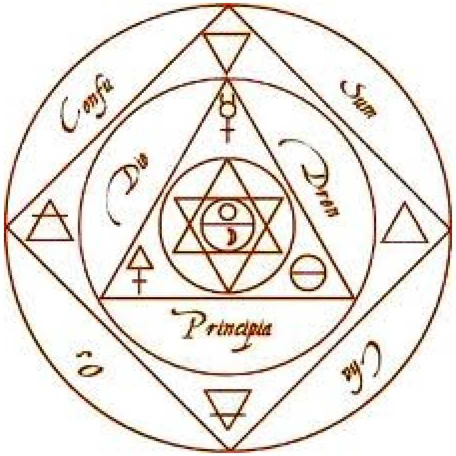
Maxime Gouzevitch

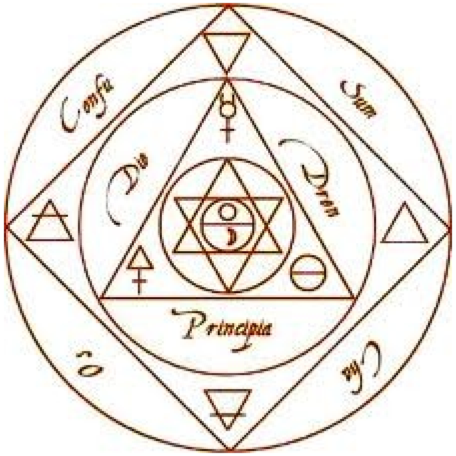
Jet physics and jet substructure at the LHC

Invited talk at WNL conference at TIFR, Mumbai, India

1) Why we have to understand QCD at the LHC
2) “Solve” QCD at the LHC
3) Measure and interpret jet results
4) Extraction of the QCD parameters
5) Testing the soft dynamics
6) Jets substructure: the new El Dorado

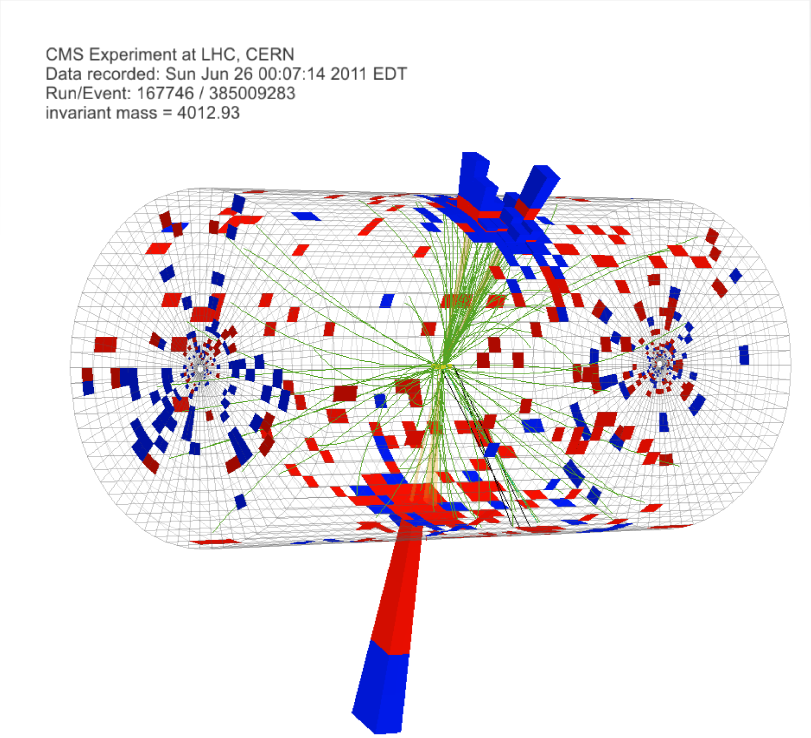
Why we have to understand QCD at the LHC





1.1) Few common places useful to recall

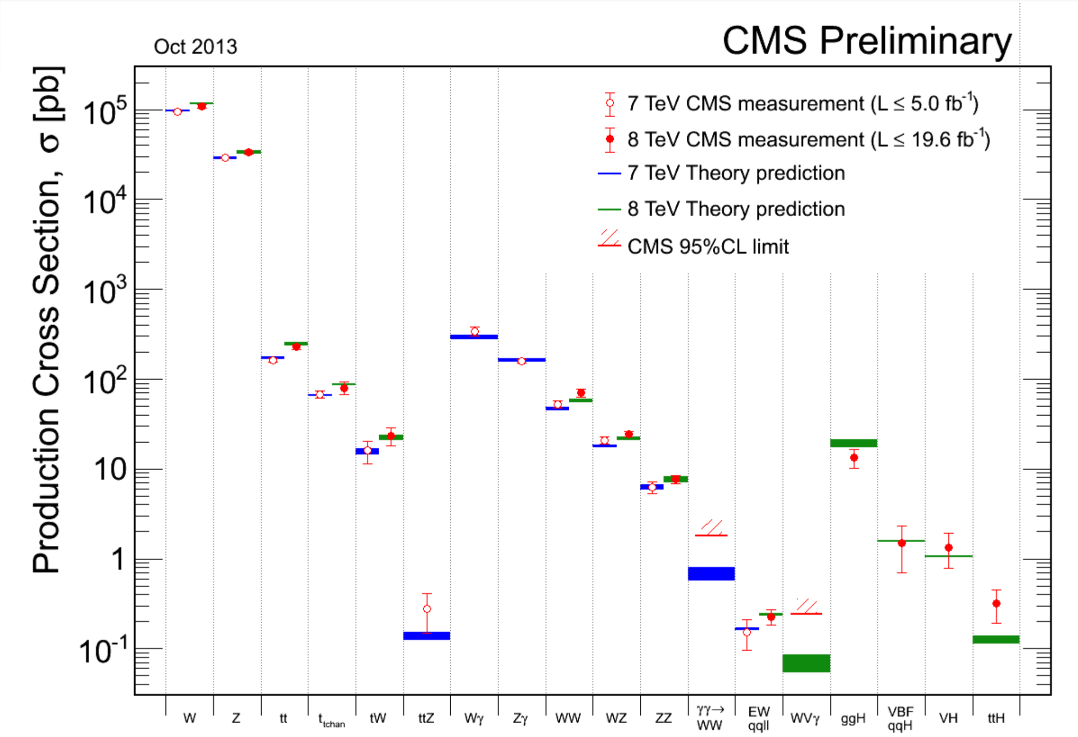
- Jet is a collimated bunch of particles.
- In a naive picture it is a macroscopic manifestation of a colored parton (quark/gluons) produced/ejected during the proton hard scattering
- Jets are THE tool to study hard QCD effects at the LHC.
- Jets are THE tool to study colored BSM (Axigluons, squaks, gluinos etc...)



- All this is common sense. What is a bit less obvious is how much the hard QCD/jets affects EW physics at the LHC.

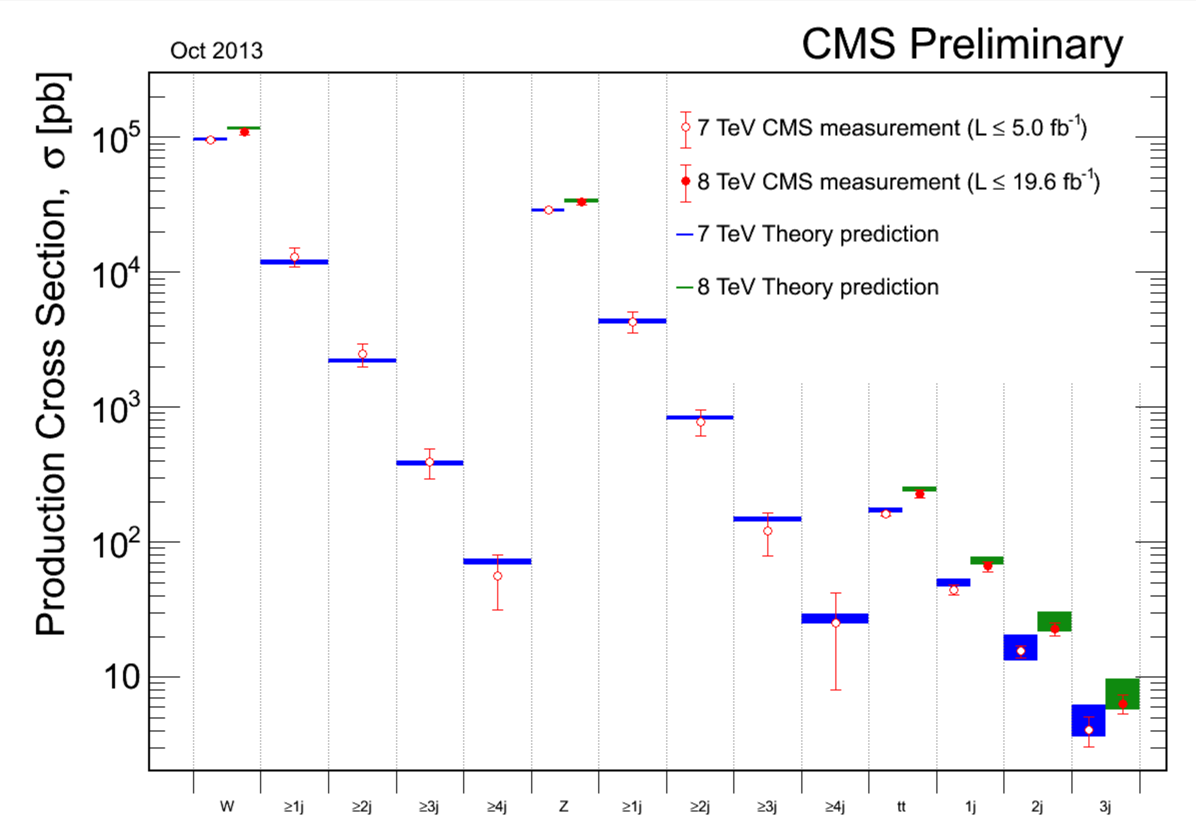
1.2) Recall: LHC was designed for EWSB mechanism

- The primary goal of the LHC was to uncover the EWSB mechanism and test the SM self-consistency. The golden signature involve usually colorless particles:
  - Higgs decays to bosons: γ, Z, W.
  - VH production, VBF H production.
  - VV scattering unitarization.
  - DY W production for mass measurement.



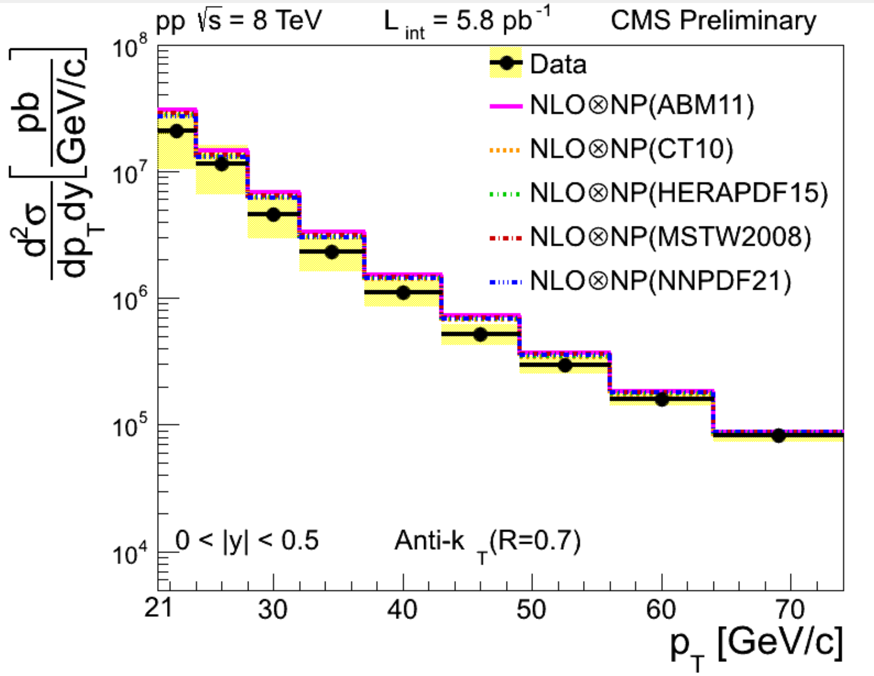
1.3) But large QCD corrections

- But the initial state partons and part of the final state ones are always colored at the LHC in difference of LEP, ILC, TLEP.
- Any EW process experience at least O(α_S) QCD corrections. The real part of those corrections corresponds to jets production.



1.4) LHC is a QCD machine

- 99.9999 % of the LHC events are QCD.
- 99% of the LHC events are QCD with at least 1 jet with p_T > 20 GeV
- In any EW event, a large contribution of PU soft QCD events O(20) at 8 TeV in 2012.



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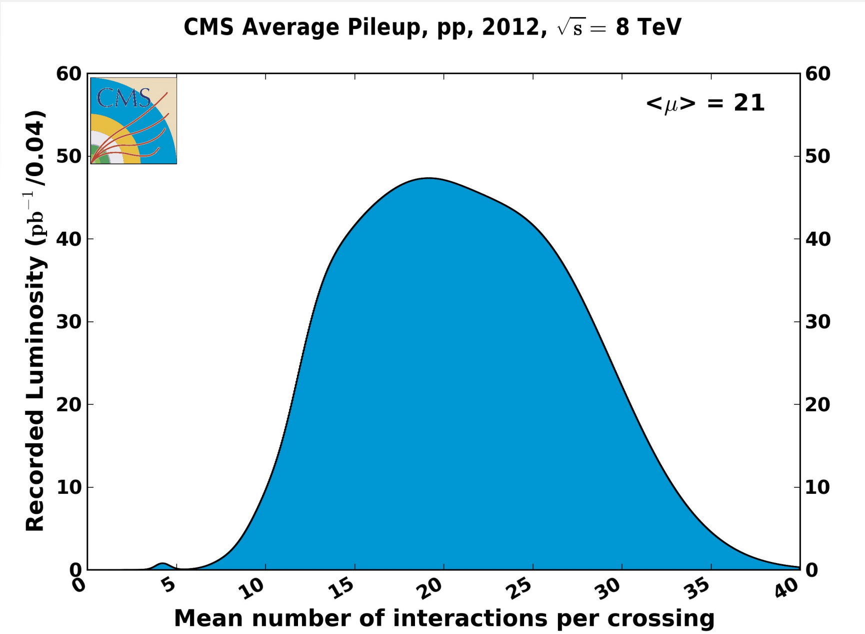
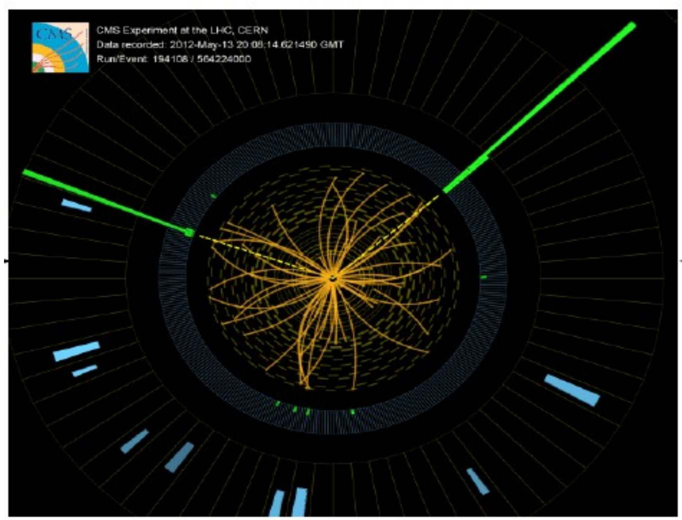
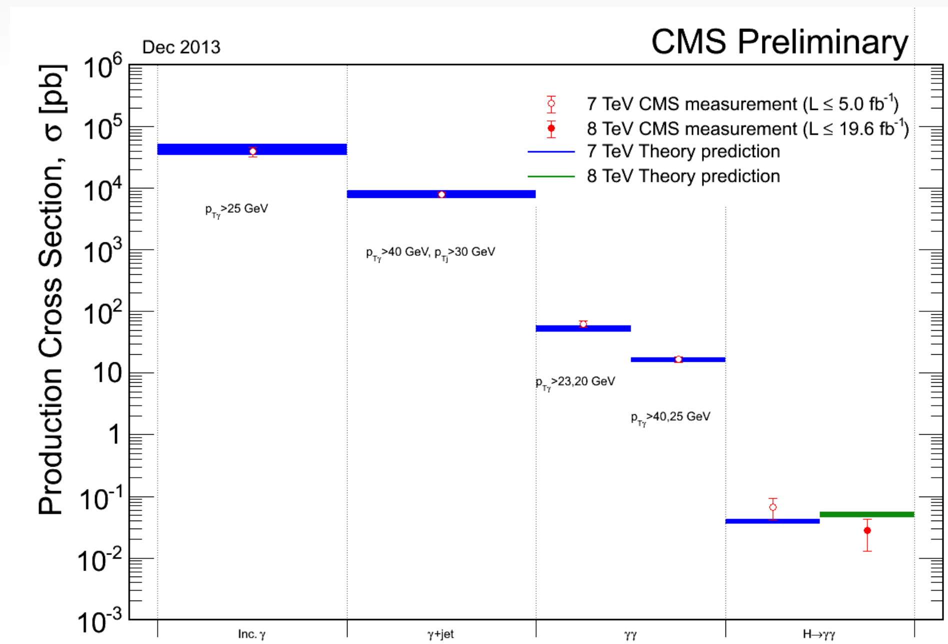


1.5) Jets mimic EW final states

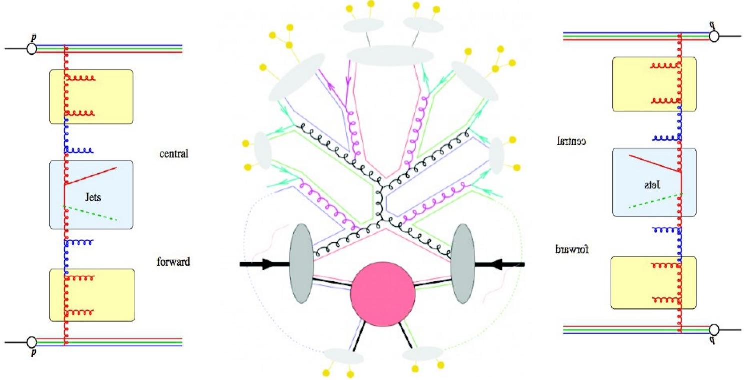
- The EW final states with neutrinos, τ and γ (to lesser extend electrons) can be faked by jets:
  - Heavy quarks decay (c,b,t): produce MET and leptons.
  - Fragmentation tail: jets with leading EM component (π^0) may fake photons or electrons. Jets with leading tracks may fake τ.
  - Detector fiducial limitation and non linearities: fake MET.
- Isolation criteria reduces the effect, but jets production is so large than the effect may remain significant.

JJ, γJ or γγ?



