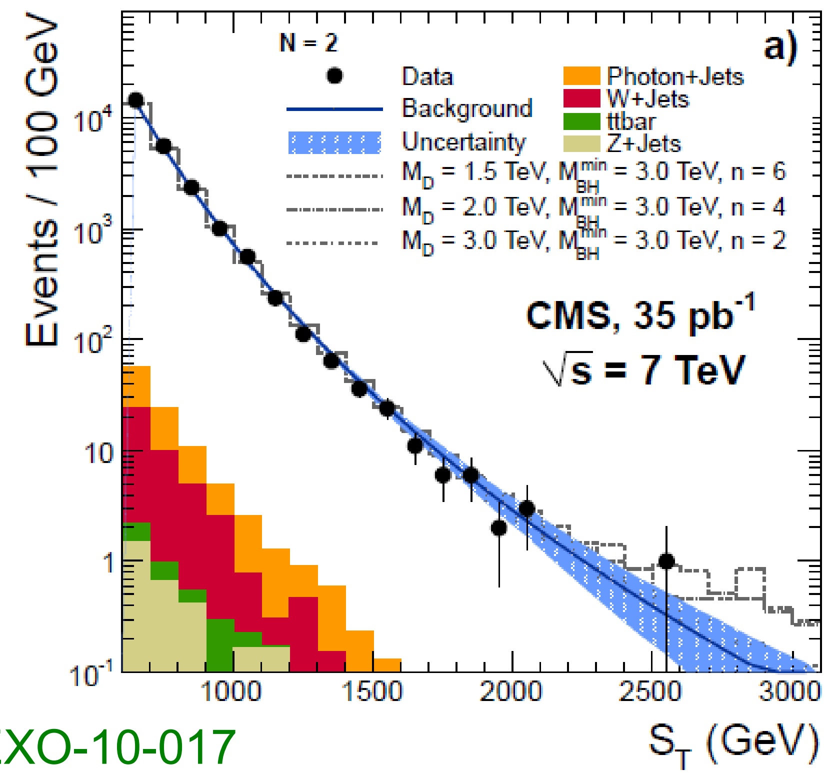


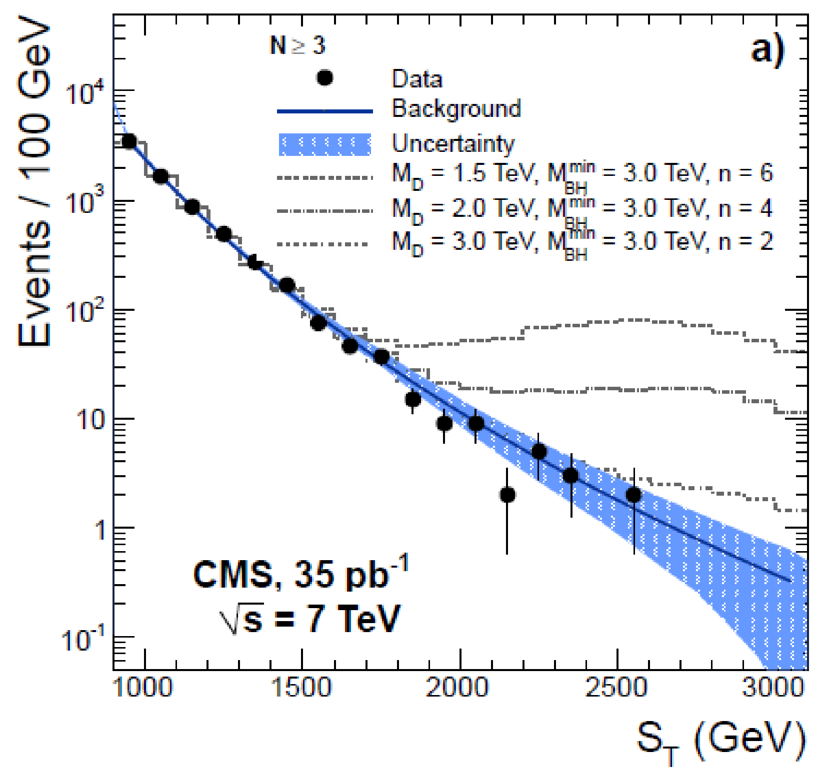


CMS PAS SUS-10/003

Black Holes

- Models with large flat extra spatial dimensions (e.g. ADD models): Black hole production at the LHC (~geometrical cross section: $\sigma = \pi \cdot R_S^2$)
- Hawking radiation: democratic evaporation (dominantly: quarks and gluons)
- **Signature:** High multiplicity of objects (p_T > 50 GeV), high $S_T = \Sigma_i \, p_{T,i}$
- **Dominant Bg:** QCD; **S_T shape independent on object multiplicity**