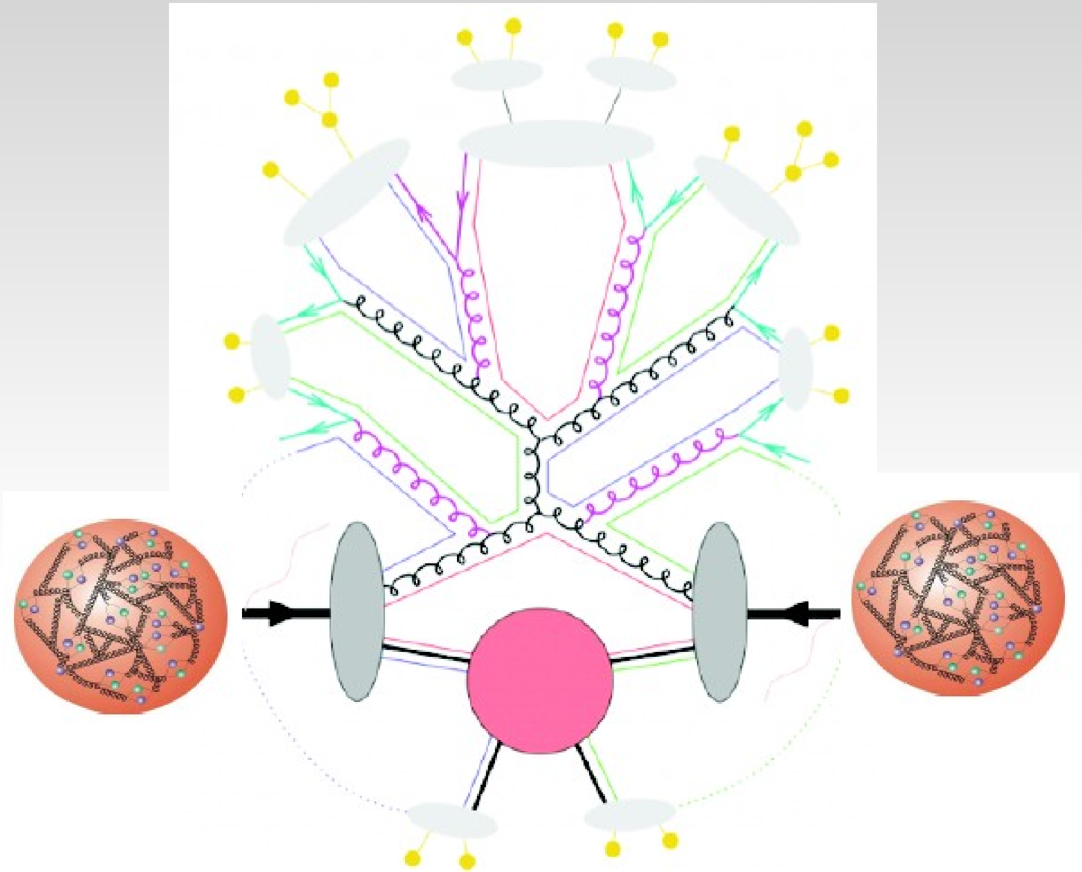


“Solve” QCD at the LHC



2.1) Typical LHC collision

CONFINMENT



HARD SCATTERING

UNDERLYING EVENT

2.2) “Solve” the QCD for hadrons collisions

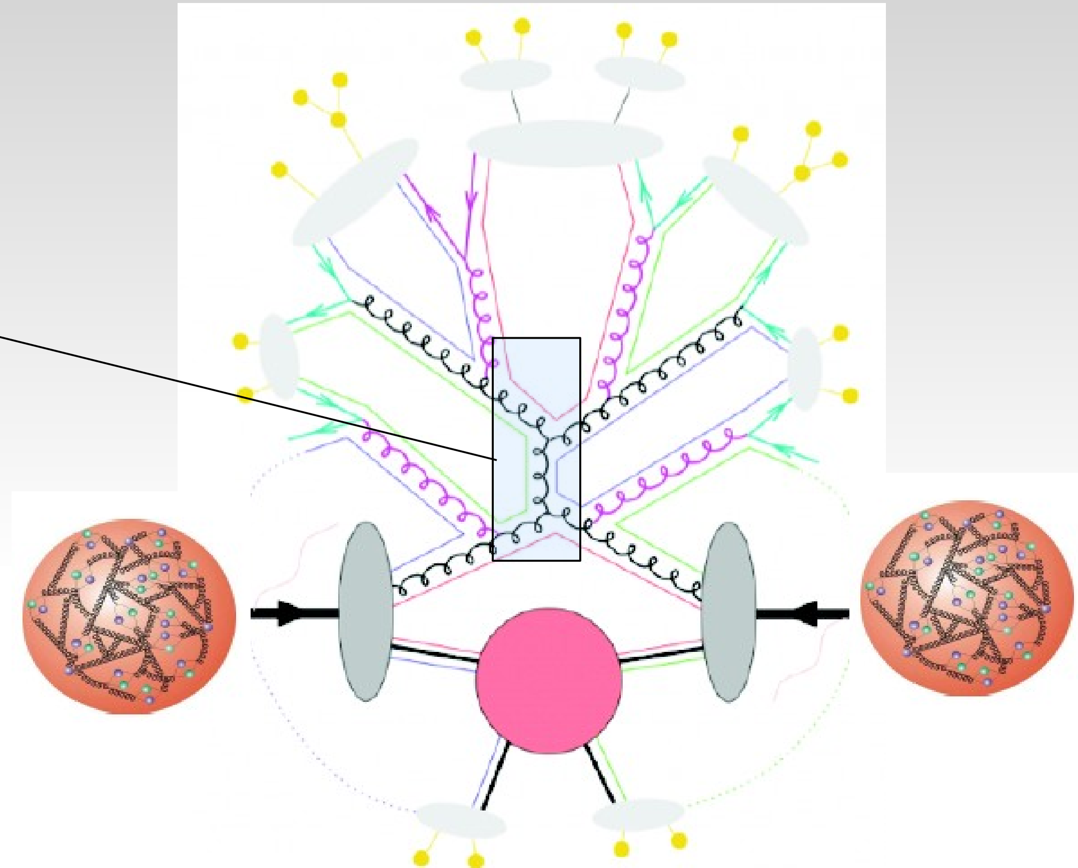
CONFINMENT

ME

$\mu_R = Q$

HARD SCATTERING

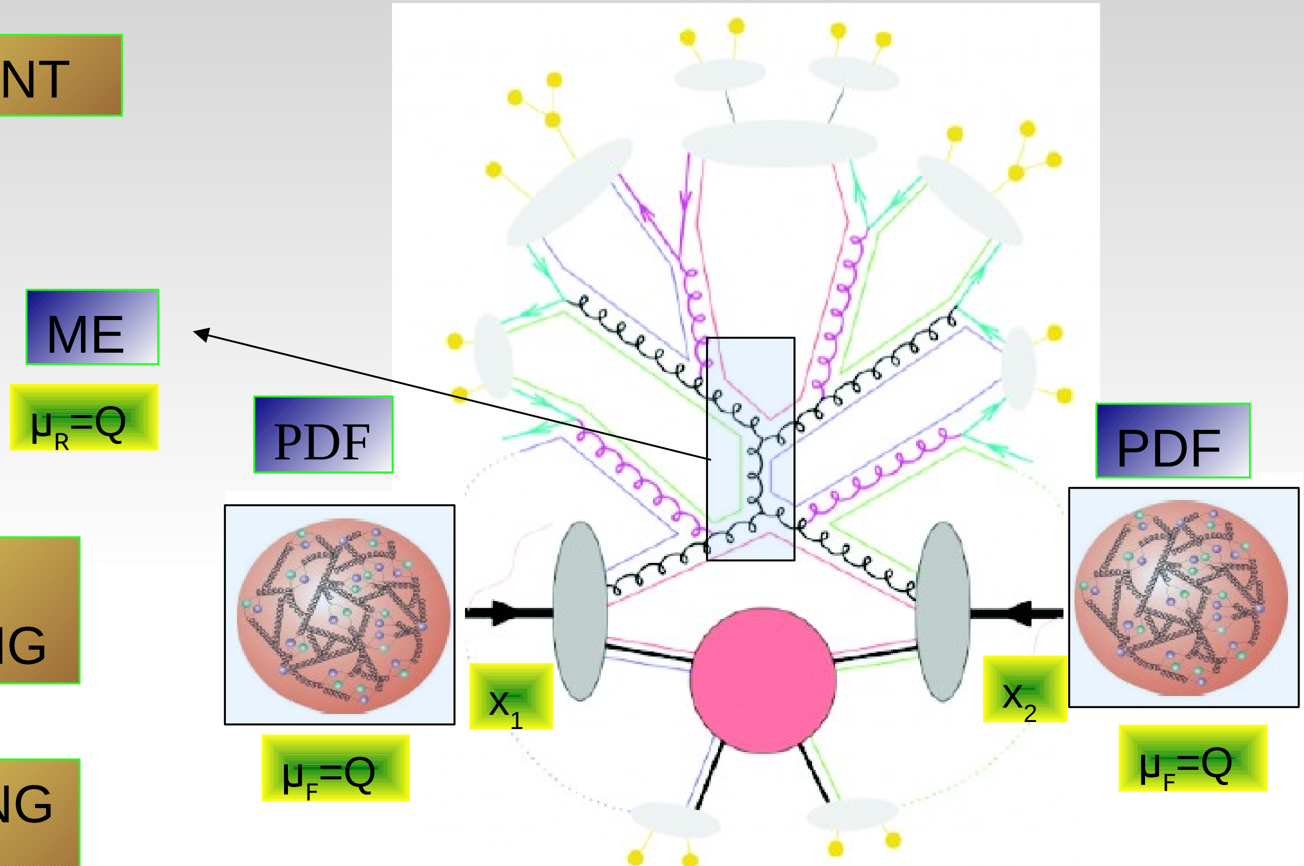
UNDERLYING EVENT



- Asymptotic freedom: Q scale (renormalization) large, $\alpha_s(Q) \sim 0.1$.
- Inclusive observables known at NNLO (V production). Differential in jets at NLO (going to NNLO now). Large computation/analytical cost of extra orders: gluons colored (self-interacting), massless (collinear/soft divergences).

2.2) "Solve" the QCD for hadrons collisions

CONFINMENT



HARD SCATTERING

UNDERLYING EVENT

- Factorisation theorem: protons source of partons: x_1,x_2 fractions of E_p. Independent on ME.
- Euristically parametrised at Q_i ~ 2 GeV.
- Evolved to a large scale Q (factorisation) with an evolution function to take in account soft/collinear radiation effects before hard scattering: DGLAP, CCFM, BFKL

2.2) "Solve" the QCD for hadrons collisions

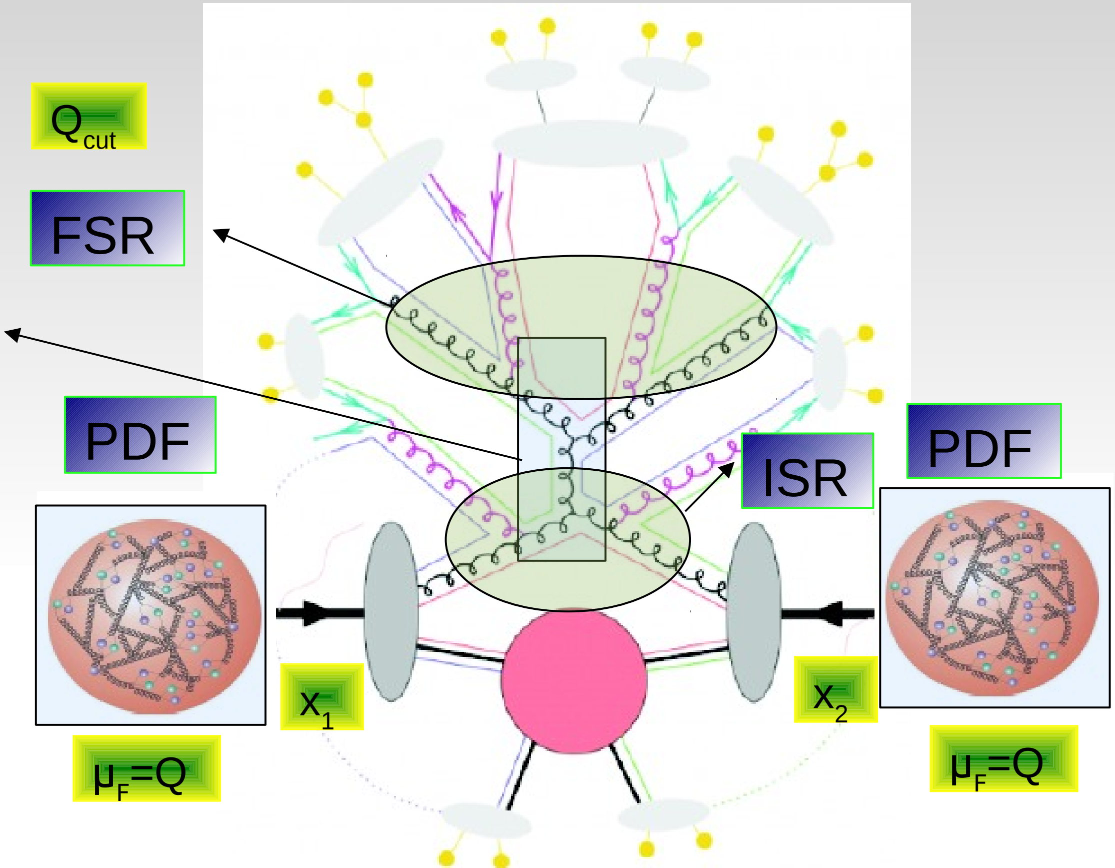
CONFINMENT

ME

$\mu_R = Q$

HARD SCATTERING

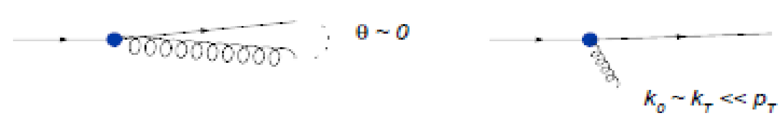
UNDERLYING EVENT



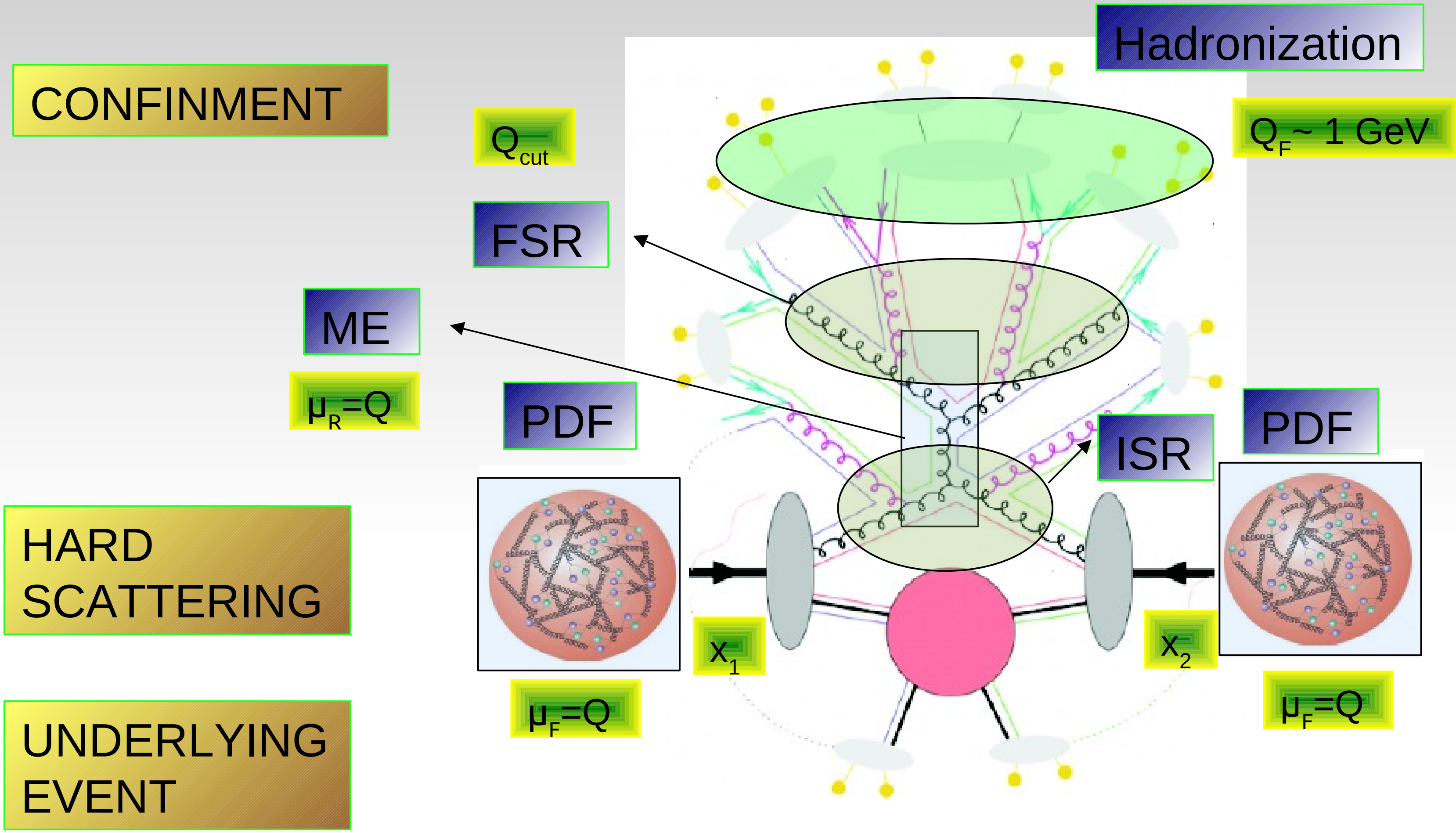
- Jets are defined in IR safe manner.
- But missing orders still important in IR regions: soft multi-jets production.

 "Solution": real emission resummation or PS.
Match to ME at $Q_{cut} << \mu_R, \mu_F$

$$d\sigma \sim \alpha_s \, d\theta / \theta \; dk_T / k_T$$



2.2) “Solve” the QCD for hadrons collisions

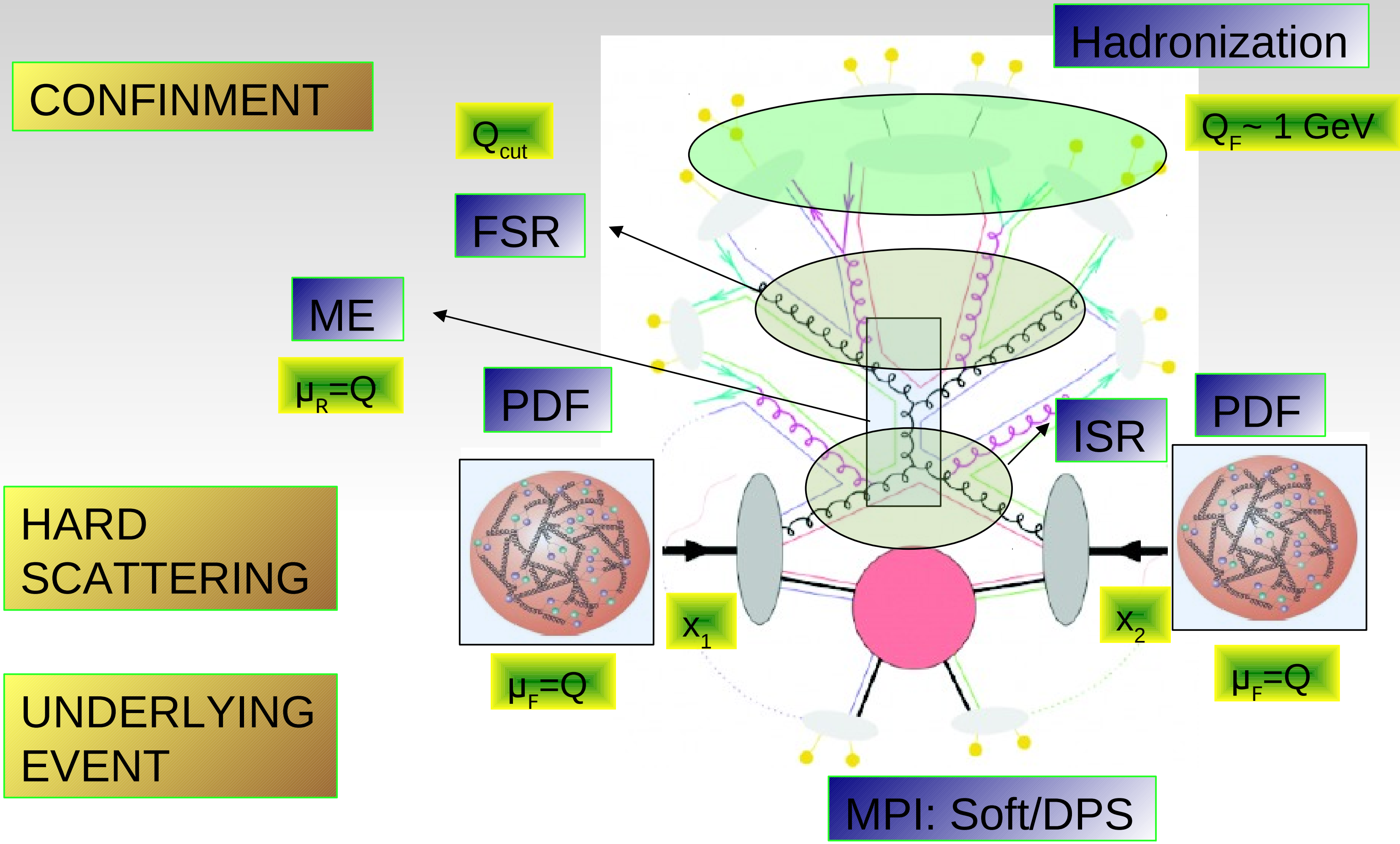


- When typical inter-parton scale Q_F ~ 1 GeV, α_S(Q)~ 1.

The theory become non-perturbative. Similar situation to PDFs.

- Solution: factorization theorem applied with universal (model dependent) fragmentation functions and their scale evolution.

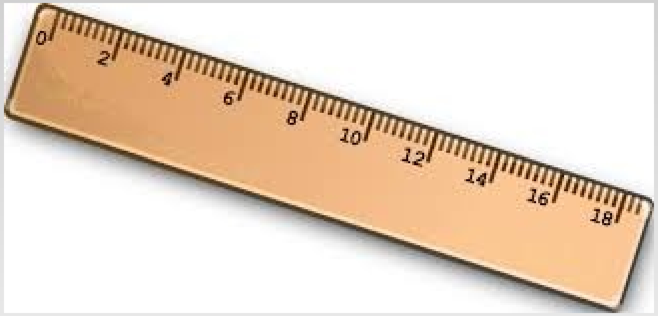
2.2) “Solve” the QCD for hadrons collisions



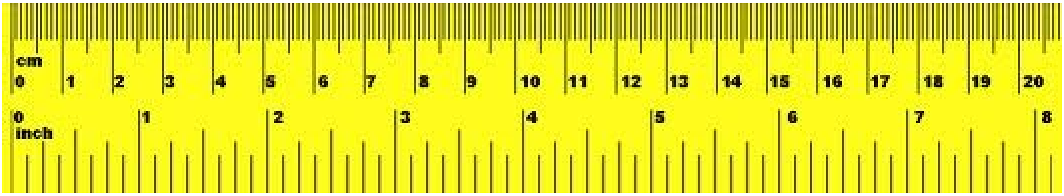
- Large partons density at low x leads to collective effects.
- Described by Multi-Partons interaction (MPI): independent mulptiple scatterings. At high momentum called Double Parton Scattering.
- All interactions might be color reconnected: coherent effects.

2.3) Structure of the LHC QCD program

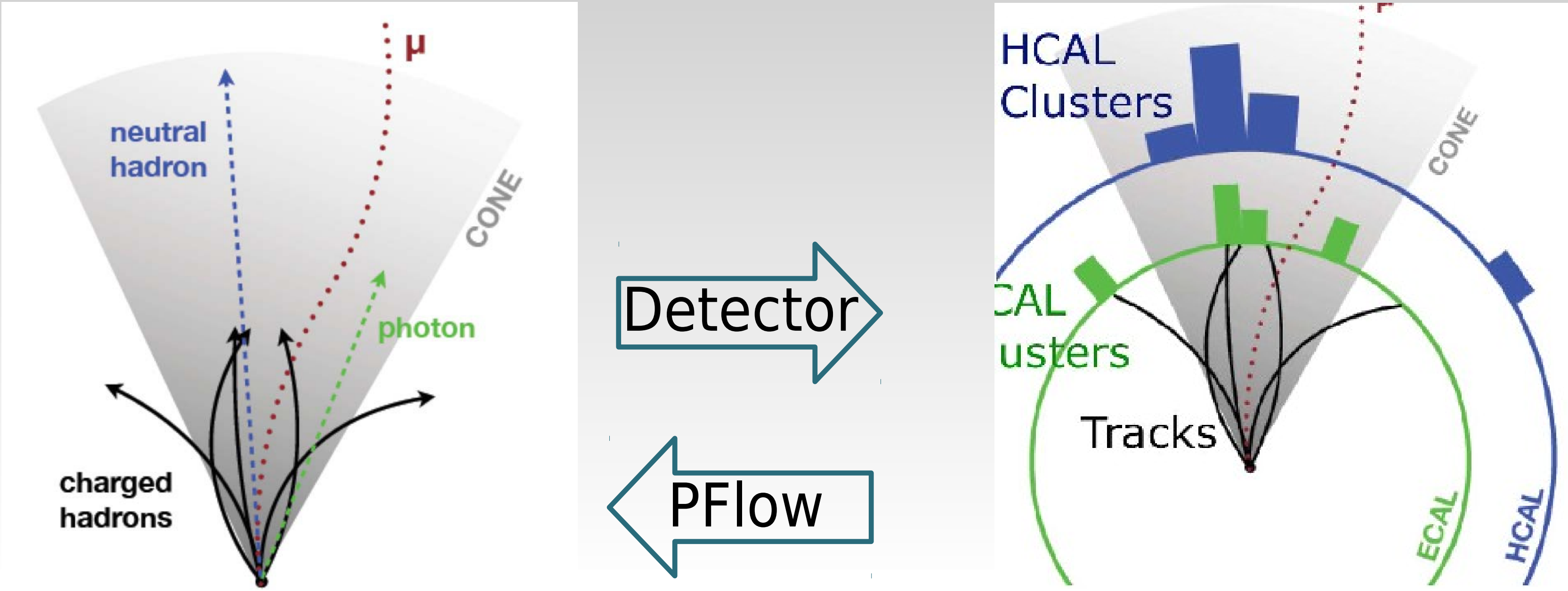
- Low PU min bias events: soft scattering including low p_T jets, UE, fragmentation.
- High p_T multi-jet events: hard matrix elements, QCD parameters (gluon PDF, α_S); collinear/soft radiation (ISR, FSR) and QCD evolution functions (DGLAP, CCFM, BFKL)
- V + jets: hard matrix elements, quarks/gluon PDF, PS
- V + HF: s,c,b PDF; Mass scales and QCD: Heavy flavour schemes in PDFs; gluons splitting.
- All: Multi-Parton interactions (MPI); Hard version of MPI: Double parton scattering (DPS).



Measure and interpret jet results



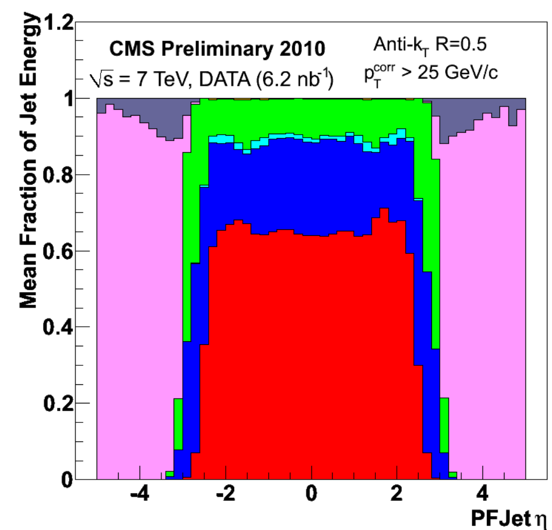
3.1) Experimental ingrediants: CMS



Particles

Clusters and tracks

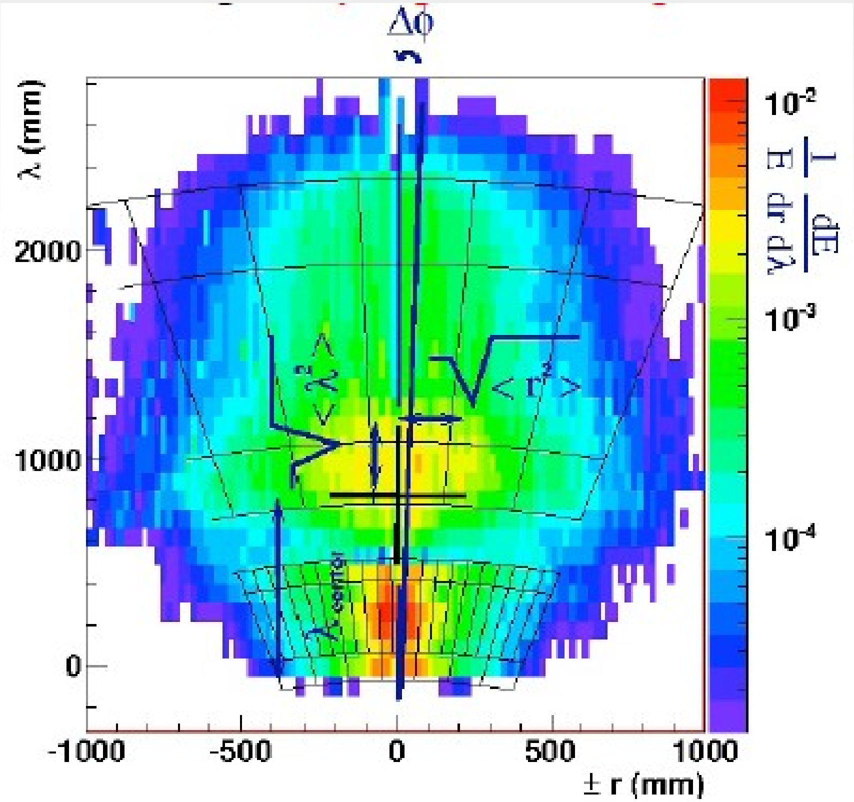
- O(5-10%) difference between rec jets and gen jets before calibration.
- Tracking provides a sensitivity to the details of the jet shapes and jet mass.
- 4-momenta are massive: m(π), m(K^0)...



3.2) Experimental ingrediants: Atlas

- Calo jets: calibrated topo clusters (heritage of non compensating LAr calorimeters H1/CDF).
- Track jets: tracks coming from the primary vertex.

- Find seed cells above noise threshold.
- Proceed with a 3D clustering around it.
- Consider topo-clusters calibration by reweighting the different layers to bring the response to the EM scale.
- 4-momentum build under assumptions:
  - Massless particles
  - Coming from primary vertex



3.4) Jets definition

- Jets are build out of particles.

Jets have to be defined infrared and collinear safe: ε change in the event kinematics produce only ε change in jet kinematics.

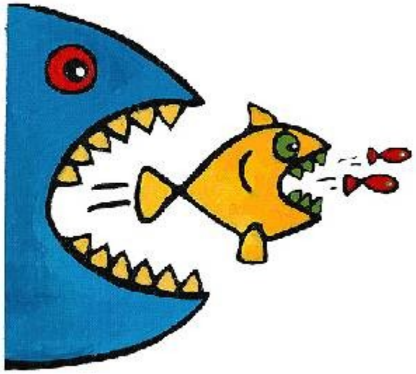
- The naive definition: a cone around the initial parton direction. Unfortunately not IR/Collinear safe in busy events.
- Today mostly iterative recombination algos used. Conic shape: anti-k_T

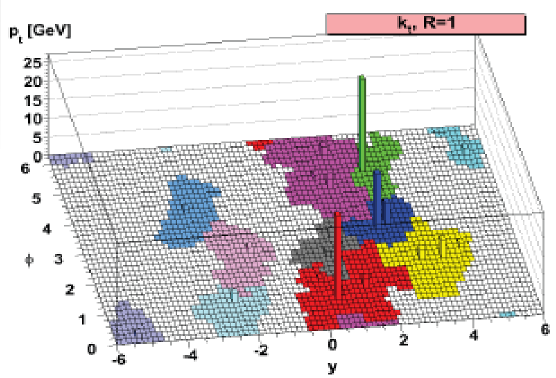
$$d_{ij} = min(k_{ti}^n, k_{tj}^n)\Delta R_{ij}^2 / R^2$$

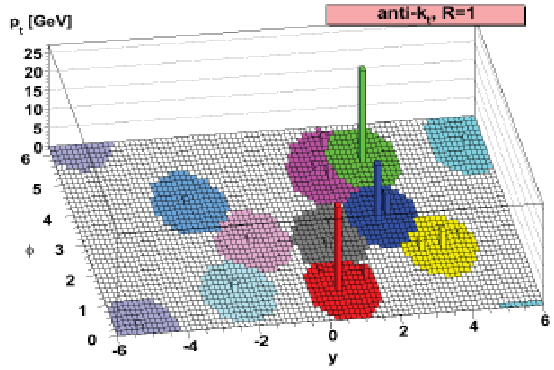
N = 1: k_T – "Small fish eat first"

N = 0: CA - "Closest fish eat first"

N = -1: anti-k_T "Big fish eat first"







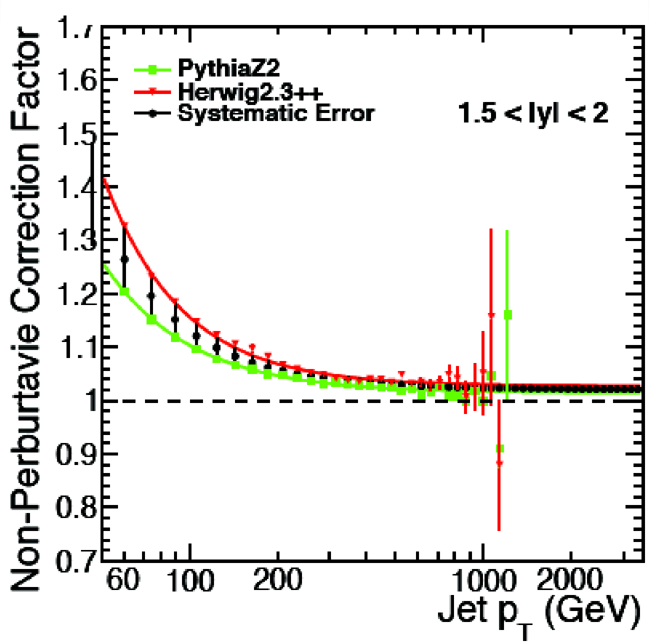
3.5) Typical measurement: Inclusive jets

- Elements explained below are generic for any analysis including jets.

$$\frac{d\sigma^2_{Data}}{dp_T\,dy} = \frac{d\sigma^2_{Det}}{dp_T\,dy} C_{Det}$$

$$\frac{d\sigma^2_{Thr}}{dp_T\,dy} = \frac{d\sigma^2_{NLO}}{dp_T\,dy} C_{NP}$$

- Measurement: corrected for detector effect to “hadrons level” (unfolding) – C_{DET}.
  - Related to limited detector response resolution to particle constituents of the jet.
  - Can be large due to steeply falling QCD spectra.
- NLO calculation: corrected for hadronization and MPI effects estimated from LO+PS MC – C_{NP}.
  - Related to absolute shift of jet p_T.
  - Can be large due to steeply falling QCD spectra.

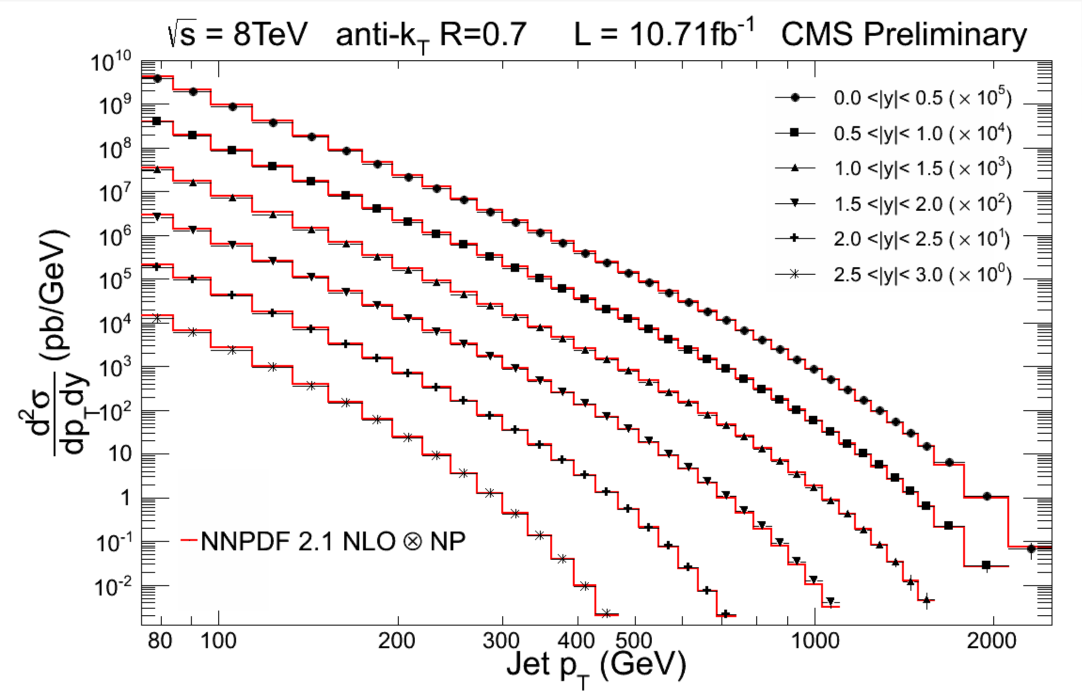


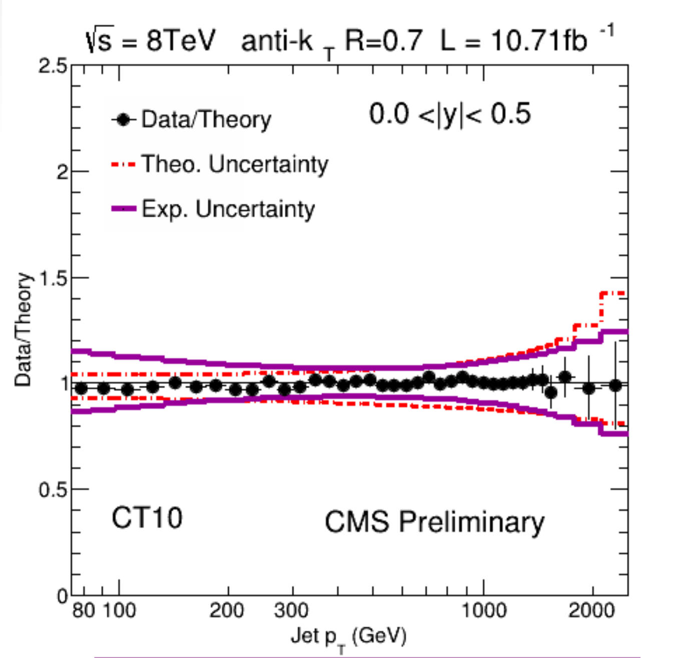
3.5) Typical measurement: Inclusive jets

- Experimental uncertainty: mainly 1-2 % uncertainty on the jet calibration factors. Become 10% due to a typical slope of n ~ 5-6.

$$\frac{d\sigma}{dp_T} \propto p_T^n$$

- Theory uncertainty:
  – Mainly expected effect of missing orders estimated by scale dependence.
  – At low p_T NP uncertainty dominates, at high p_T PDF uncertainty dominates.





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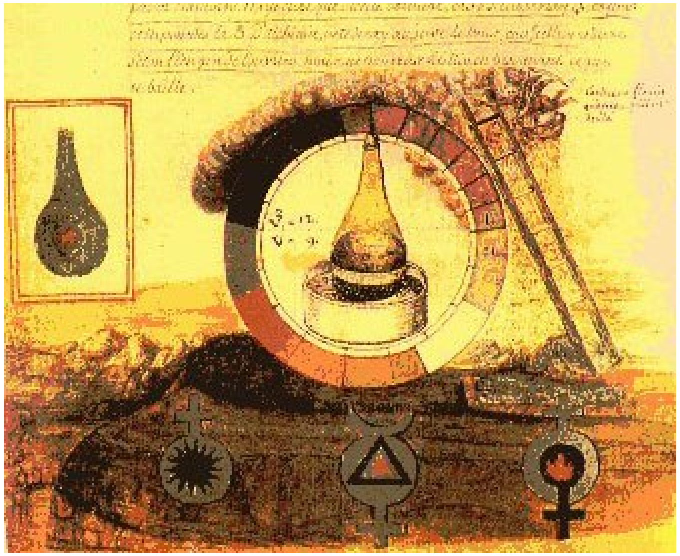
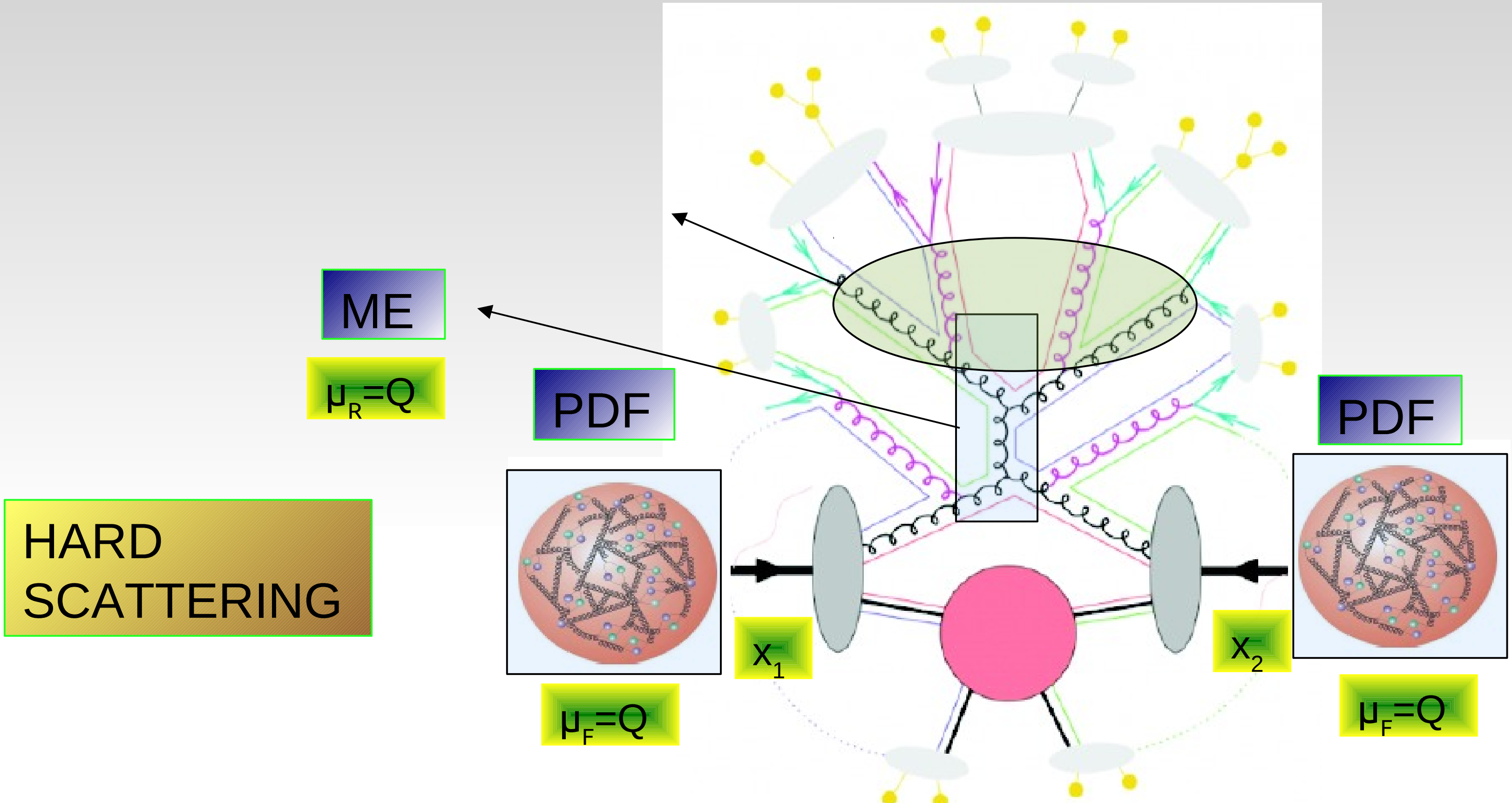
Extraction of the QCD parameters

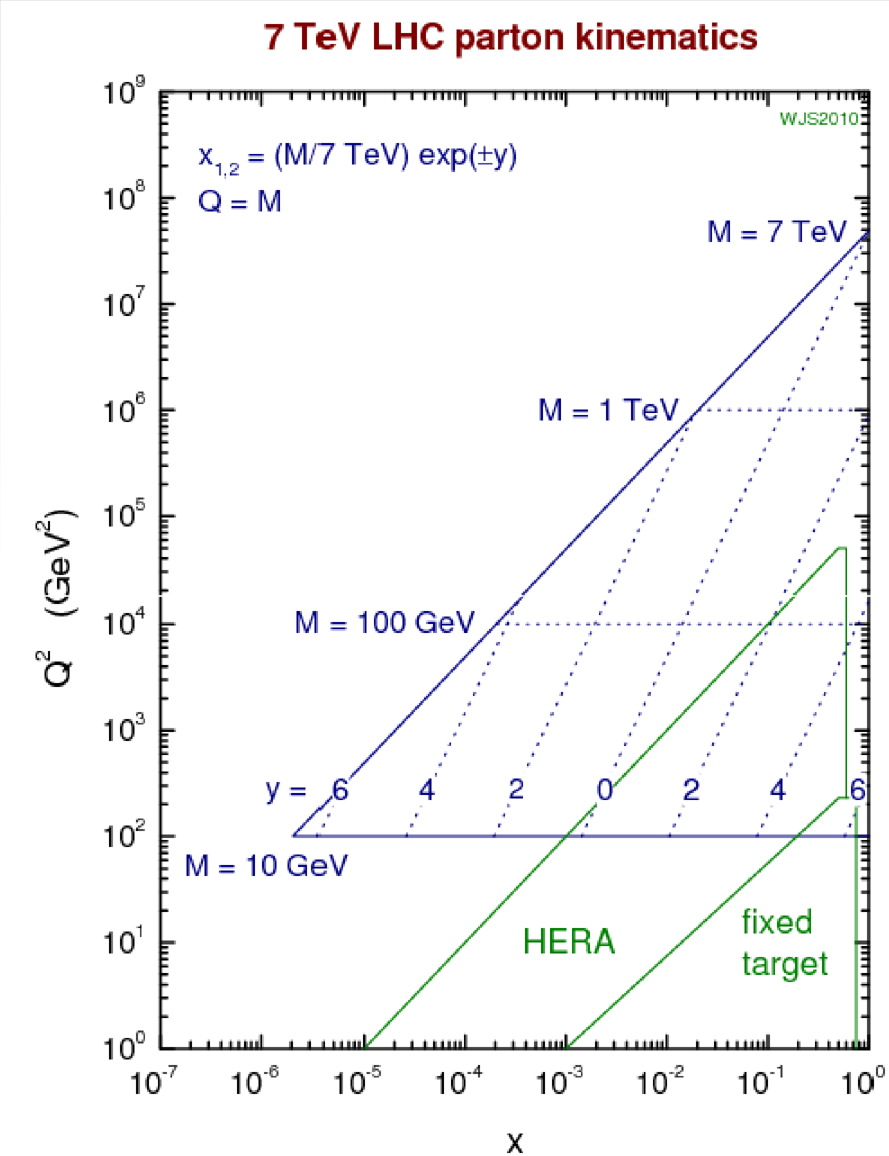


4.1) How to determine QCD parameters

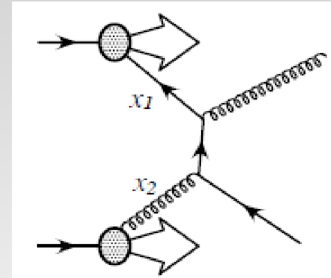


- Go to a phase-space region sensitive to mainly hard scattering component.
- The $\alpha_S(\mu_R=Q)$ sensibility appears through the jets counting as function of Q.
- The PDF(μ_F=Q) sensibility appears through the Q dependence of a (simple) process.

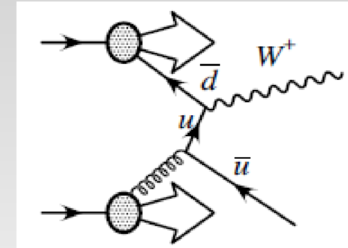
4.2) LHC sensitivity



Gluons density

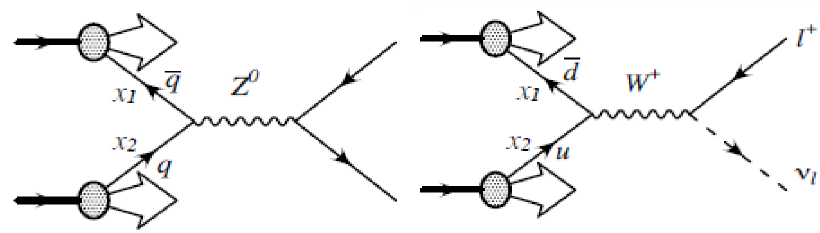


Dijets



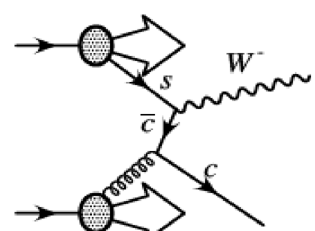
QCD Compton
V+ 1 jet

Light quarks density



DY: Single V/V*

Heavy quarks density

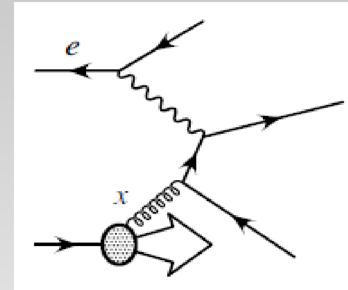


QCD Compton:
V+HF

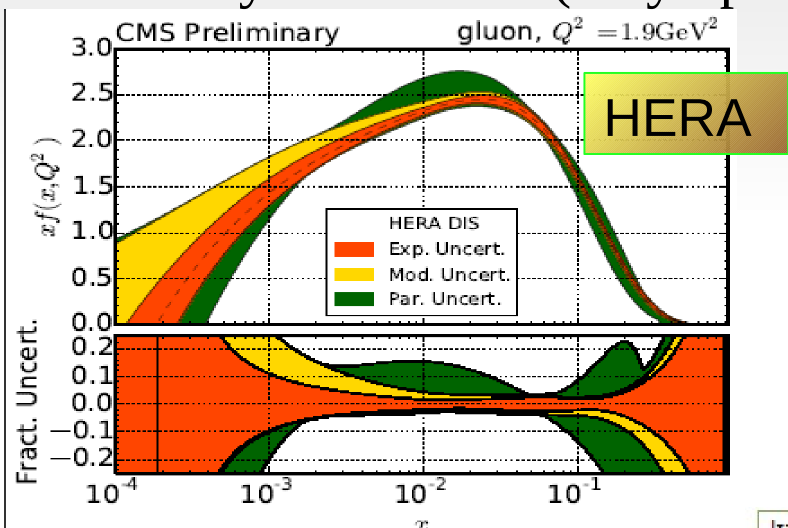
4.3) Gluon from Inclusive jets

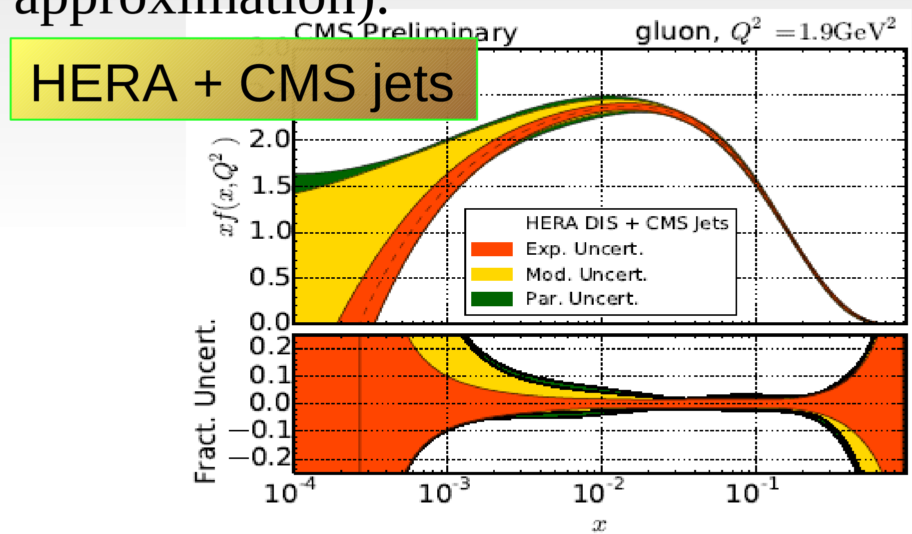
- Backbone of PDF extraction: HERA DIS data

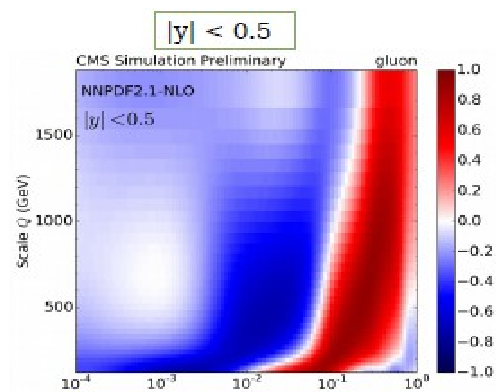
$$d\sigma_{\mathrm{DIS}} \sim (1-(1-y_{\mathrm{Bj}})^2)F_2(x,Q^2) - y_{\mathrm{Bj}}^2 F_L(x,Q^2)$$
$$F_2 = x\sum_q e_q^2(q(x)+\bar{q}(x))$$



- HERA DIS data only indirectly sensitives to gluon (trough DGLAP evolution)
- In this exercise we add CMS jet data on top of HERA DIS. No scale uncertainty considered (very optimistic approximation).