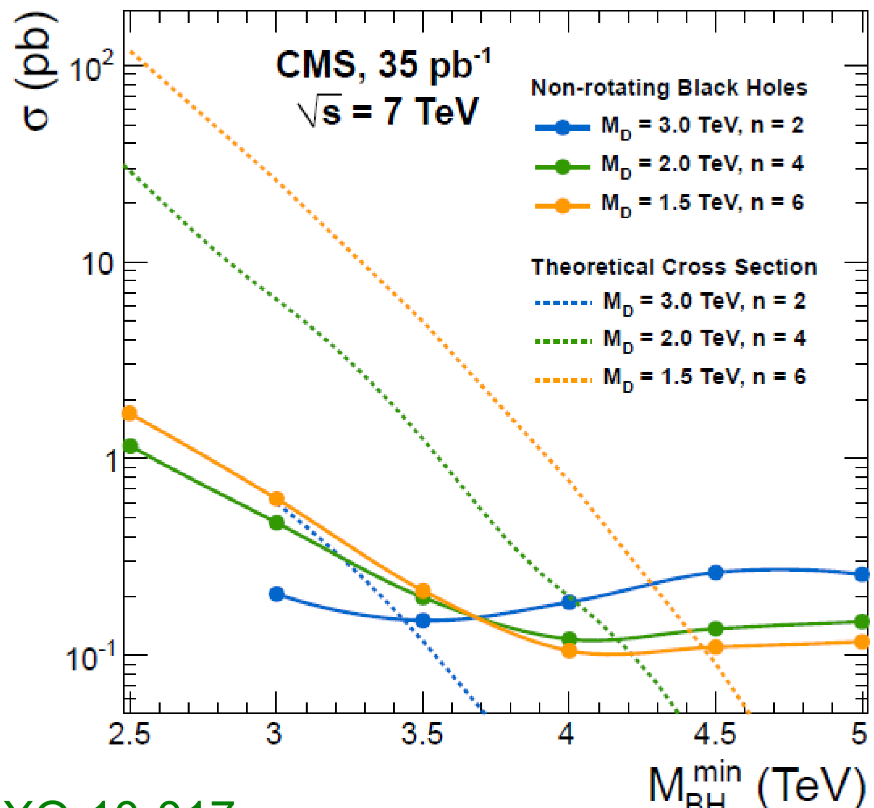


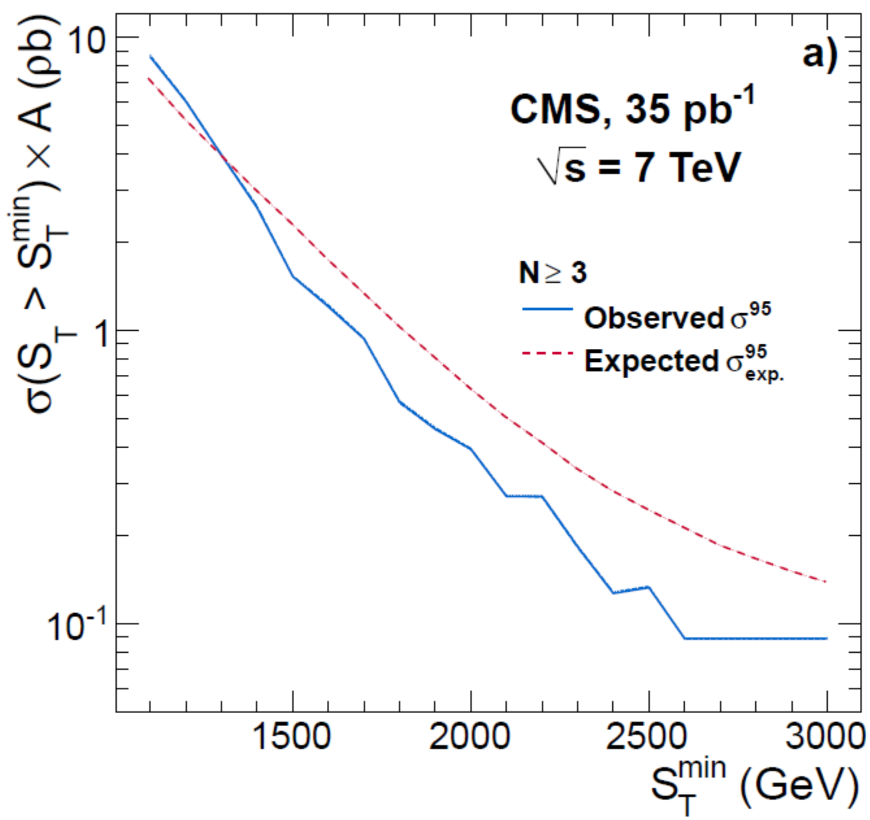
CMS PAS EXO-10-017

Black Holes

No excess at large S_T observed → **Limits:**

- **Model dependent limits** on minimal BH mass ~3.5 and ~4.5 TeV
- **Model independent limits** on cross section for New Physics from counting experiments with $S > S_T^{min}$





CMS PAS EXO-10-017

Outline

Introduction

Performance of Detectors

Rediscovery of the Standard Model

Beyond the Standard Model

Summary

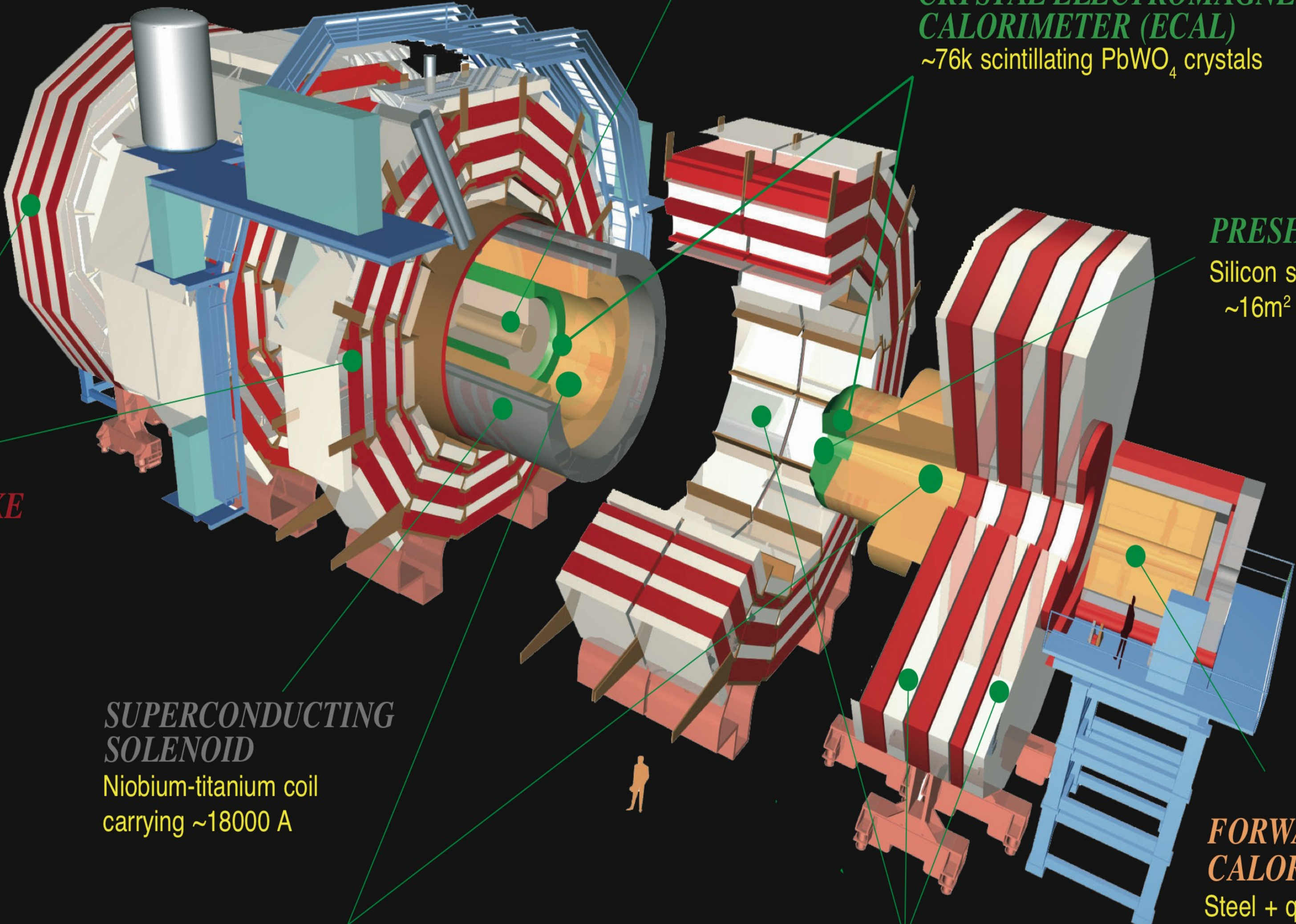
Summary

- LHC physics program has started successfully
- All **detectors commissioned** and operating with high efficiencies
- The **Standard Model has been rediscovered** → 2011/12 data set will allow precision measurements and has potential to discover (or exclude) the SM Higgs boson over largest part of allowed mass region
- Due to higher center of mass energy (compared to Tevatron) the LHC experiments are **exploring new parameter regions of BSM models with the first pb^{-1}**