Phys. Rev. D 87 (2013) 112002

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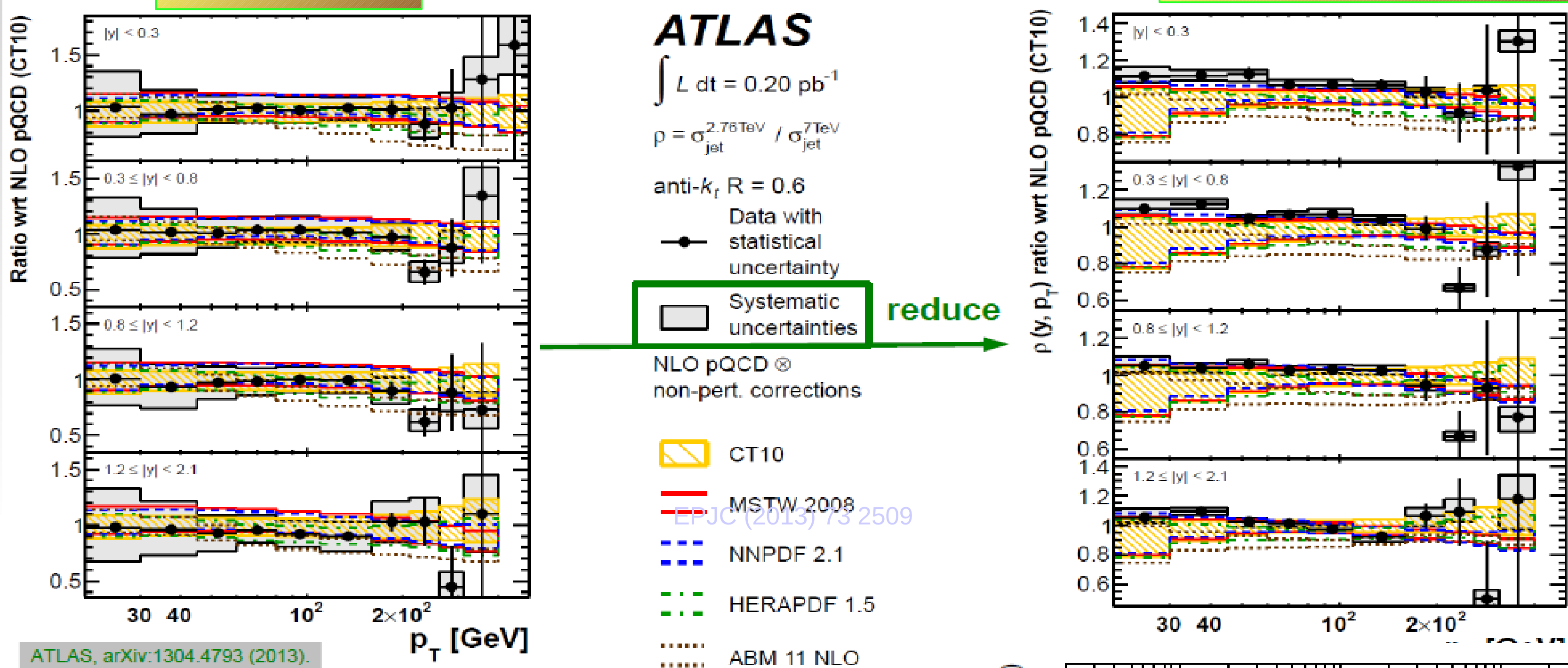
4.3) Gluon from Inclusive jets

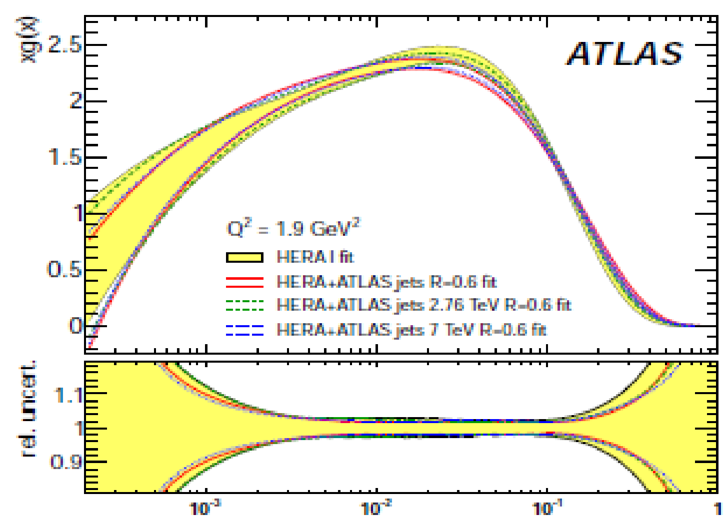
EPJC (2013) 73 2509

2.76 TeV

2.76 TeV/7 TeV



- The ratio provide a better improvement than each cross section taken separately. But the effect seems to be small.
- But the scale uncertainties are also small. Therefore neglecting scale uncertainties in the ratio is much more correct than for the absolute X sections.

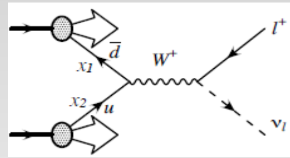


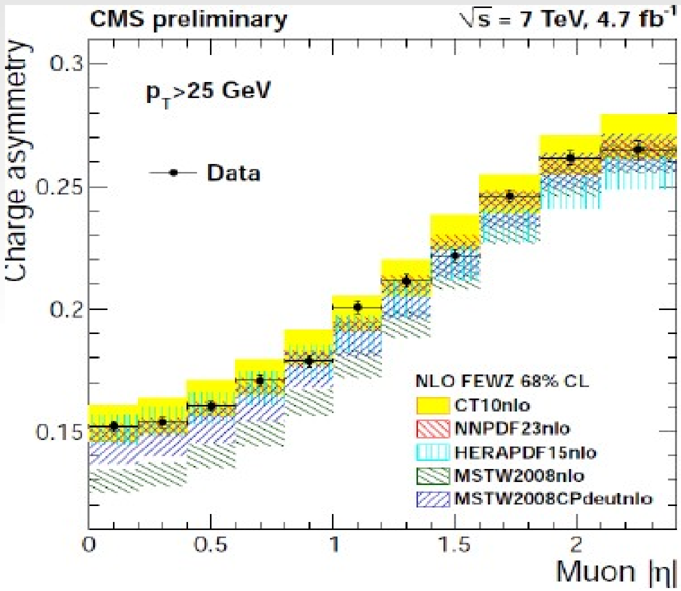
4.4) Light quarks from W asymmetry

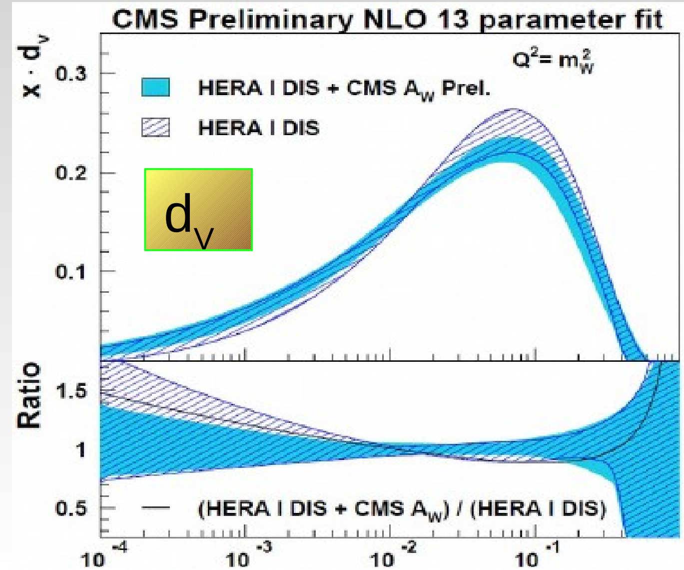
arXiv:1312.6283

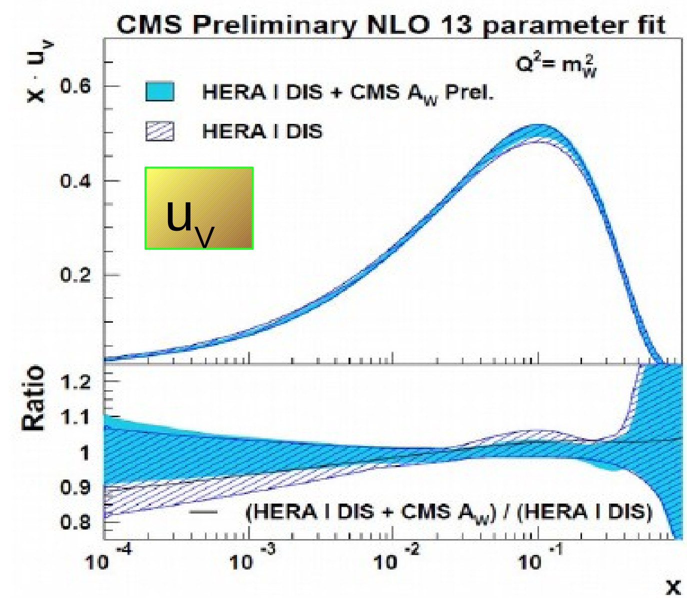
W lepton asymmetry

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{\mathrm{sea}}}$$









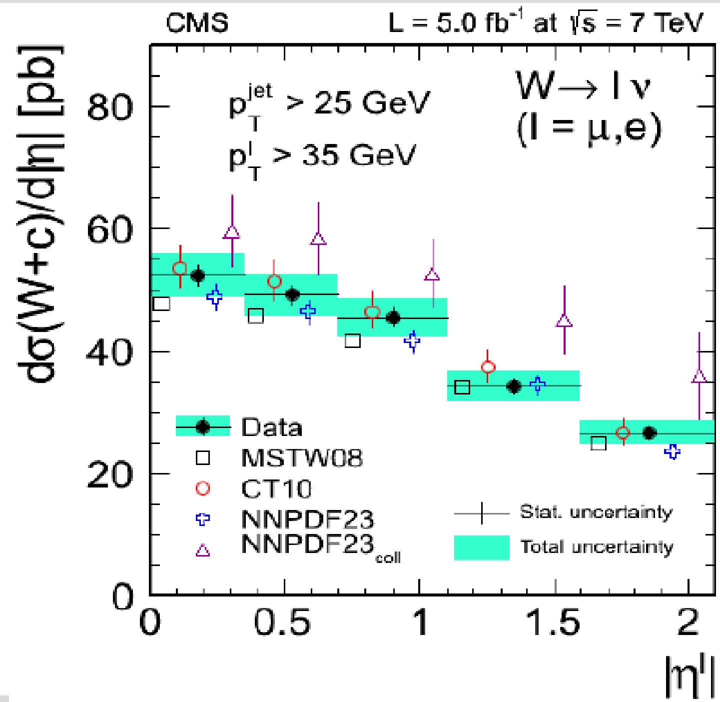
- HERA I DIS do not have enough sensitivity to d_V due to limited amount of e+p collisions ($e+d \rightarrow \nu+u$).

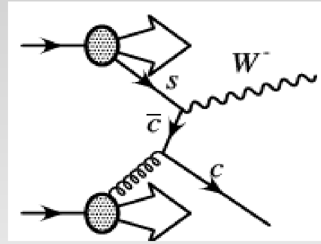
4.5) Quarks from W+c and W asymmetry

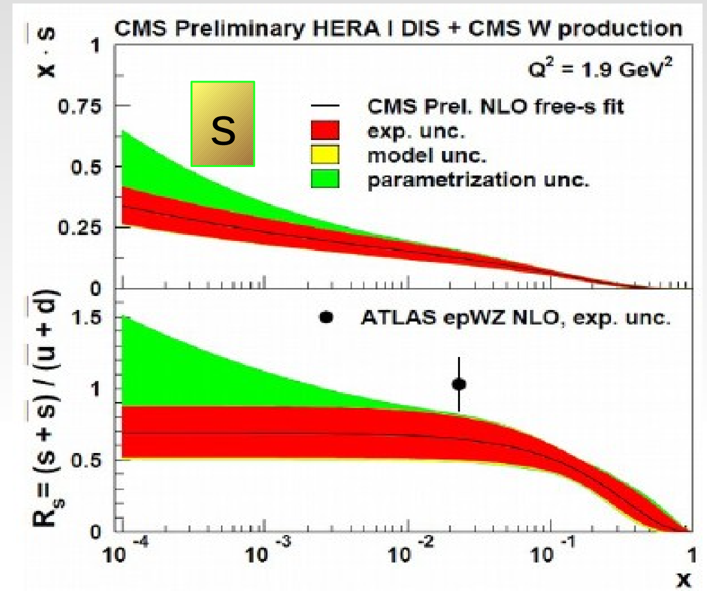
arXiv:1312.6283

arXiv:1310.1138

W+c

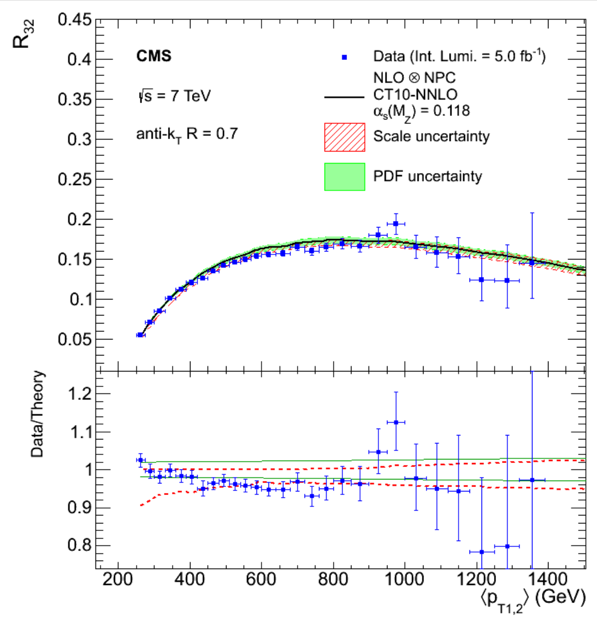






- HERA I DIS do not have any sensitivity to strangeness. Use input from fixed target data with not so well known nuclear corrections.

4.6) Strong coupling

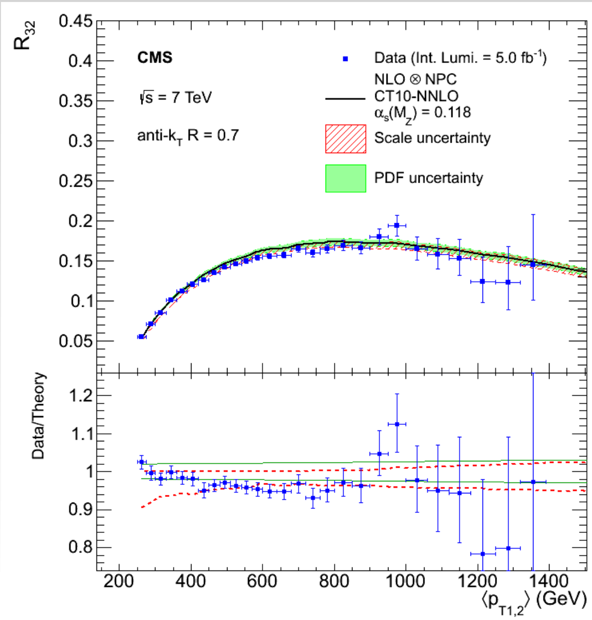


$$\sigma_{3\text{jets}} \propto \alpha_S^2$$
$$\sigma_{2\text{jets}}, \sigma_{\text{ttbar}} \propto \alpha_S$$
$$R_{32} \propto \alpha_s$$

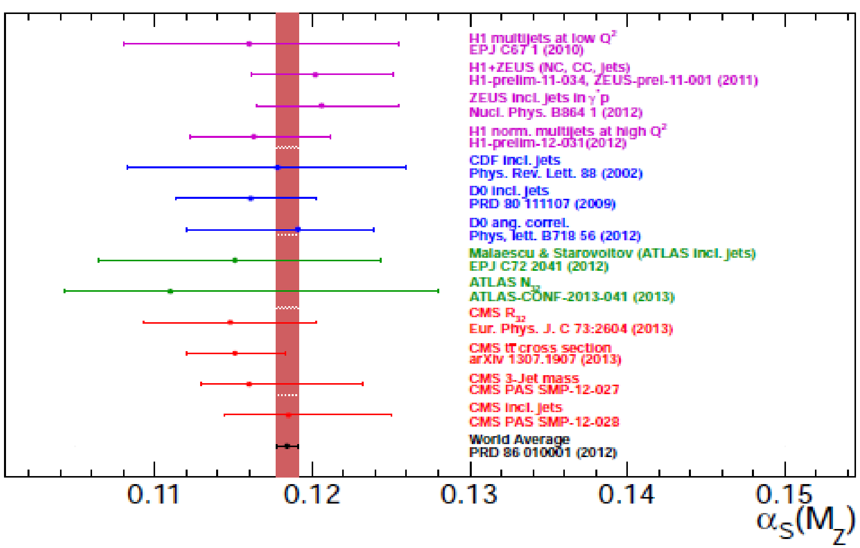
- Jet observables proportional to α_s^n
- R32 is the less sensitive to PDF

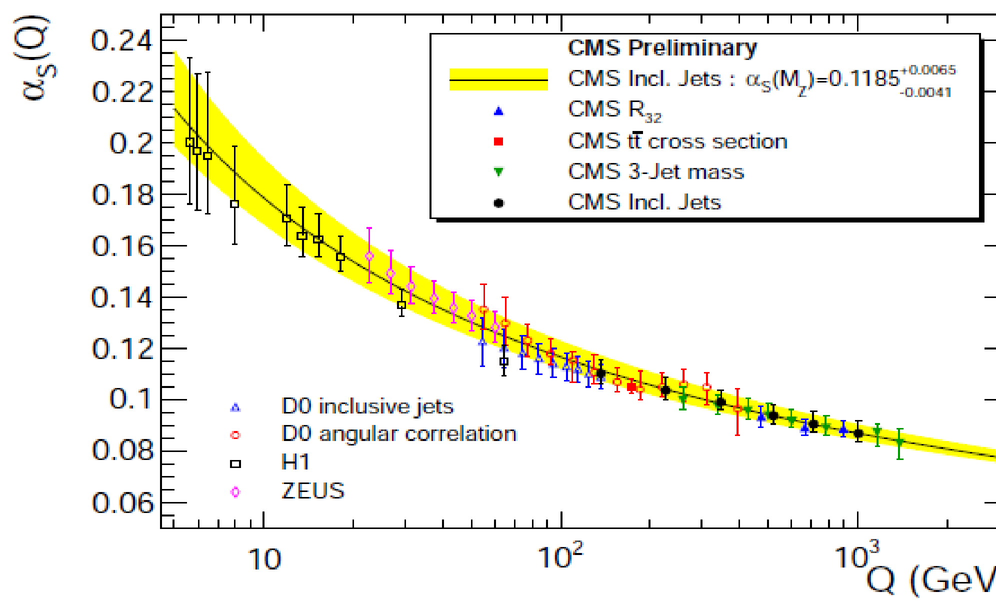
4.6) Strong coupling

$$\sigma_{3jets} \propto \alpha_S^2$$
$$\sigma_{2jets}, \sigma_{ttbar} \propto \alpha_S$$
$$R_{32} \propto \alpha_s$$



- Jet observables proportional to α_s^n
- R32 is the less sensitive to PDF
- Scale uncertainties are dominant. Need NNLO to promote them. Expected for dijets. But:
  - α_S(Q ~ 1 TeV) tested.
  - Jet rates not so sensitives to PDF so can be used for search for new fermions/ extra dim.



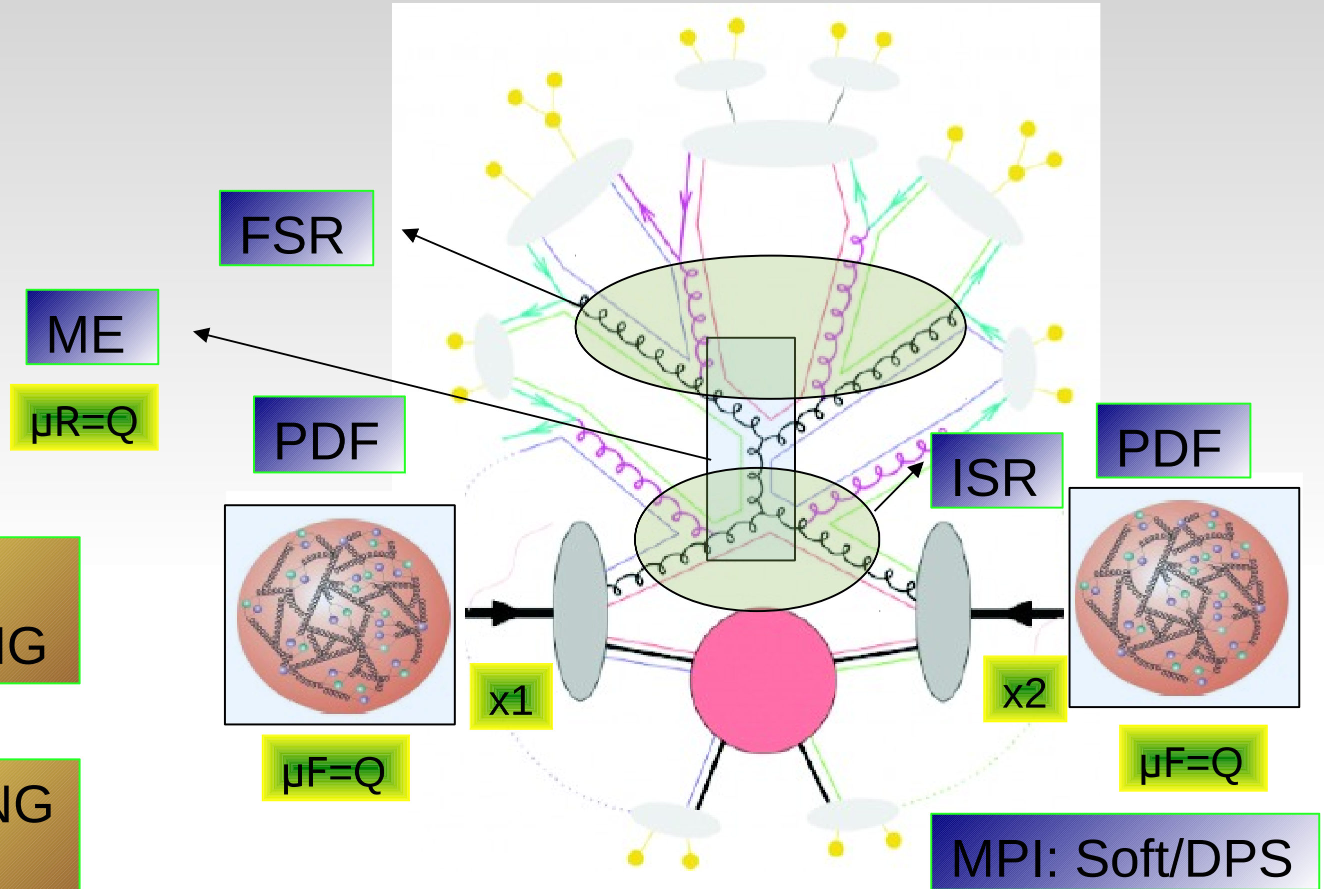


Testing the soft dynamics

5.1) “Solve” the QCD for hadrons collisions

HARD SCATTERING

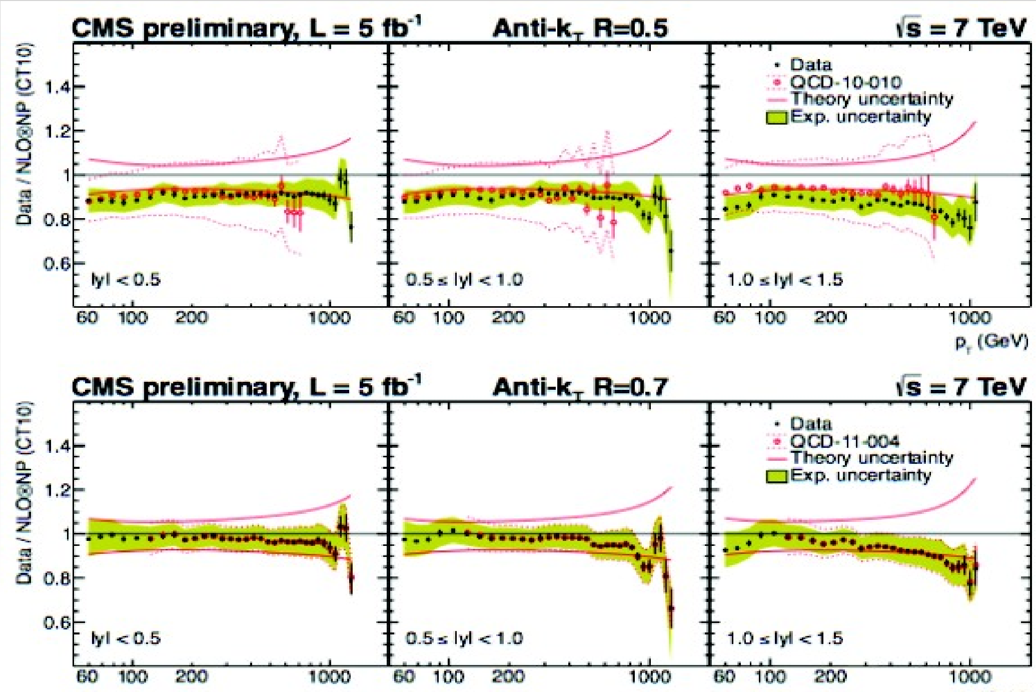
UNDERLYING EVENT



- Go to a region of phase space where the missing orders beyond NLO matters.
- Study the interplay between collinear/IR re-summations (PS) and ME multi-jet topologies at LO/NLO.
- Emphasis different regimes: ISR/FSR dominated, color coherence sensitives, gluon splitting to heavy quarks in ISR/FSR.