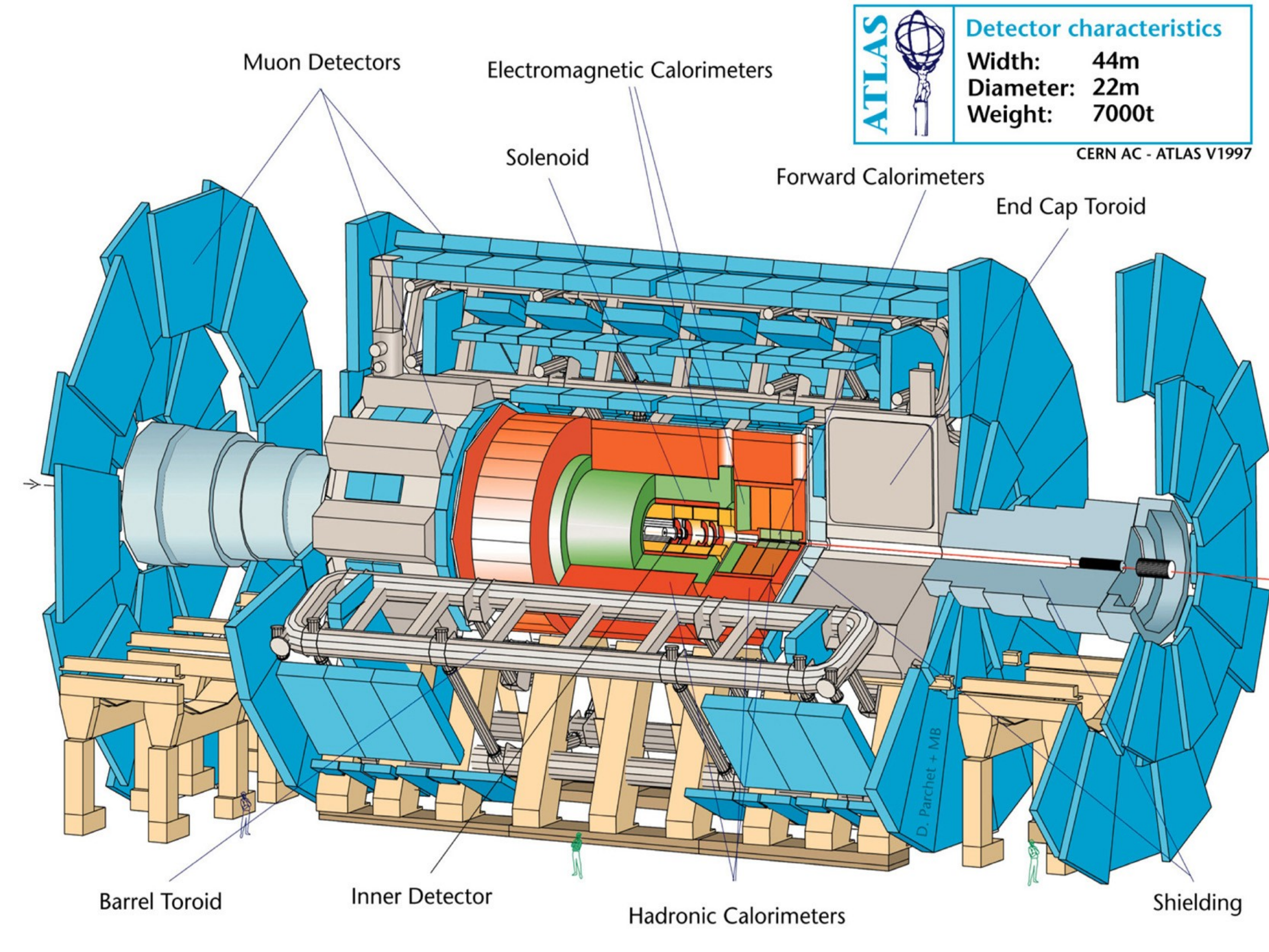
Very exciting times ahead of us …

Backup

CMS Detector

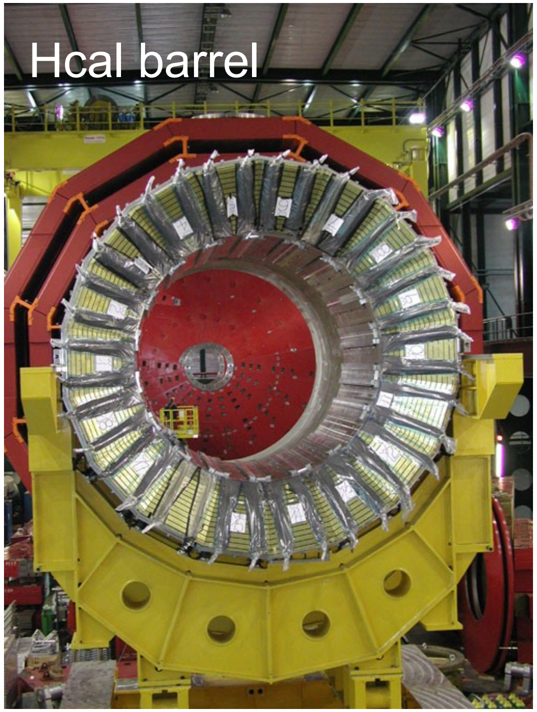


Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T


Detector characteristics
ATLAS
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

CMS Calorimeter

- **ECal:** Lead-Tungstate $PbWo^4$ crystals
  - Coverage: $|\eta| < 3$
  - High granularity $\Delta\eta\times\Delta\phi$ = 0.0175×0.0175 (~80k crystals)
  - ~26 X_0
- **HCal:** Copper (brass) / scintillator sampling calorimeter
  - Coverage: $|\eta| < 5$
  - Granularity (barrel) $\Delta\eta\times\Delta\phi$ = 0.087×0.087 (~4k cells)
  - ~7-11 λ (+ 4 λ from HO in barrel)
- **Calorimeter towers:**
  - One HCal cell and 5×5 crystals
  - Tower thresholds between of 0.5 GeV and 0.85 GeV
  - 82 towers in η and 72/36/18 towers in ϕ



CMS HCal

- Granularity decreases with increasing $|\eta|$
- Coverage up to $|\eta| < 5$
- Most parts inside of magnet except OuterBarell (OB)

from CMS Physics TDR Vol. II

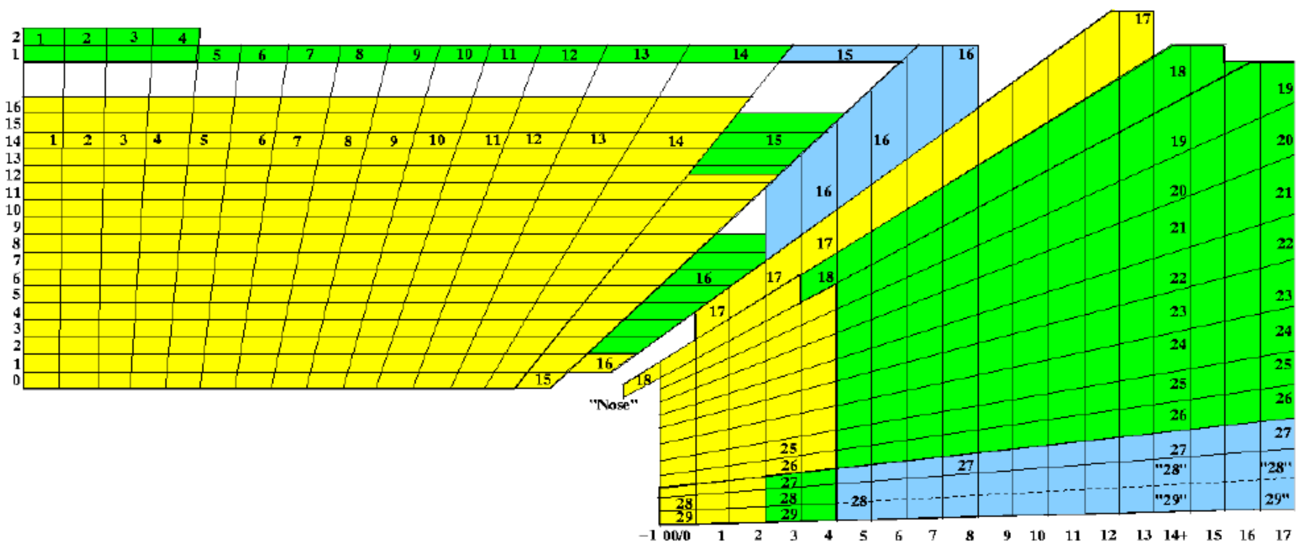


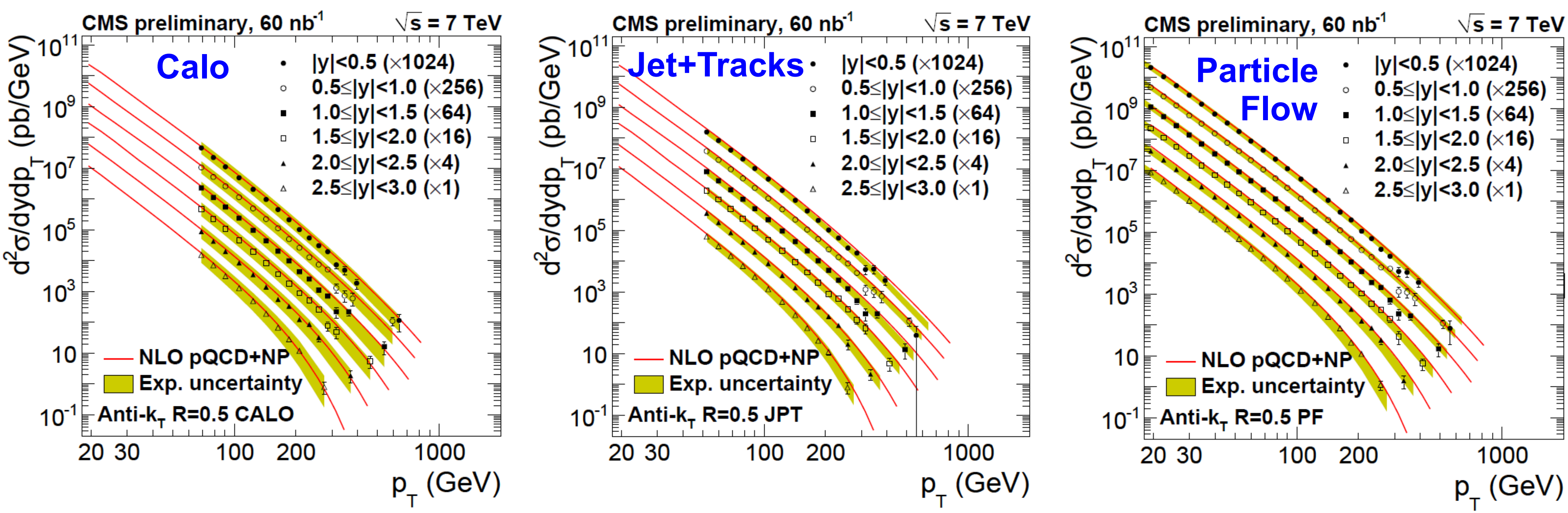
Figure 5.1: A schematic view of the tower mapping in r-z of the HCAL barrel and endcap regions.