5.2) FSR radiation effects

SMP-13-002



R=0.5

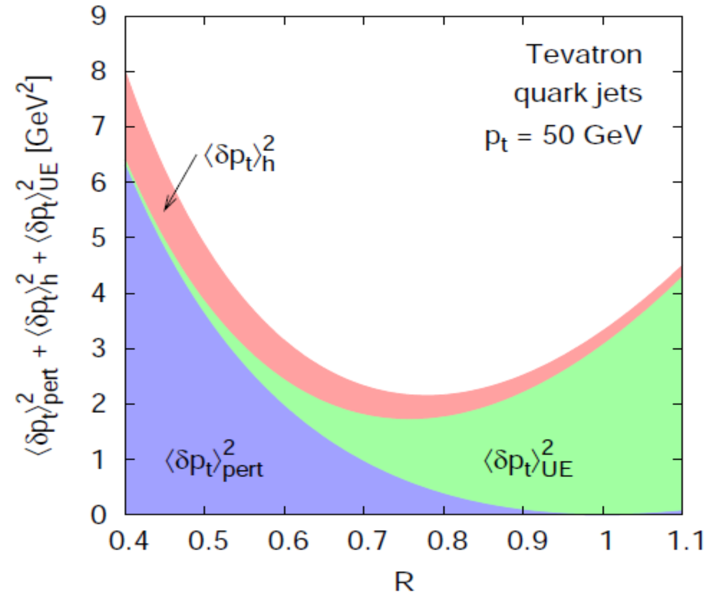
(2010, 36 pb^{-1})

R=0.7

(2011, 5 fb^{-1})

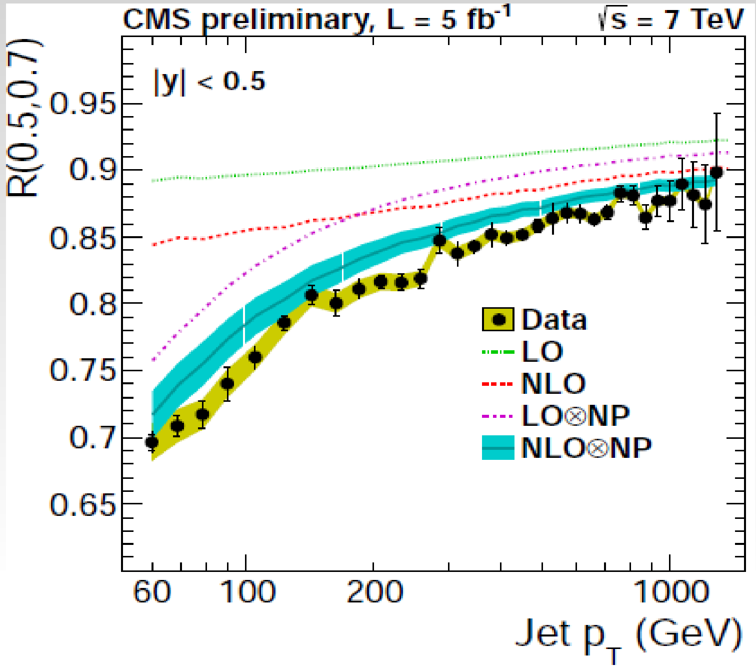
ArXiv:0712.3014

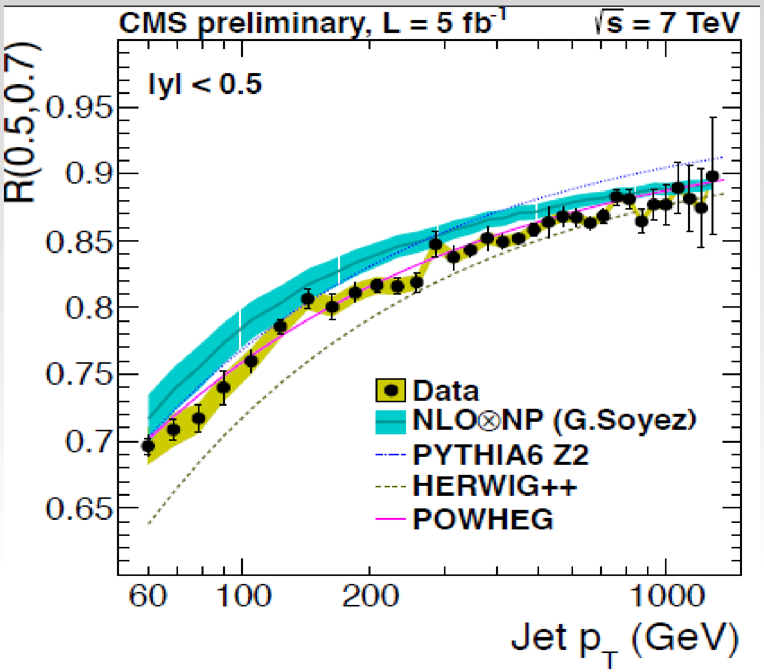
- Smaller R at LHC shows more tension with NLO QCD predictions and QCD parameters extracted independently
- Jet radius choice is a compromise between FSR out-of-cone migration $\propto \ln 1/R$
NP out-of-cone migration $\propto 1/R$
UE in-cone capture $\propto R^2$



5.2) FSR radiation effects

SMP-13-002

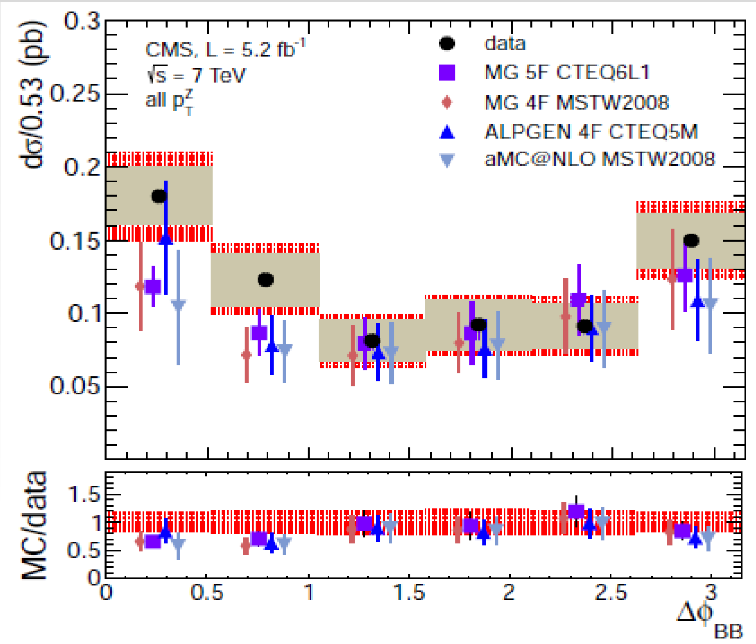


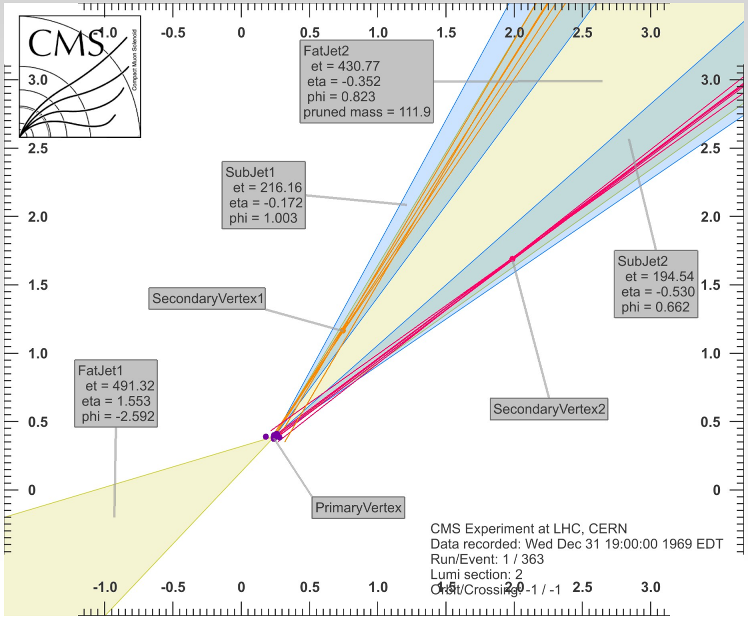


- Many uncertainties cancel out. Percentage precision!
- Jet Radius Ratio: $\frac{\sigma_{\text{2jets,R1,NLO}}}{\sigma_{\text{2jets,R2,NLO}}} = R_{12,LO}$. Fail to describe the ratio!
- A trick can be used to compute $R_{12,NLO}$ from $\sigma_{\text{3jets,R1,NLO}}$ and $\sigma_{\text{3jets,R2,NLO}}$. Works better.
- In fact the best is PS, but even better 2 jets NLO+PS (POWHEG).
- Moral: if you want to use jets for QCD parameters extraction do not go too low in R otherwise you need re-summations.

5.3) Gluon splitting in FSR

J. High Energy Phys. 12 (2013) 39



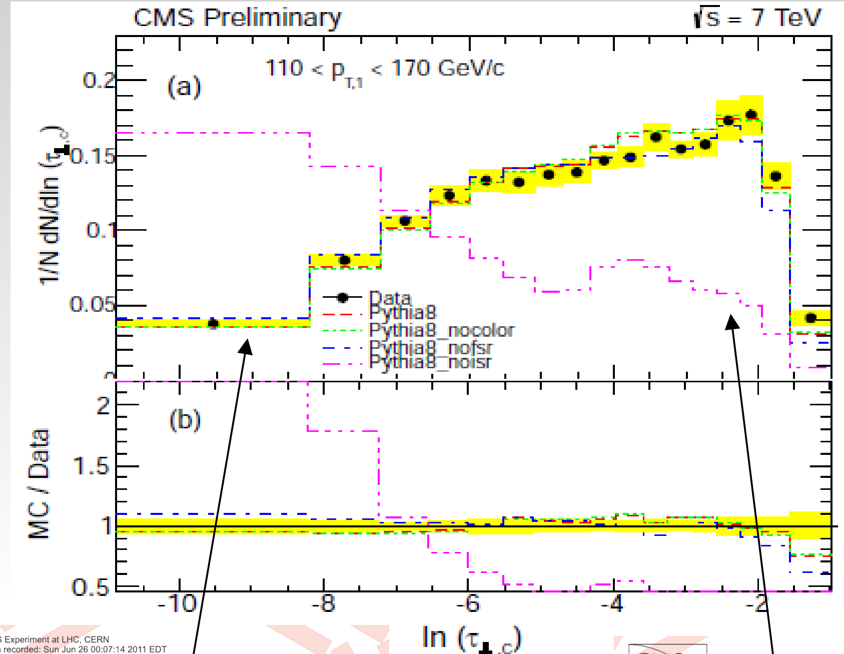


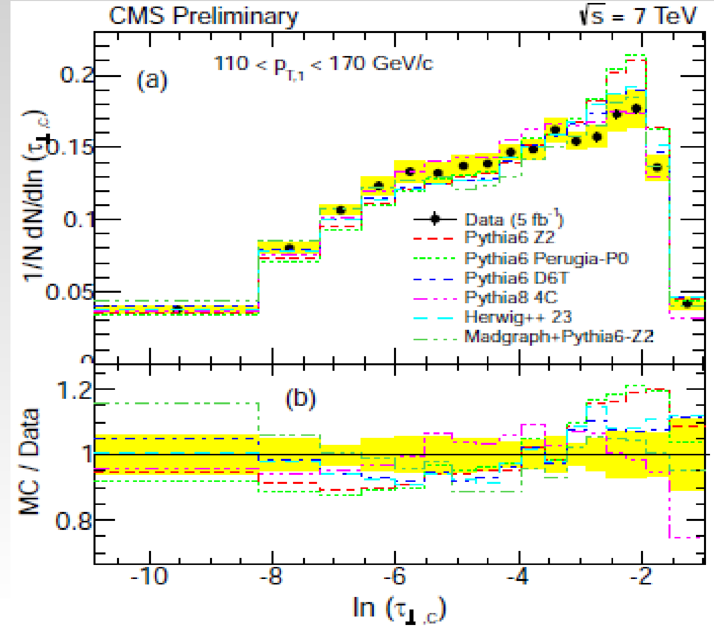
Example of IVF for a BSM event

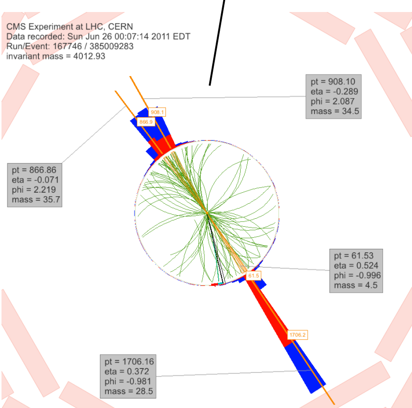
- Z→νν + b quark is a typical background for 3rd generation SUSY. Frequently Z+bb looks like Z+b due to inefficiency of classical b-taggers. In many searches MC used since data Z+bb do not benefit from sufficient statistics.
- Specially developed inclusive vertex finder used for b-quarks.
- MC underestimate data by 40% in the collinear region

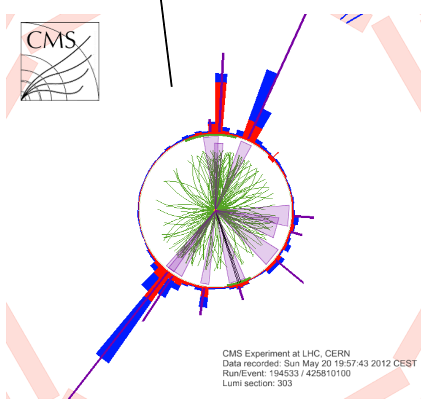
5.4) Event shapes and ISR

SMP-12-022







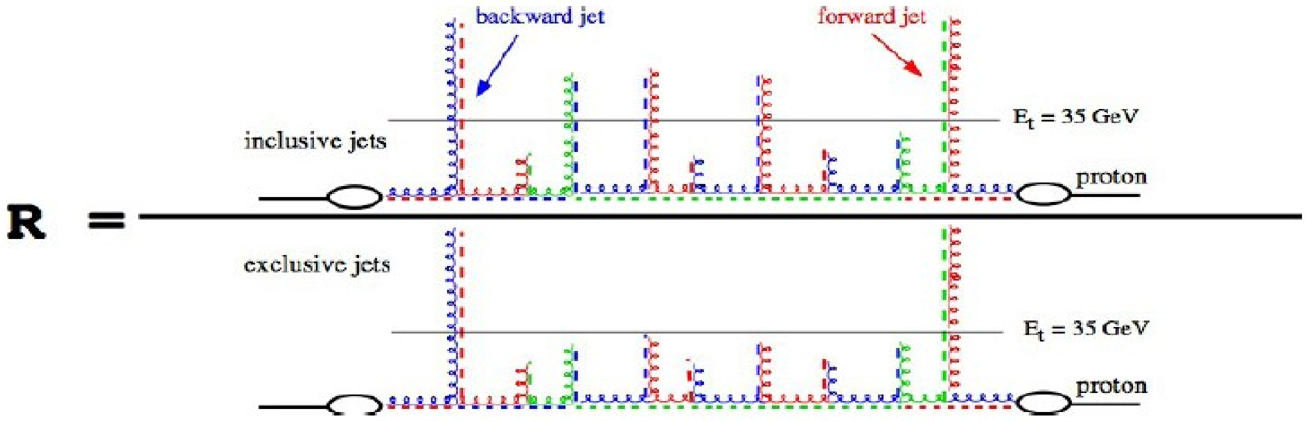


- Transverse thrust: sensitive to large angle production of soft radiation.
- The combination of multi-jet ME production at LO and PS produce the best description.

5.5) Resummation approach

arXiv 1204.0696
EPJC72(2012) 2216

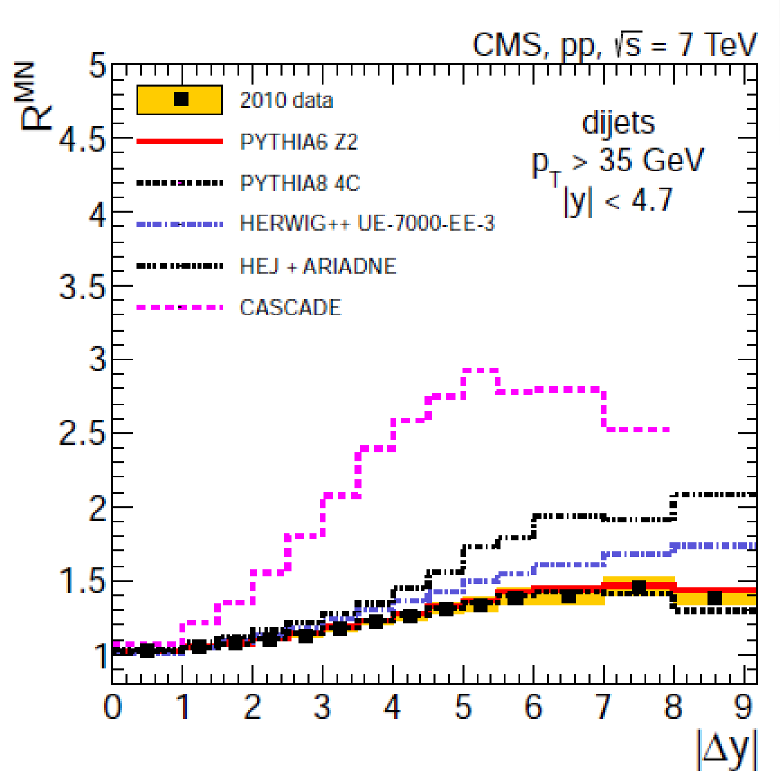
- Measure ratio of inclusive dijets events to exclusive dijet events : canlcelation of systematics
- |Δy| ~|Δη| < 9 !!! between the two most external jets (Mueller-Navlett).
- Hope to see non DGLAP dynamics in the ladders between two jets.
- Strategic region for VBF physics : large |Δy| and central jets veto



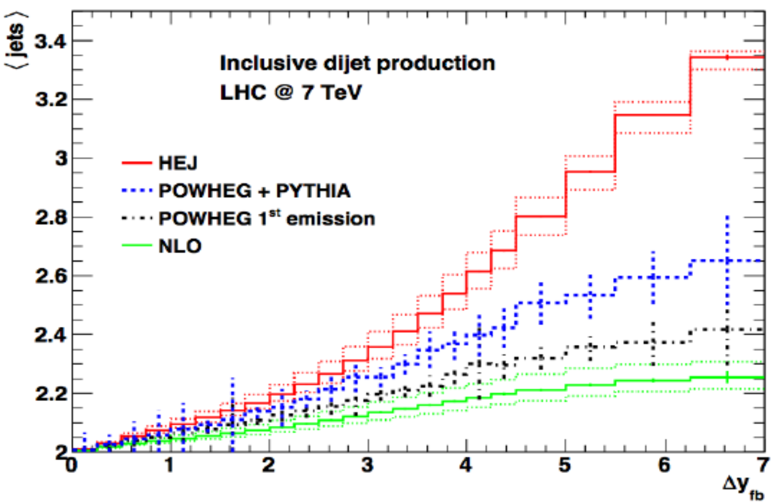
5.5) Resummation approach

ArXiv 1204.0696
EPJC72(2012) 2216

- Ratio only described by PYTHIA (surprising ?). Influence of the tune and MPI small.
- Deviation of most of the other models at large |Δy|.
- Cascade, HEJ : include elements of CCFM or BFKL like dynamics.



S. Alioli et al arXiv 1202.1475v1

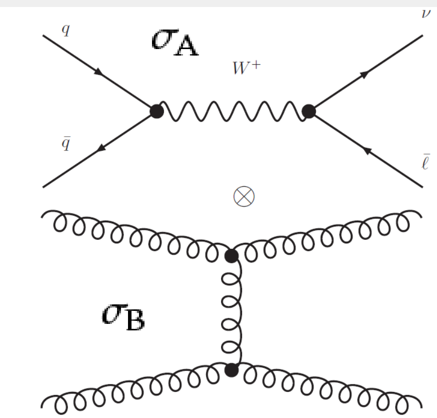


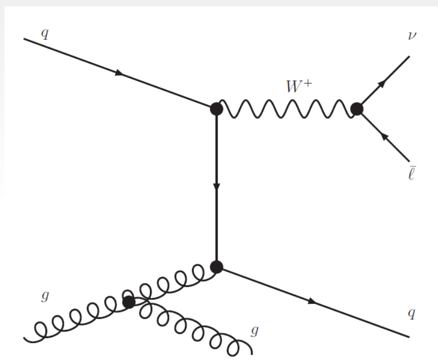
5.6) Discover the DPS?