Tower index	η range Low	High	Detector	Size η	ϕ	Depth segments
1	0.000	0.087	HB, HO	0.087	5°	HB=1, HO=1
2	0.087	0.174	HB, HO	0.087	5°	HB=1, HO=1
3	0.174	0.261	HB, HO	0.087	5°	HB=1, HO=1
4	0.261	0.348	HB, HO	0.087	5°	HB=1, HO=1
5	0.348	0.435	HB, HO	0.087	5°	HB=1, HO=1
6	0.435	0.522	HB, HO	0.087	5°	HB=1, HO=1
7	0.522	0.609	HB, HO	0.087	5°	HB=1, HO=1
8	0.609	0.696	HB, HO	0.087	5°	HB=1, HO=1
9	0.696	0.783	HB, HO	0.087	5°	HB=1, HO=1
10	0.783	0.870	HB, HO	0.087	5°	HB=1, HO=1
11	0.879	0.957	HB, HO	0.087	5°	HB=1, HO=1
12	0.957	1.044	HB, HO	0.087	5°	HB=1, HO=1
13	1.044	1.131	HB, HO	0.087	5°	HB=1, HO=1
14	1.131	1.218	HB, HO	0.087	5°	HB=1, HO=1
15	1.218	1.305	HB, HO	0.087	5°	HB=2, HO=1
16	1.305	1.392	HB, HE	0.087	5°	HB=2, HE=1
17	1.392	1.479	HE	0.087	5°	HE=1
18	1.479	1.566	HE	0.087	5°	HE=2
19	1.566	1.653	HE	0.087	5°	HE=2
20	1.653	1.740	HE	0.087	5°	HE=2
21	1.740	1.830	HE	0.090	10°	HE=2
22	1.830	1.930	HE	0.100	10°	HE=2
23	1.930	2.043	HE	0.113	10°	HE=2
24	2.043	2.172	HE	0.129	10°	HE=2
25	2.172	2.322	HE	0.150	10°	HE=2
26	2.322	2.500	HE	0.178	10°	HE=2
27	2.500	2.650	HE	0.150	10°	HE=3
*28	2.650	3.000	HE	0.350	10°	HE=3
29	2.853	2.964	HF	0.111	10°	HF=2
30	2.964	3.139	HF	0.175	10°	HF=2
31	3.139	3.314	HF	0.175	10°	HF=2
32	3.314	3.489	HF	0.175	10°	HF=2
33	3.489	3.664	HF	0.175	10°	HF=2
34	3.664	3.839	HF	0.175	10°	HF=2
35	3.839	4.013	HF	0.174	10°	HF=2
36	4.013	4.191	HF	0.178	10°	HF=2
37	4.191	4.363	HF	0.172	10°	HF=2
38	4.363	4.538	HF	0.175	10°	HF=2
39	4.538	4.716	HF	0.178	10°	HF=2
40	4.716	4.889	HF	0.173	20°	HF=2
41	4.889	5.191	HF	0.302	20°	HF=2

Inclusive Jet Production

- Inclusive jet p_T spectra for all three jet approaches used in CMS (Calo, JPT, PF)
- Systematic uncertainties dominated by luminosity (~11%) and absolute jet energy scale (JES) uncertainty (~20% to ~80% depending on jet approach and p_T); minor contributions from relative JES and p_T resolution
- For particle flow jets the distributions can be extended down to 18 GeV !!!

All results in good agreement with NLO* theory



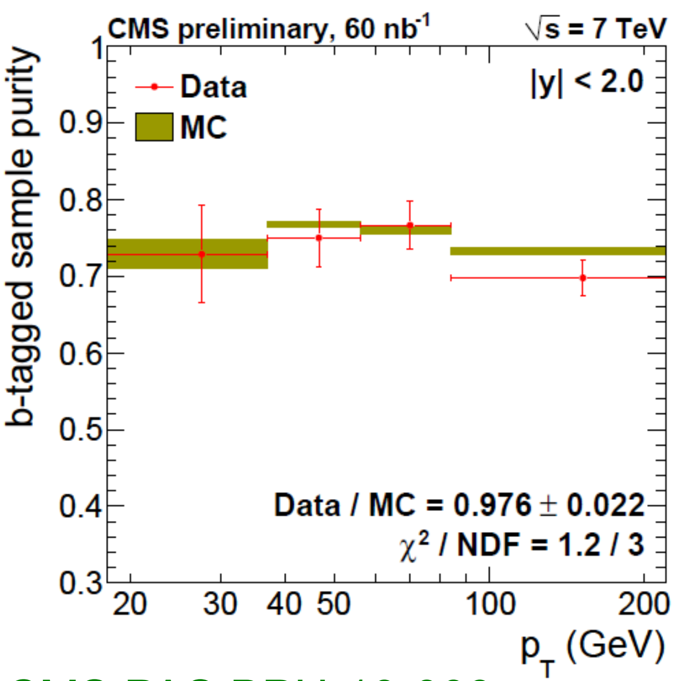
* NLOJET++ within fastNLO framework and CTEQ-6.6 pdfs

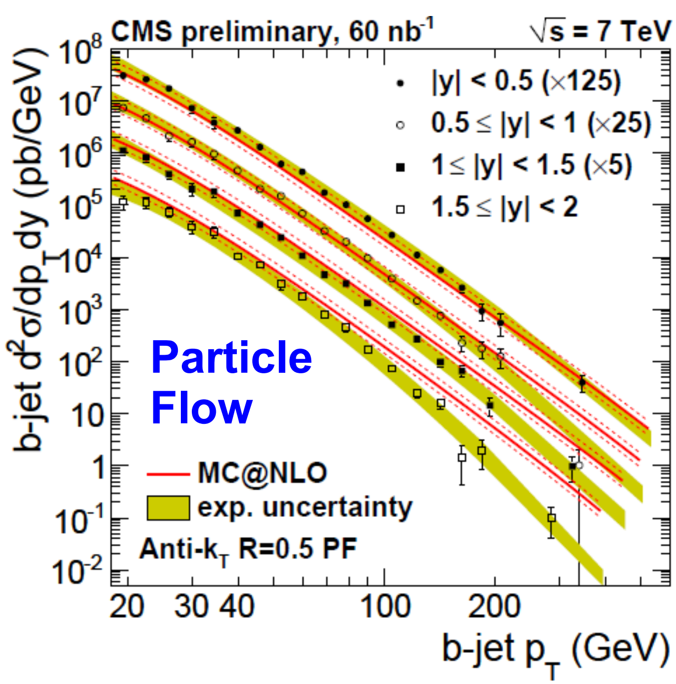
CMS PAS QCD-10-011

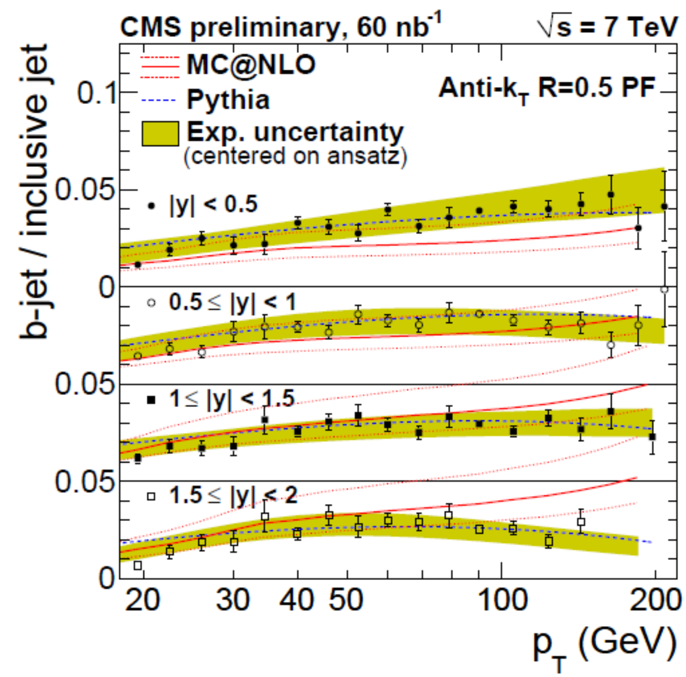
b Jets Production

- Test of implemented *b*-tagging tools (here: high purity version of the SV Tagger)
  - Purity of *b*-tagged sample extracted from fit to mass of the SV with templates
  - *b*-tagging efficiency from MC, but data driven uncertainty (~20%)
  - Mistag rate from negative tails of the *b*-tag distributions
- Ratio of *b*-incl. to jet-incl. cross section cancels out common systematic uncertainties

Agreement with MC@NLO (CTEQ6M) but discrepancies in p_T and y shapes







CMS PAS BPH-10-009