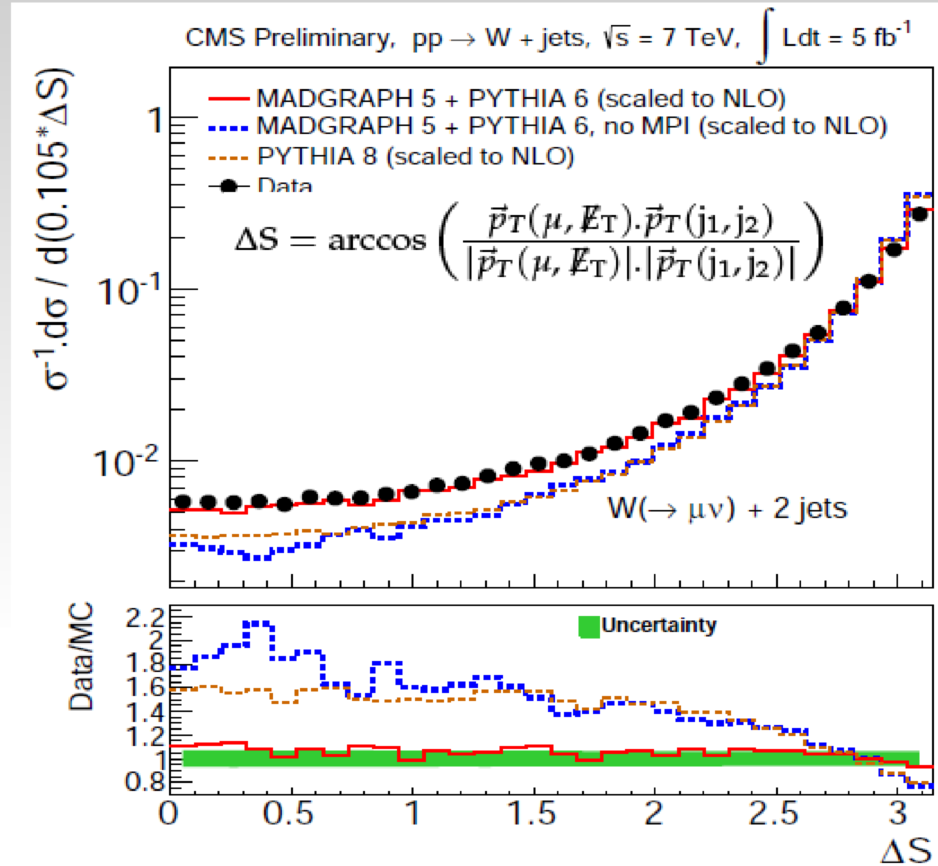
Azimuthal angle W and Dijets

$$\sigma_{\rm eff} = \frac{m}{2}\frac{\sigma_A \cdot \sigma_B}{\sigma^{DPS}_{A+B}}$$

$$\sigma^{DPS}_{A+B}$$



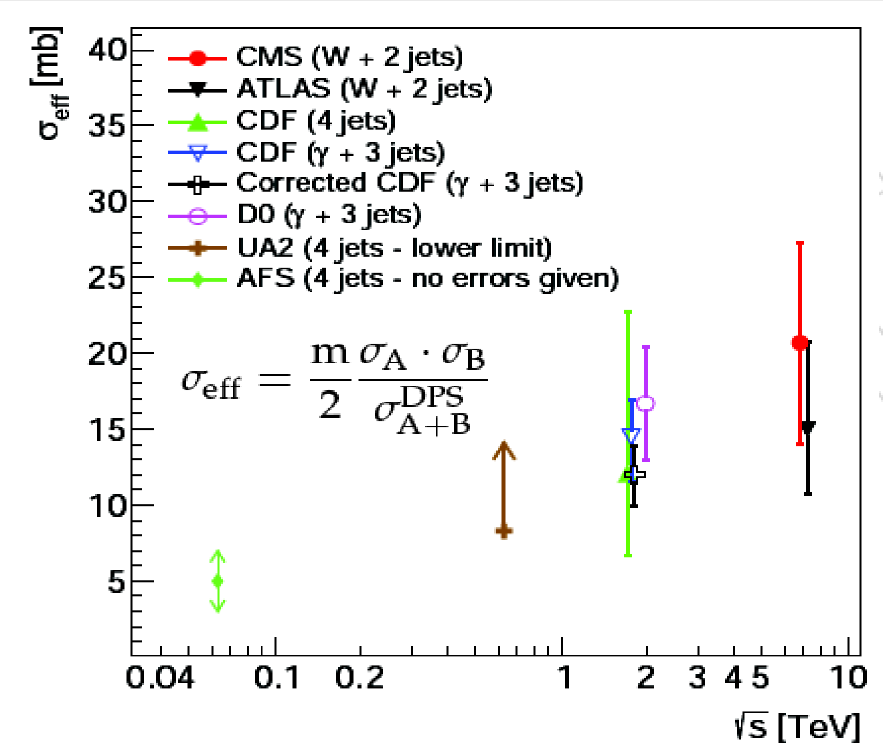




- In the DPS there is no angular correlation between the 2 interactions, while in SPS they are correlated back-to-back.
- DPS can be extracted from processes where A && B have a much larger cross section than SPS A+B.

arXiv:1312.5729

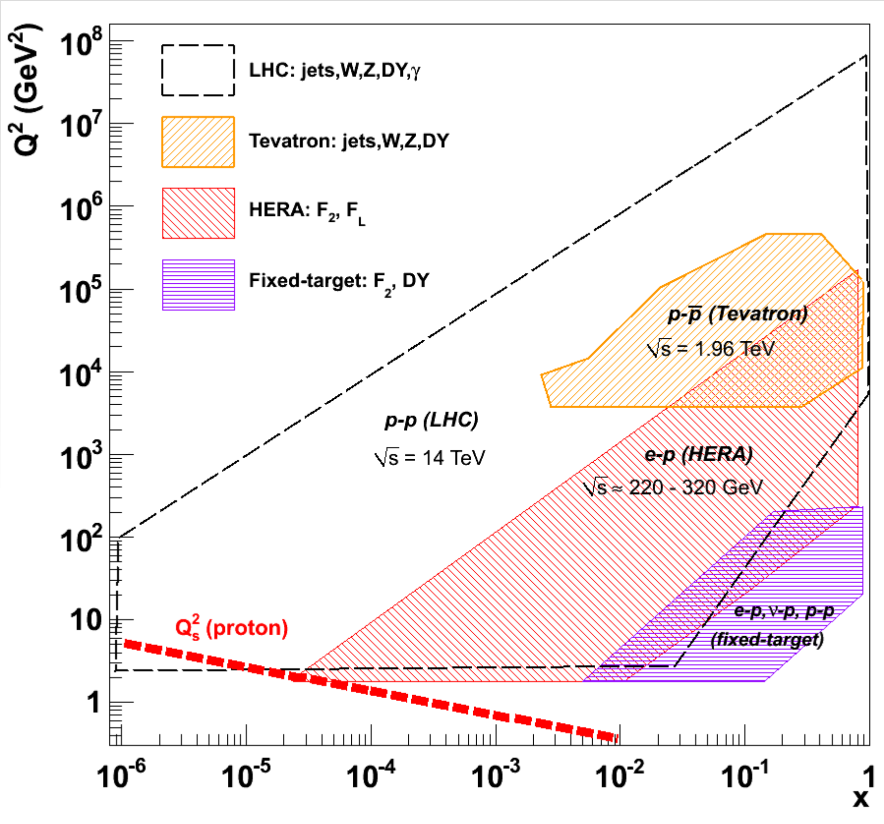
5.6) Discover the DPS?



- The measurements performed till now do not allow to distinguish between the dependence and in-dependence of $\sqrt{s}$.
- Remaining Run I and Run II measurements may provide an answer there.
- DPS have contributions to soft VV production, background to Higgs production. Need to be sure we understand it well.

5.7) Run I/II what else?

- The first Run II data would be used for high priority Standard Model analyses:
  - Inclusive V production
  - V+jets production
  - V+HF production
  - VV production
- Those measurement are expected to provide the information for additional MC retuning on top of Run I: PS, MPI.
- Extra PDF constraints mainly through DGLAP evolution: Cross sections ratios 13 TeV/8 TeV + high p_T tails at 13 TeV would be of critical use.



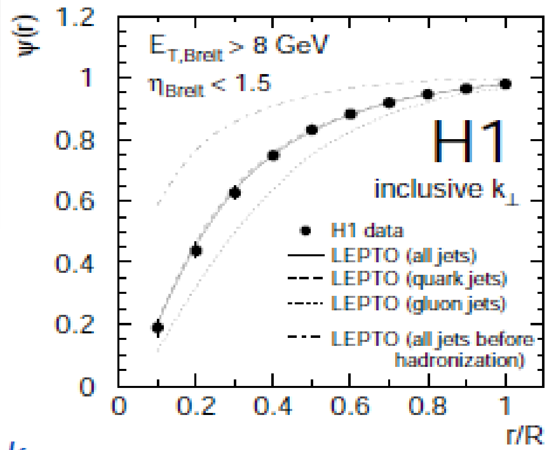
m_H (GeV)	Cross Section (pb)	+error %	- error %	+scale %	-scale %	+(PDF+α_s) %	-(PDF+α_s) %
125	49.85	19.6	-14.6	12.2	-8.4	7.4	-6.2

HXSWG gg→ H

Jets substructure: the new El Dorado

6.1) A bit of history

- Jet shapes existed already in the previous generation of colliders (LEP, HERA, Tevatron) times.
  - Study QCD parameters and soft gluon effects.
  - Improve jets calibration for non-compensated calorimeters.
  - Distinguish jets flavours:
    - quark, gluon – all sorts of energy flows;
    - c-jet, b-jet – “charge” flow like vertices or displaced tracks.
    - Up/down – jet charge (see later…).



DESY-98-208

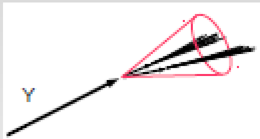
- But the QCD matrix element: $d\sigma \sim \alpha_S \, d\theta / \theta \, dk_T / k_T$
  - No intrinsic mass above b-quark mass (4-5 GeV depending on the definition). Just QCD radiation.

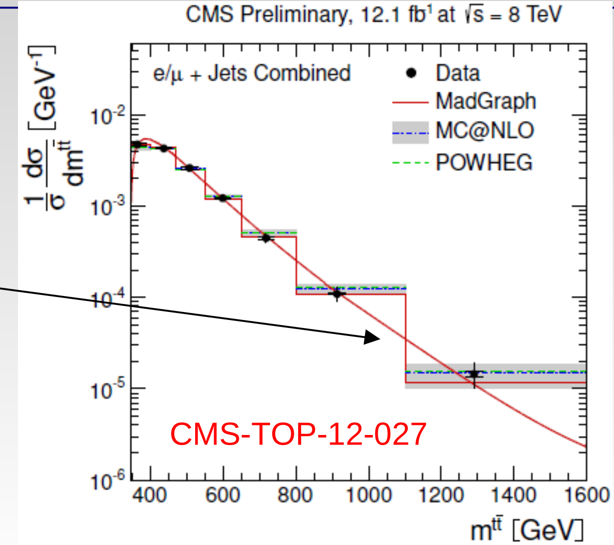
$$\langle M_J^2 \rangle_{NLO} \simeq \overline{C}\left(\frac{p_J}{\sqrt{s}}\right) \alpha_s\left(\frac{p_J}{2}\right) p_J^2 R^2,$$

  - No intrinsic angular scale = no instrinsic multipolar structure.

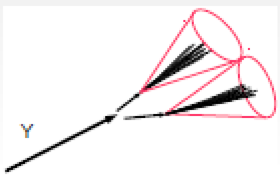
6.2) New boosted regime: come back of V→qq

1) Substructure : $\Delta R < R_j$

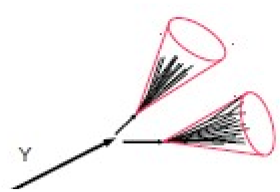


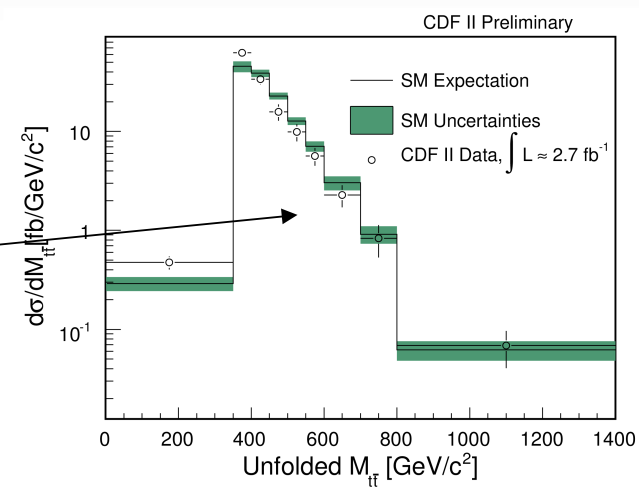


2) Transition region : $\Delta R \sim R_j$



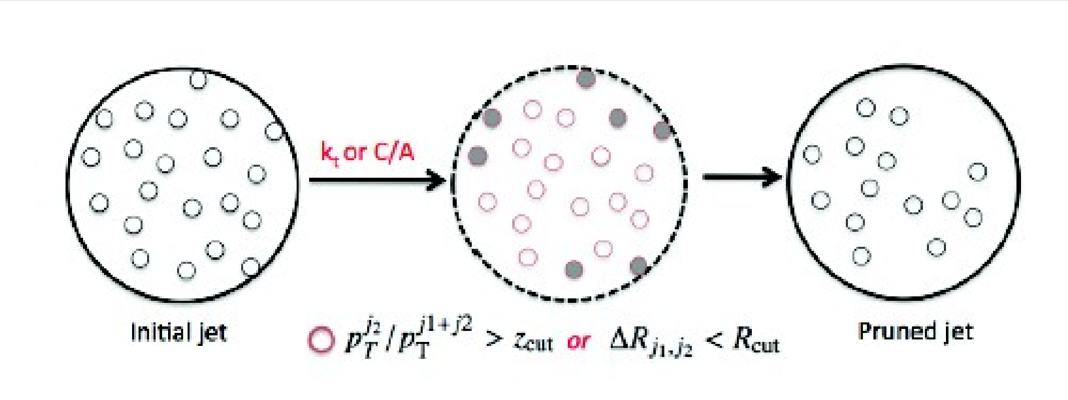
3) Separated jets : $\Delta R > R_j$

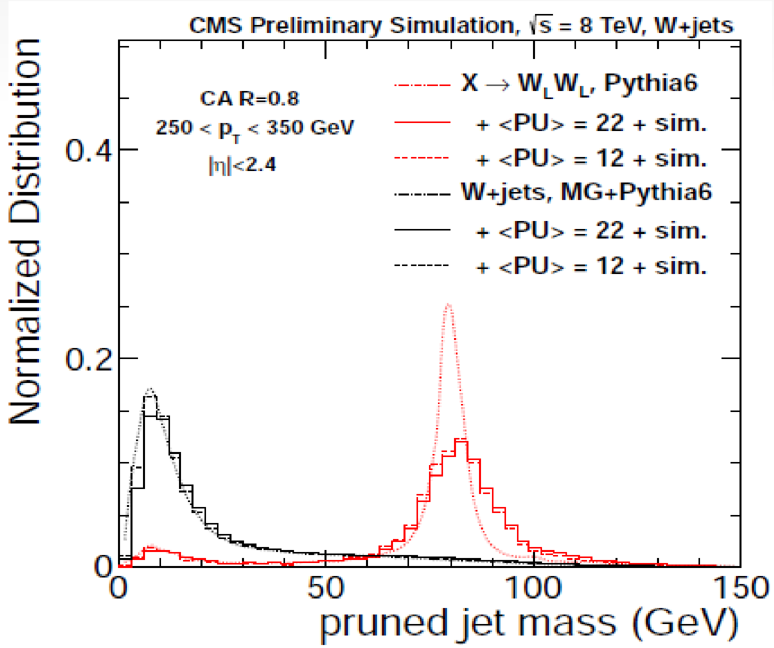




Typically pair production: $\Delta R = \frac{4M_Y}{M_X} \approx \frac{2M_Y}{p_T} \approx \gamma_Y$ $\quad \Delta R = \frac{4M_t}{M_{tt}}$

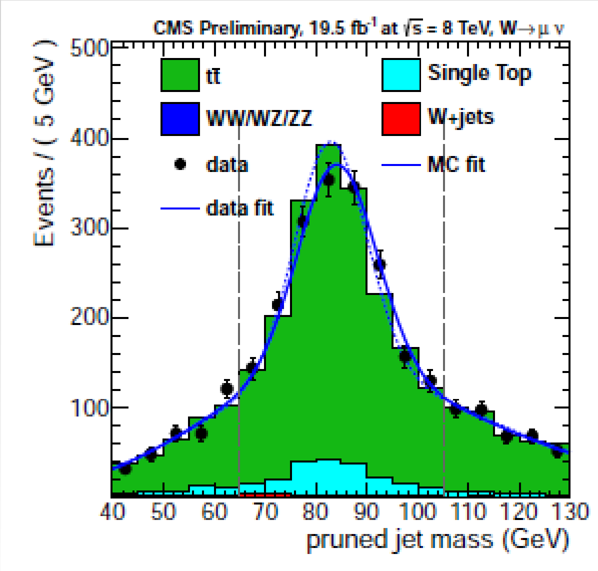
6.3) Jet mass and grooming algorithms



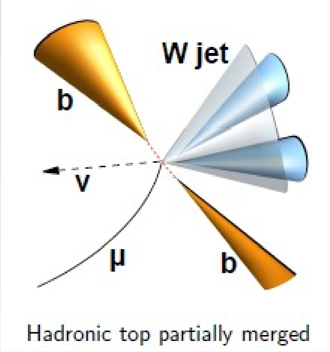


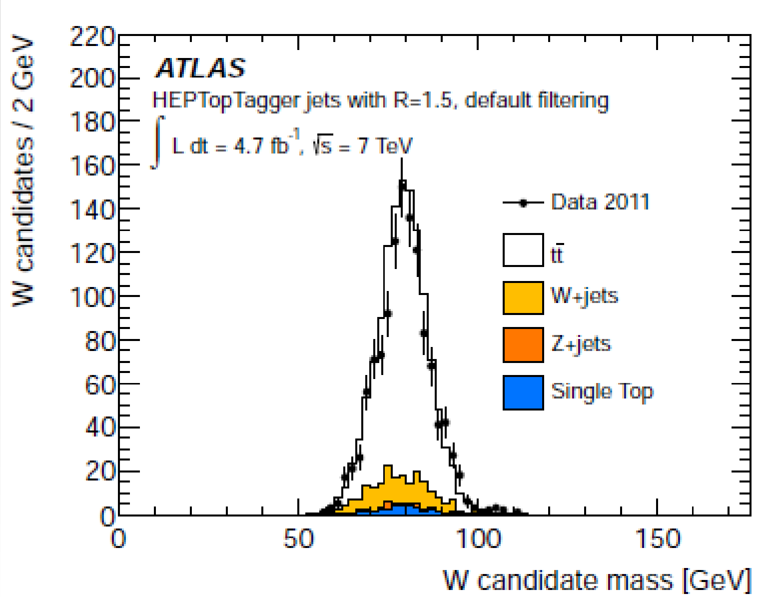
- Grooming remove soft large-angle radiation.
- Many algorithms was suggested (pruning/trimming/filtering).
- Their impact is similar at leading order but might be sensitive to the IR/Collinear details.

6.4) Measurement of W→qq parameters



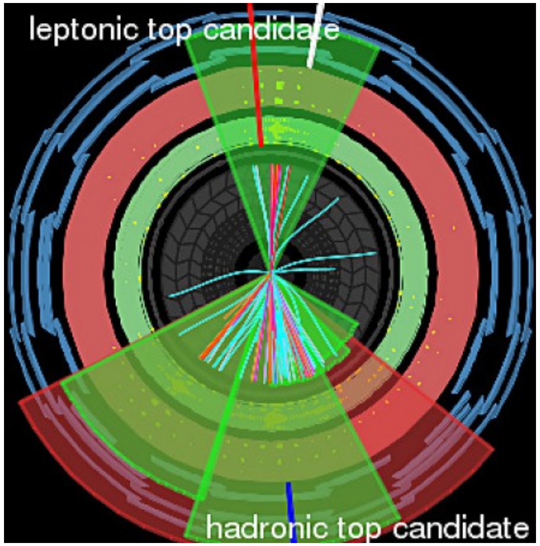
$$\langle m \rangle_{\rm sim} = 83.4 \pm 0.4~\mathrm{GeV}\,,$$
$$\langle m \rangle_{\rm data} = 84.5 \pm 0.4~\mathrm{GeV}\,,$$





$$\mu_{\rm data} = 86.9 \pm 0.8~\mathrm{GeV}$$
$$\mu_{\rm MC} = 87.4 \pm 0.2~\mathrm{GeV}$$

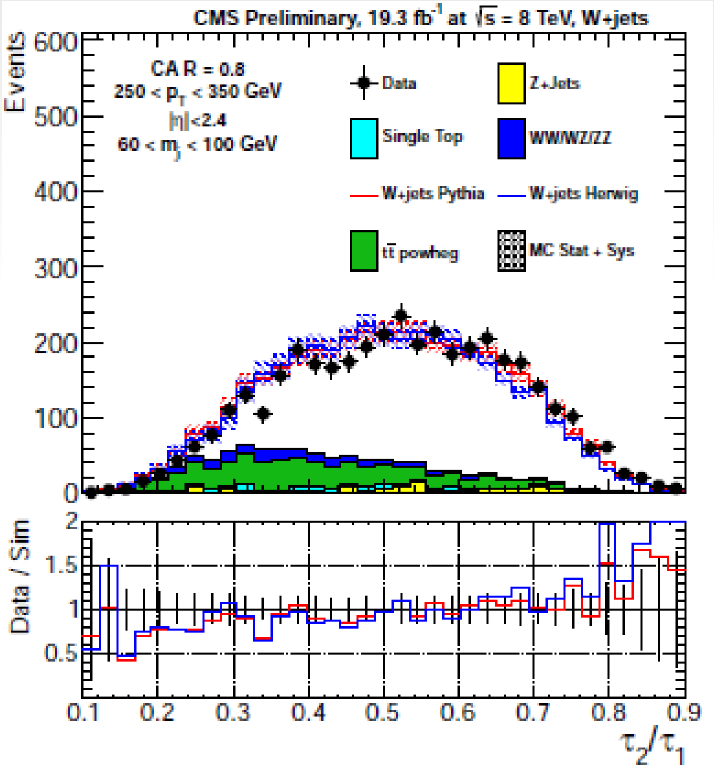
- Allow to monitor the jet mass calibration for groomed jets with real substructure.
- Tool limited to $p_{\mathrm{T,j}} \in [\frac{2M_W}{R_j}, \frac{2M_t}{R_j}] \approx [200~\mathrm{GeV}, 450~\mathrm{GeV}]$ to go further subjet mass have to be considered.
- Resolution typically of 8%.



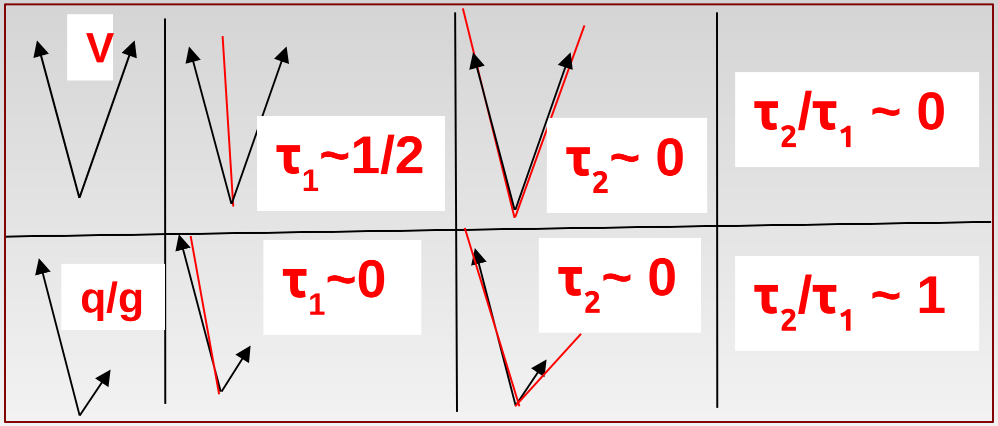
6.5) Substructure information

$$\tau_N = \frac{1}{d_0}\sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk})$$

$$d_0 \equiv \sum_k p_{Tk} \times R$$



CMS-JME-13-006



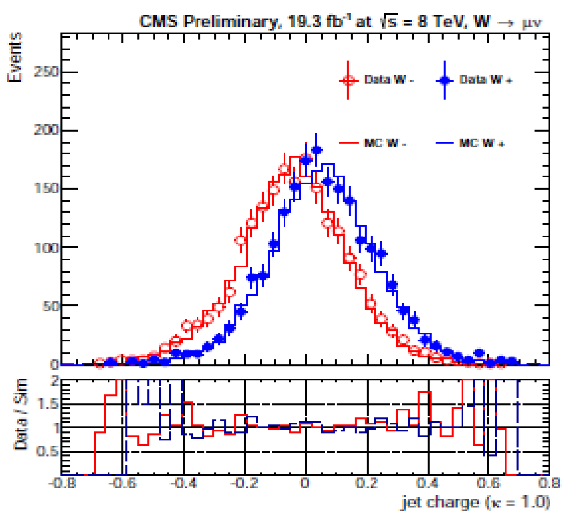
- N-subjettiness indicate the polarity of the jet (monopole, dipole etc...)
- Provide extra information with respect to the groomed mass.

6.6) To finish: jet charge

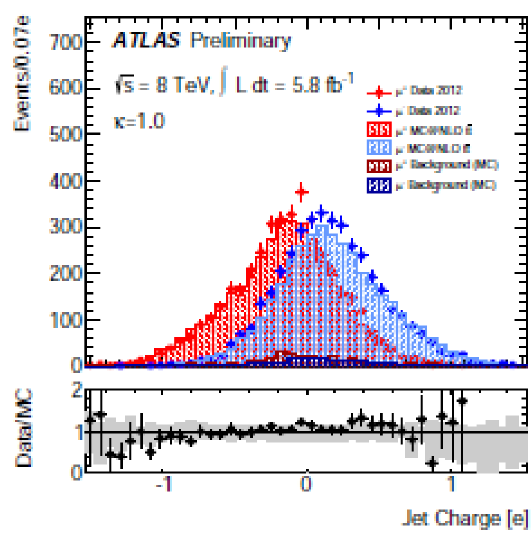
- Idea! Weight the track charge by it's momentum power something (to be tuned).

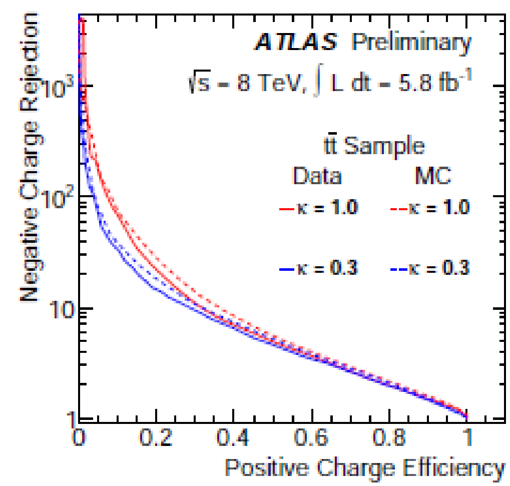
$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- Does it still exist with 40 PU and 100 GeV jets?
  - Why not suggested out theorists fiends (2012 - arXiv:1209.3019v3).
  - It works answered CMS/Atlas in 2013.
- k = 0.3: tracks democracy is preferred to k = 1.0 leading track oligarchy.



CMS-JME-13-006

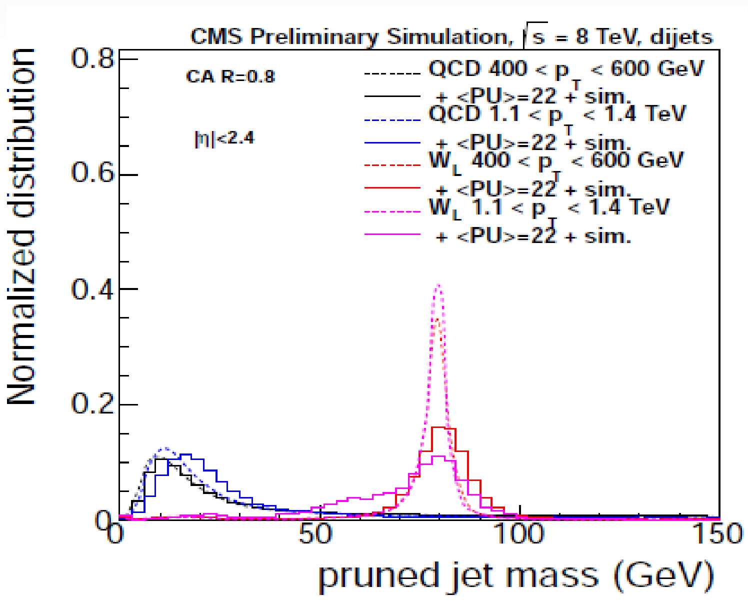


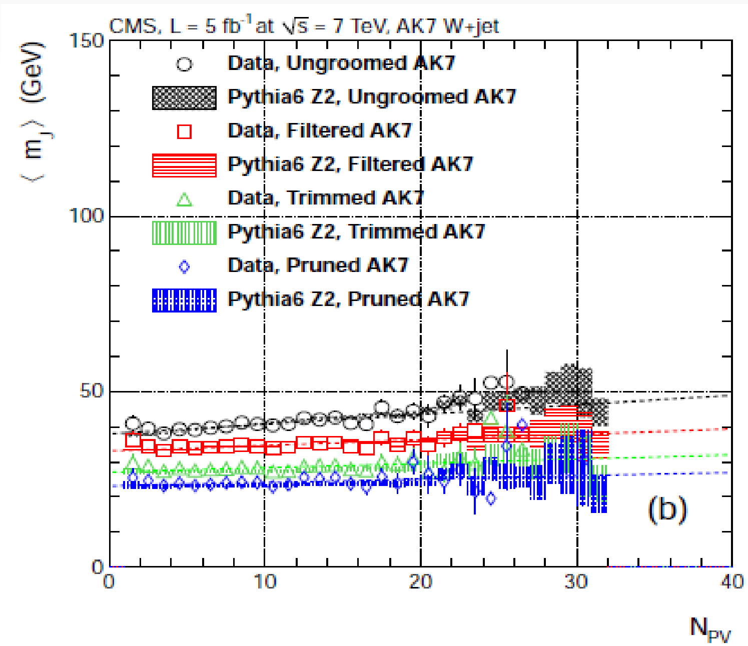


ATLAS-CONF-2013-086

6.7) What next?

- The Run I started the era of substructure physics and sensitivity to V→qq decays in the hadronic colliders.
- Run II would produce a large population of boosted vectors.
- We would be able to validate our tools but one need to be careful to the behavior in high PU and high p_T conditions of substructure algorithms.
- Grooming may become a leading tool for PU cleaning even for QCD jets.





SUMMARY

1) LHC has provided and is about to finalize the bread and butter measurements to improve/validate the the QCD calculations designed to keep at the LHC a high sensitivity to the EW physics.

2) Run II would benefit from those efforts and the tuning/measuring machinery established for the Run I shall allow to quickly improve the tunings to the new energy scale.

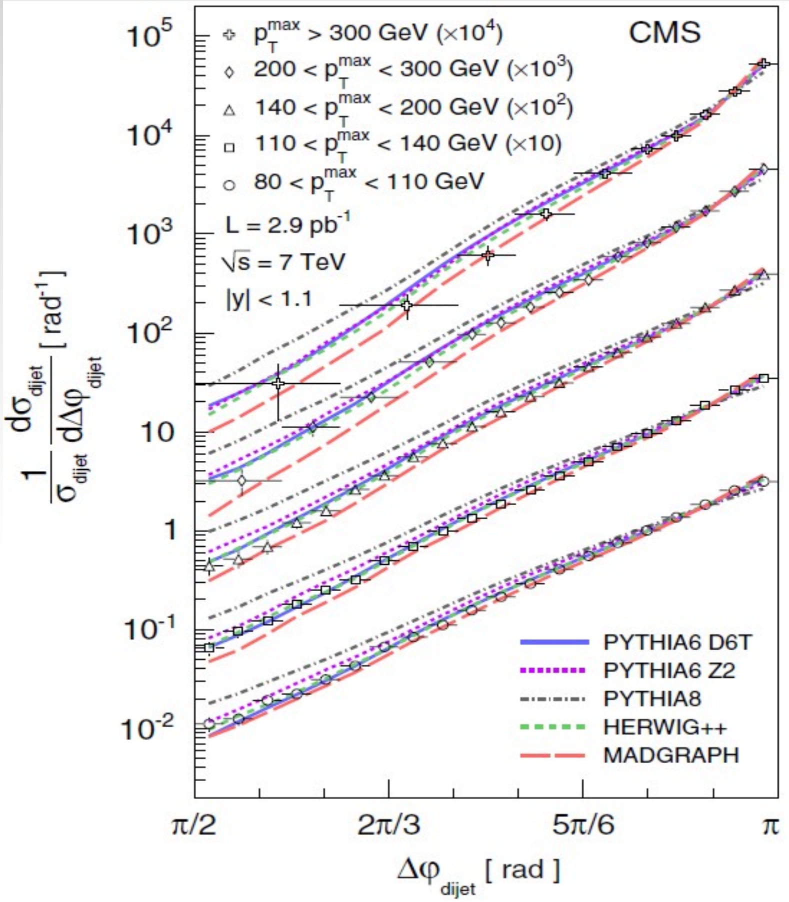
3) Our task is to guarantee the finalization of 8 TeV program which is the “Golden age” of many topics that cannot be explored at higher PU.

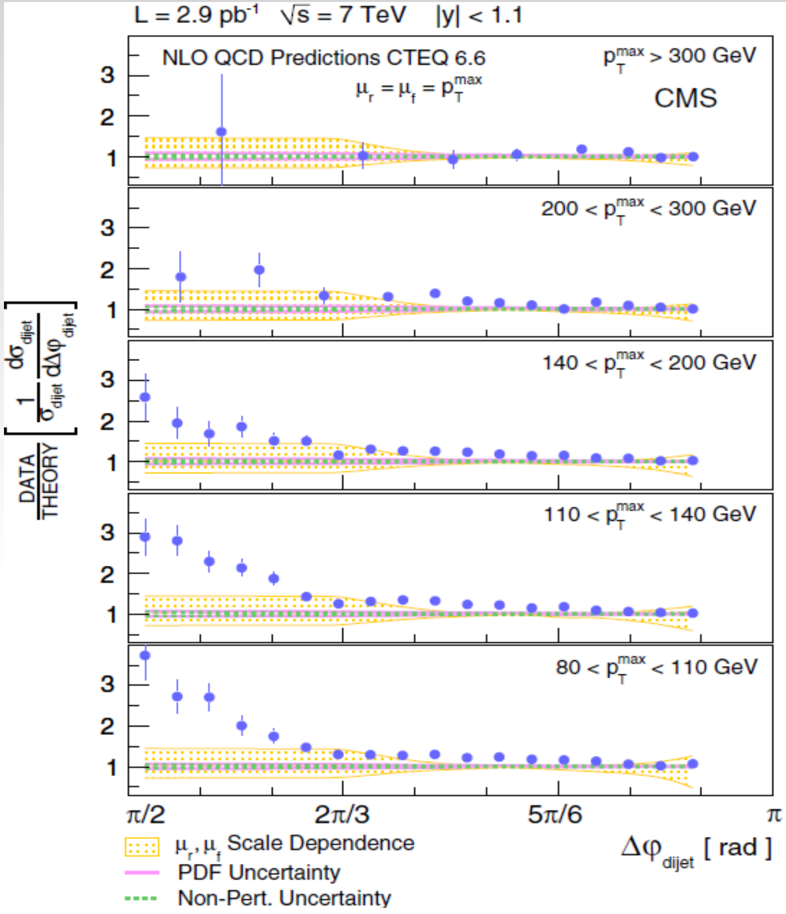
4) Our task is to be ready for a bunch of High Priority measurements with first “medium PU run” with lumi that that would be granted to us. We need to defend a solid case.

BACKUP

3.1) Dijet azimuthal decorrelation

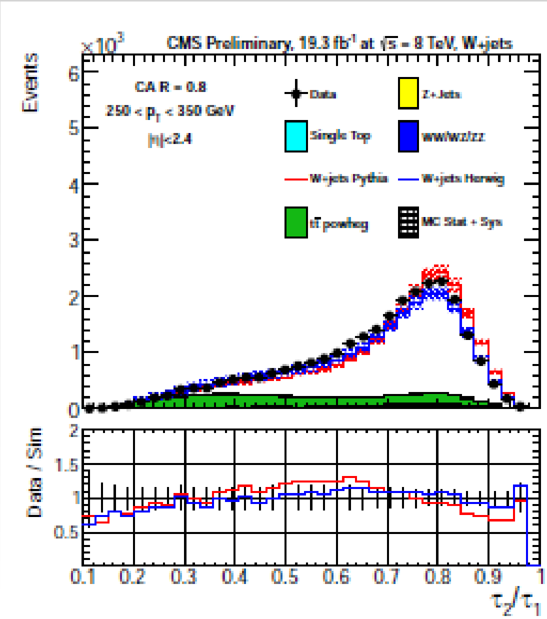
PhysRevLett.106.122003

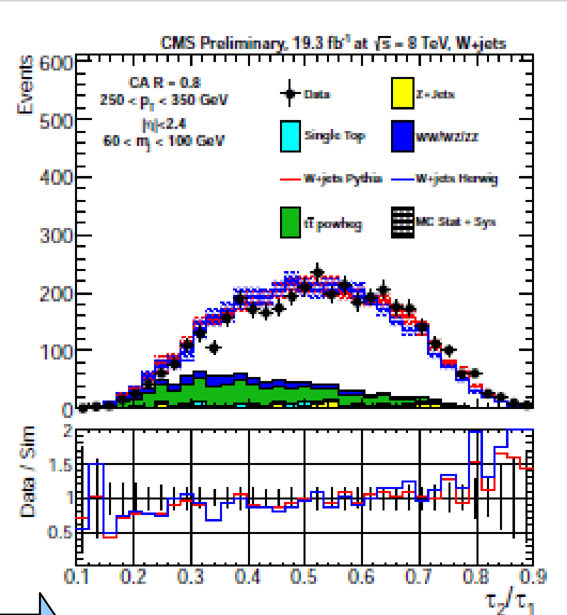


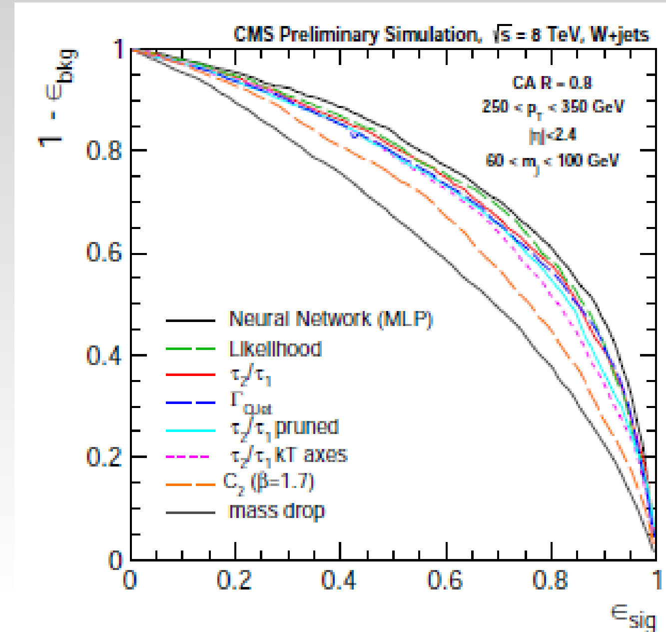


- At LO 2 jets are back to back : Δφ ~ π. True at large p_T.
- At low p_T ISR and FSR play a significant role. NLO+NP starts to fail to describe decorrelation. But LO+PS MC describe well.
- Simple evidence of importance of PS : large corrections beyond NLO!

3.2) W tagger optimisation





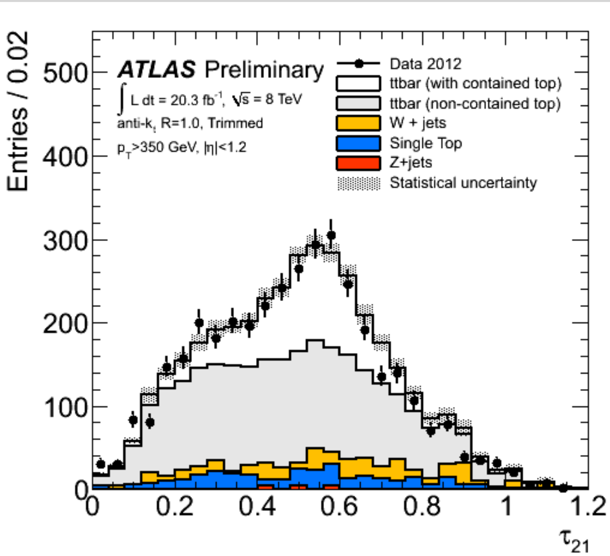


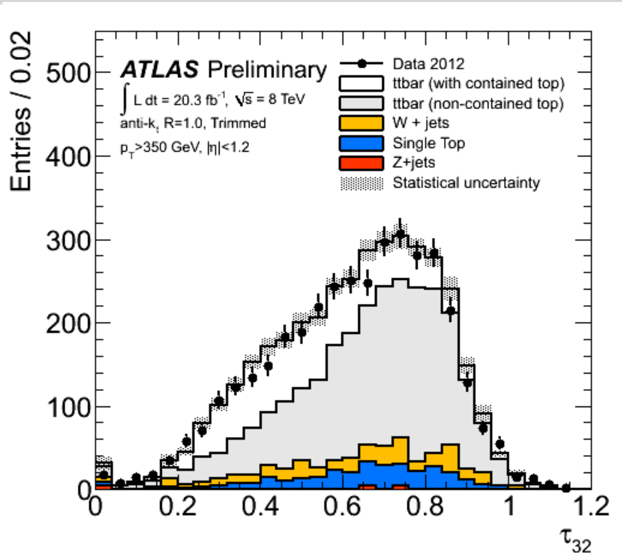
Mass cut

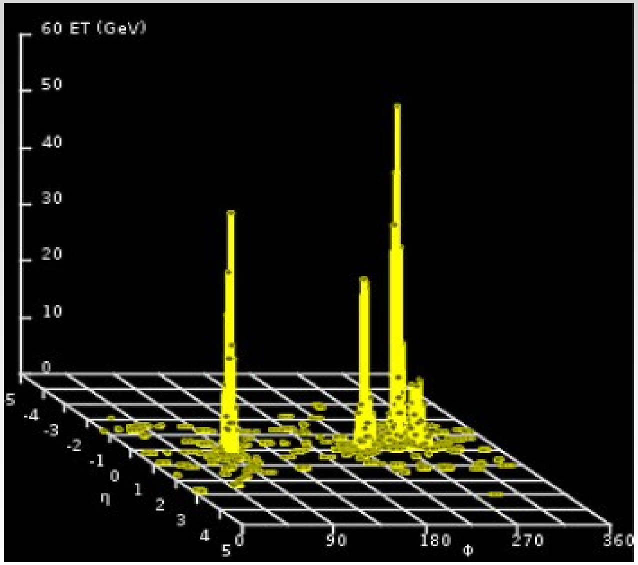
CMS-JME-13-006

- N-subjettiness correlated to the prunned W mass: normal need a “dipole” structure for a large mass.
- On top of mass cut - A combination of many taggers (N-subjettiness, mass drop, C_2 etc...) improve slightly the S-B separation wrt to N-subjettiness.
- More taggers considered by ATLAS: splitting scales etc...
- Additional taggers brings 80% bkg rejection for 60% signal efficiency wrt to the jet mass.

3.3) Top tagging: generalisation



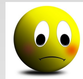




ATLAS-CONF-2013-052

- In top tagging we face a recursive splitting effect:
  - τ_{21} shows the top → Wb splitting
  - τ_{23} shows the top → Wb → qqb splitting.
- Other taggers:
  - splitting scales √d12, √d23 (ATLAS-CONF-2013-084).
  - Template method arXiv:1211.2202 (1211.2202)

3.4) W charge

- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity 

3.3) W charge

- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity.
- Idea! Weight the track charge by it's momentum power something (to be tuned).

$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- Does it work?

arXiv:1209.3019

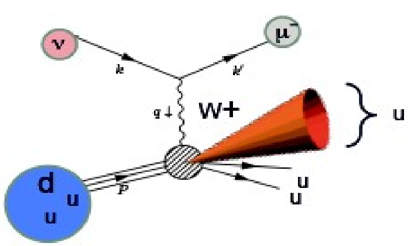
3.3) W charge

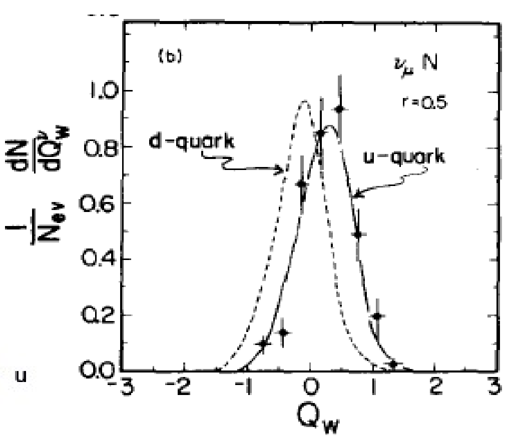
- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity :(
- Idea! Weight the track charge by it's momentum power something (to be tuned).

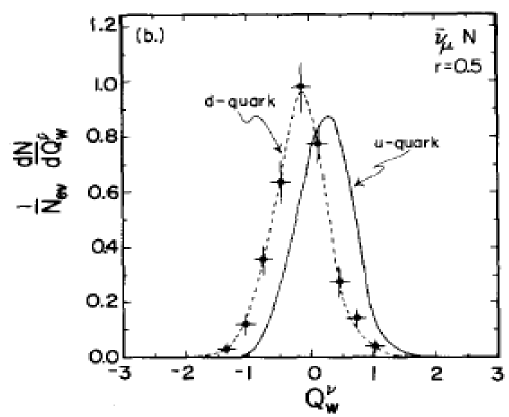
$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

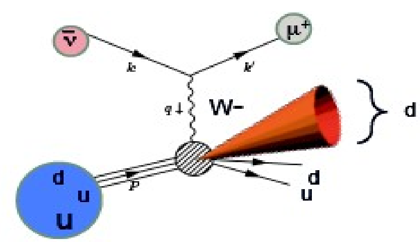
- Yes it does!

Fermilab Data (1980)







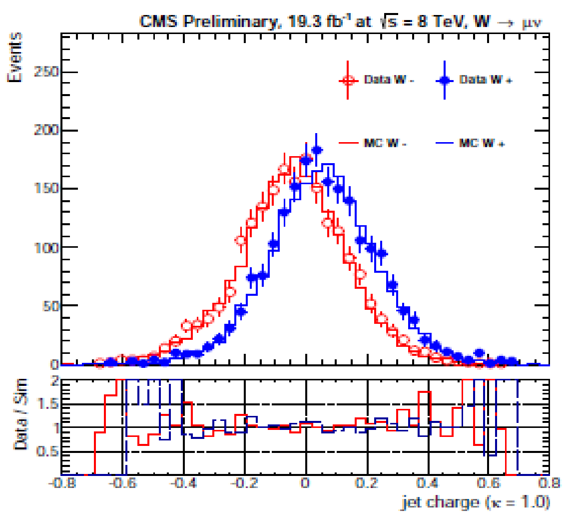


3.3) W/Z charge

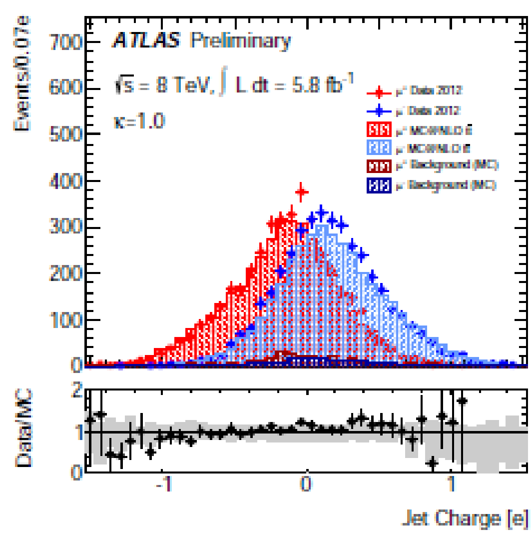
- Idea! Weight the track charge by it's momentum power something (to be tuned).

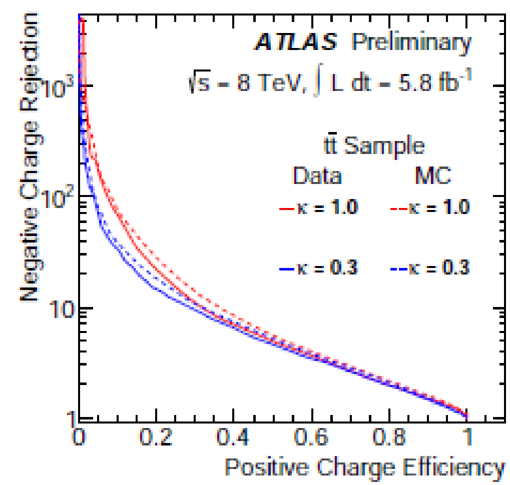
$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- Does it still exist with 40 PU and 100 GeV jets?
  - Why not suggested out theorists fiends (2012 - arXiv:1209.3019v3).
  - It works answered CMS/Atlas in 2013.
- k = 0.3: tracks democracy is preferred to k = 1.0 leading track oligarchy.



CMS-JME-13-006



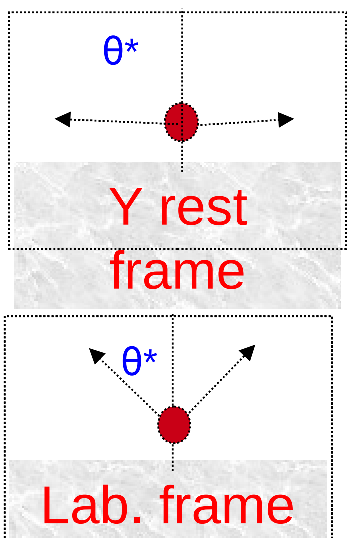


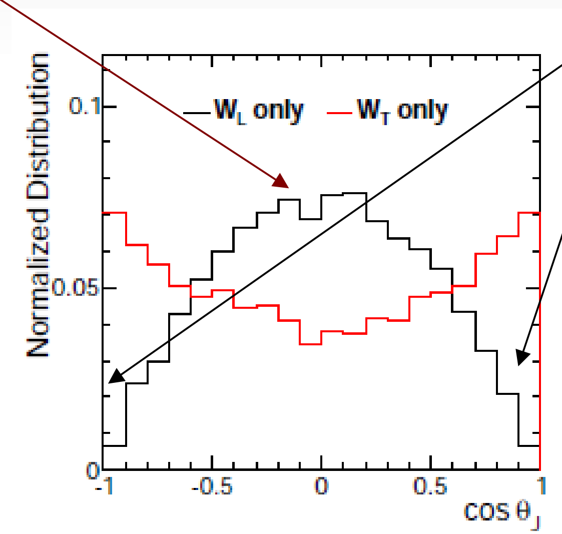
ATLAS-CONF-2013-086

3.4) W/Z polarization

- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - No sensitivity to the parity (no quark – anti-quark tagging yet)
  - Better acceptance for WL than WT

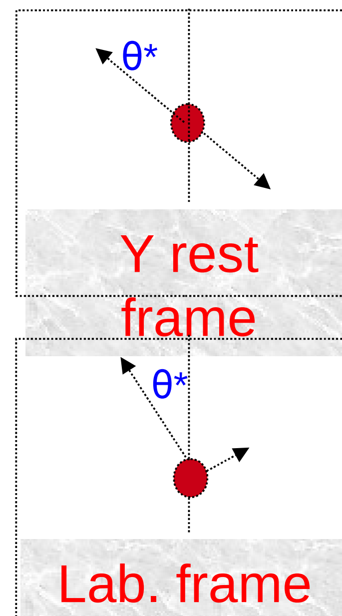
Symmetric
low ΔR
$\cos\theta^* \sim 0$





CMS-JME-13-006

Asymmetric
high ΔR
$\cos\theta^* \sim \pm 1$



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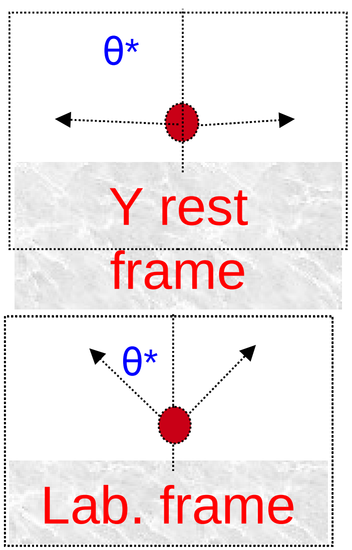
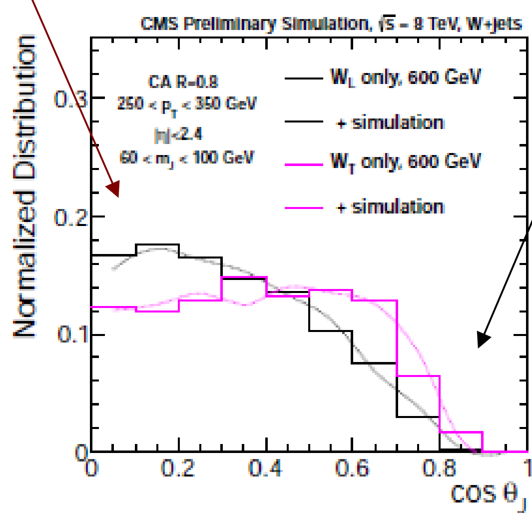
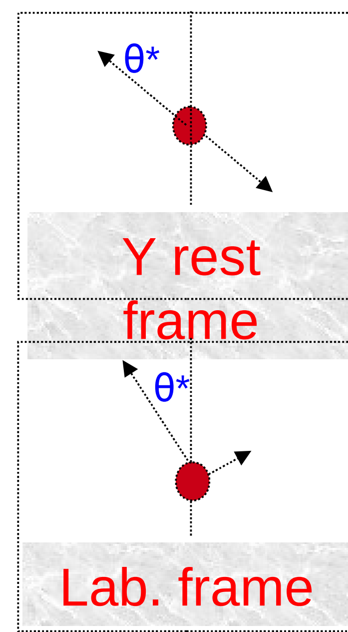




CMS-JME-13-006

Asymmetric
high ΔR
$\cos\theta^* \sim \pm 1$

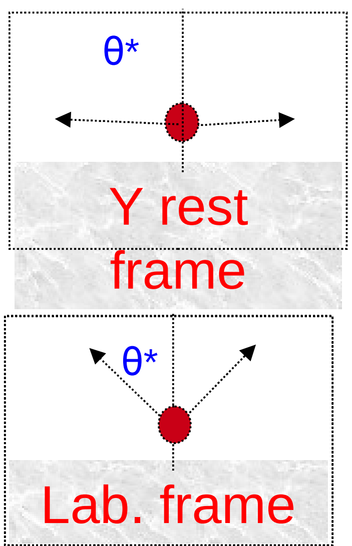


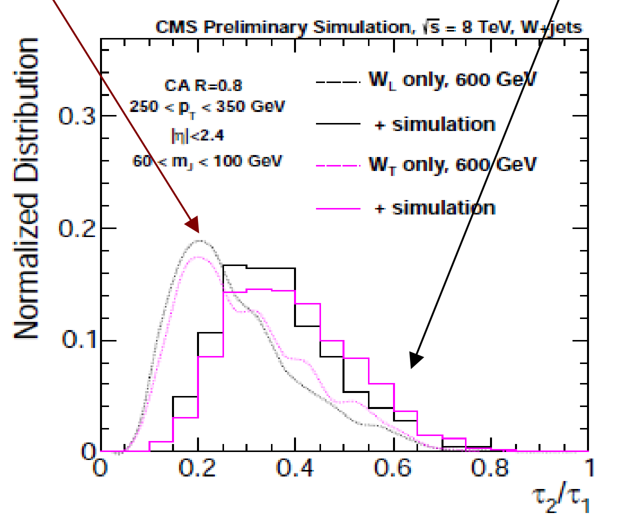
3.4) W/Z polarization

- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - W_L are in average more dipolar than W_T

Symmetric
low ΔR
$\cos\theta^* \sim 0$

Asymmetric
high ΔR
$\cos\theta^* \sim \pm 1$





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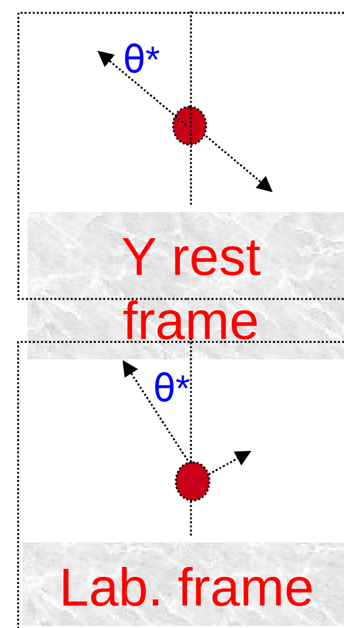
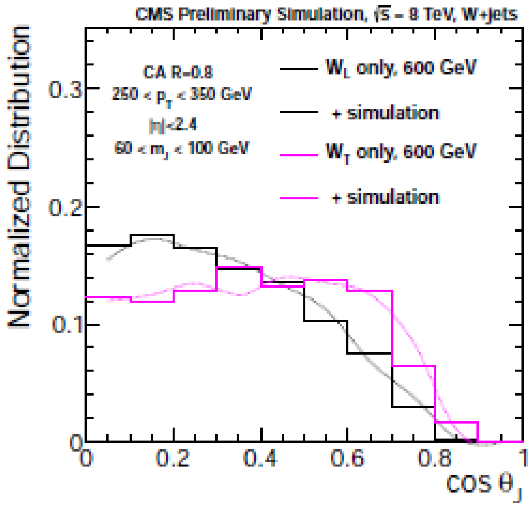


3.4) W/Z polarization

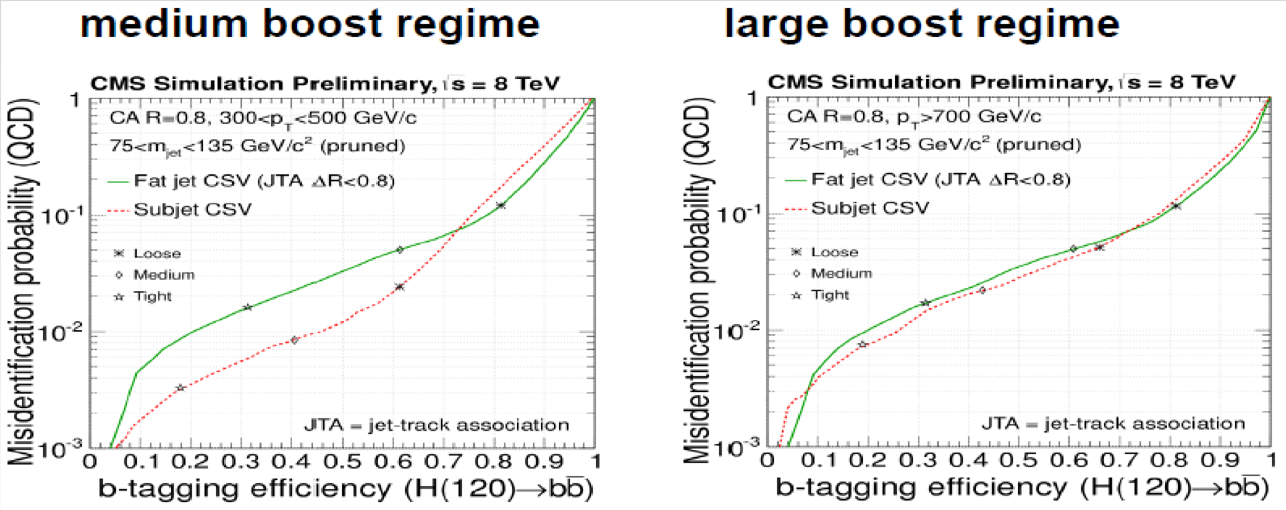
- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - No sensitivity to the parity (no quark – anti-quark tagging yet)
  - Better acceptance for W_L than W_T
- CMS measured the resolution:
  - σ(ΔR) ~ 10 mrad : σ(ΔR)/ΔR ~ 3% for p(W) = 500 GeV!!!
  - Do not impact W_L/W_T separation

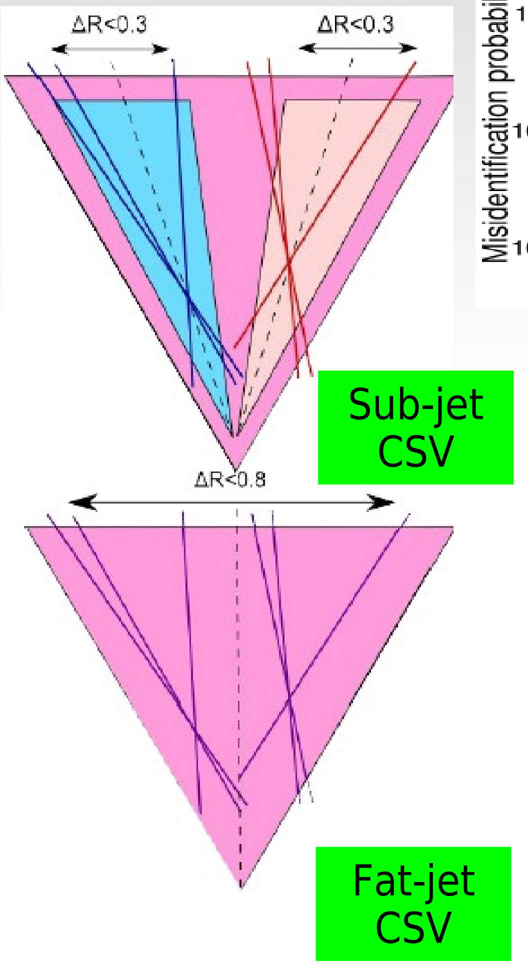


CMS-JME-13-006

3.5) Subjet b-tagging

CMS-BTV-13-001



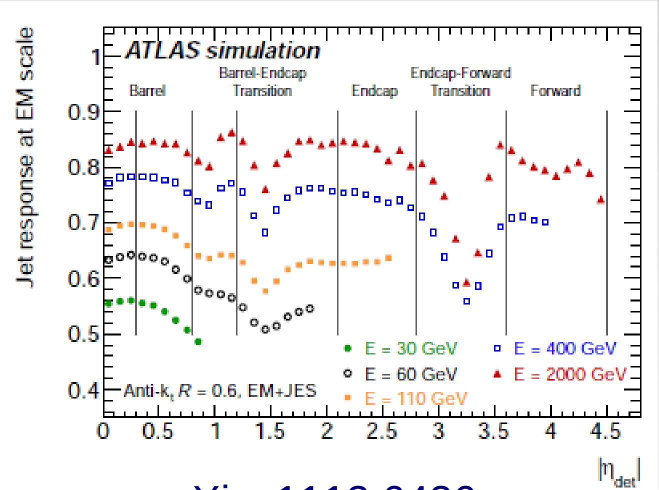


- We need to prepare the boosted H→ bb program (first interesting source of bb jets). B-tagging for highly boosted tops shall be improved.

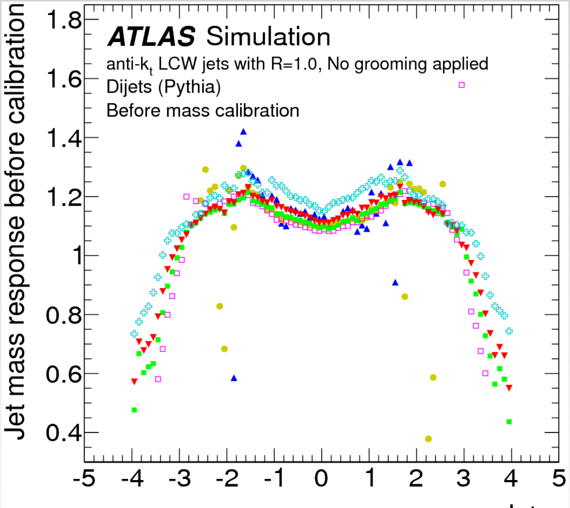
- CSV tagger: combine vertex and track counting info.
- Fat-jet CSV tagger: apply CSV to Fat jets.
- Subjet tagger: CSV tagger within R < 0.3. 2 tags for b and 1 for top.

- Subjet b-tagging doing a great job till the subjets start to merge. Tested in data with ttbar events.

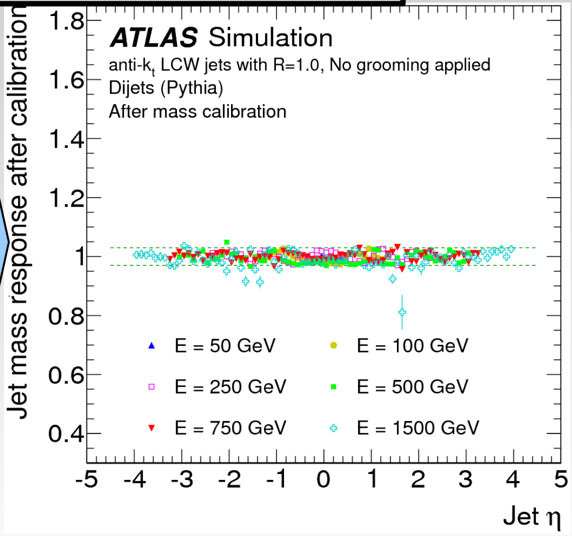
2.2) Jet mass calibration for substructure studies



arXiv :1112.6426

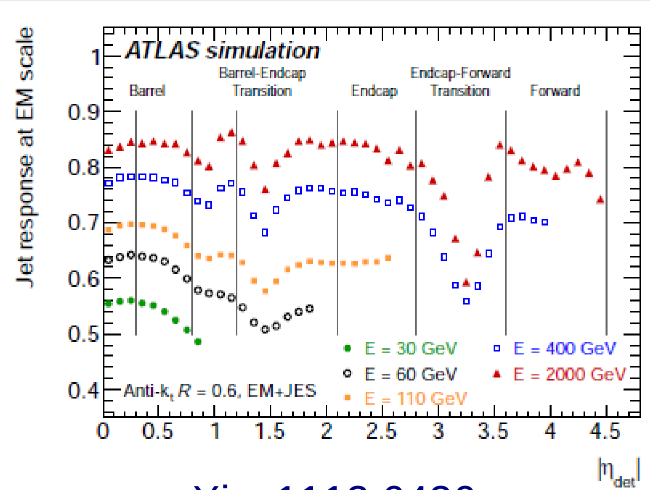


arXiv:1306.4945v1

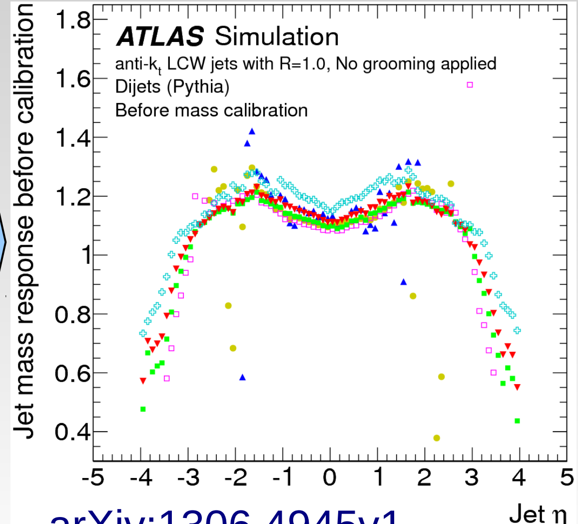


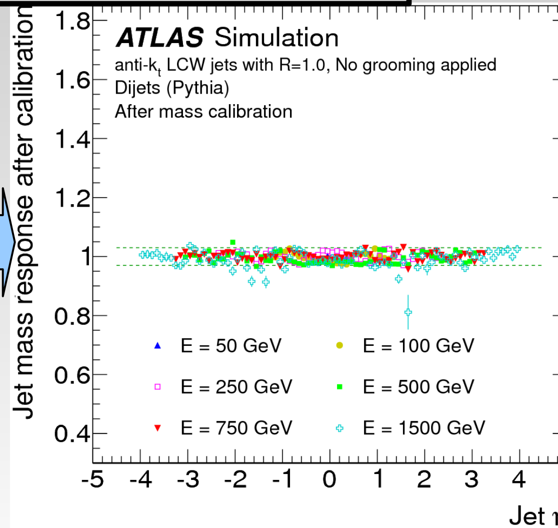
- ATLAS: p_T calib.; O(20%) remain eff.; additional mass calib., no PU calib.

2.2) Jet mass calibration for substructure studies

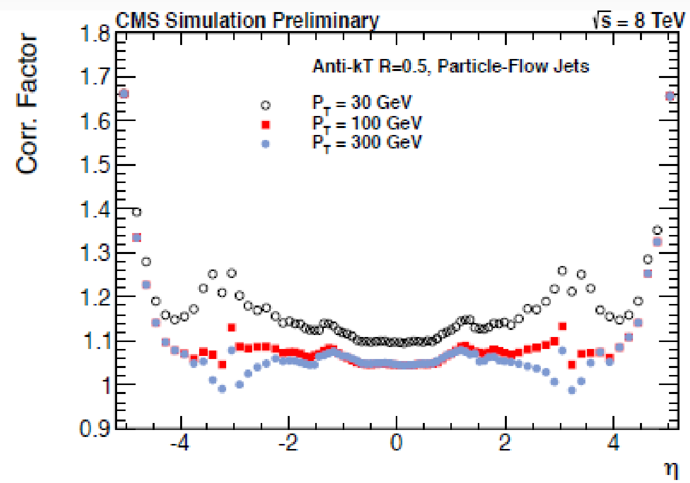


arXiv :1112.6426

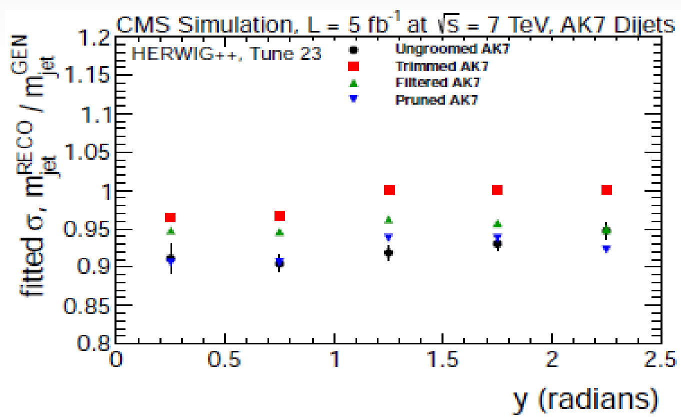




arXiv:1306.4945v1



DPS-2013/011



arXiv:1303.4811

- ATLAS: p_T calib.; O(20%) offset in mass; extra mass calib., no PU calib.
- CMS: p_T calib. with PU corr. (track + jet Area); O(5%) offset in Mass;

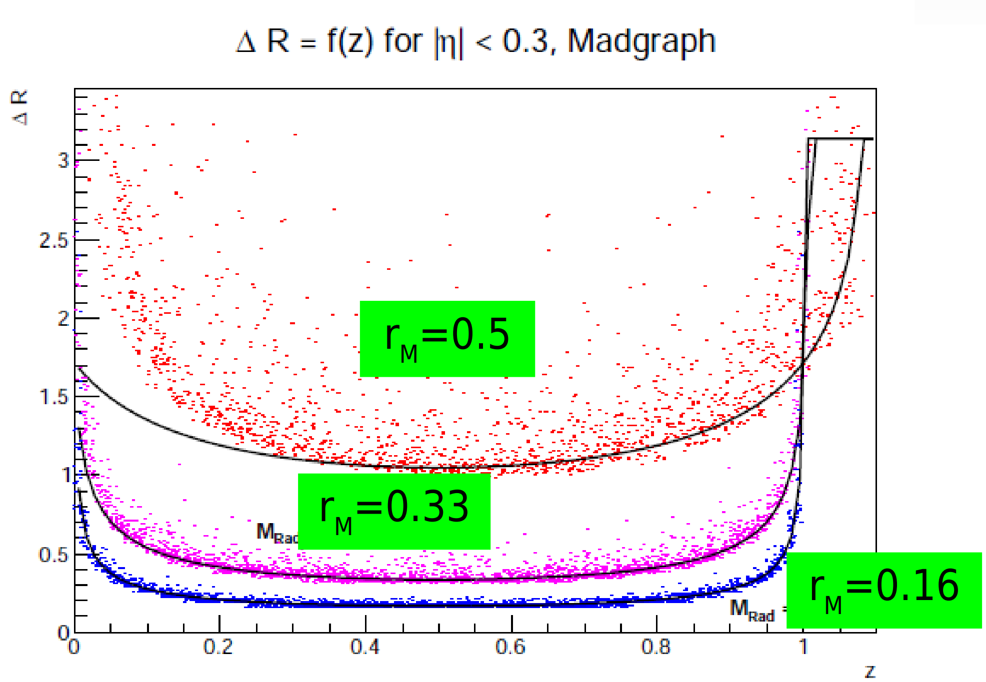
1.4) The boosted regime and substructure

- All V taggers might be described in the plane:

$$z = \frac{p_{T,1}}{p_T}$$

$$\Delta R = \sqrt{(\phi_2 - \phi_1)^2 + (\eta_2 - \eta_1)^2}$$

- In Y rest frame: 1 degrees of freedom θ^*.
- Boost: 1 degree of freedom r_M. Then $\Delta R = f(\theta)$!



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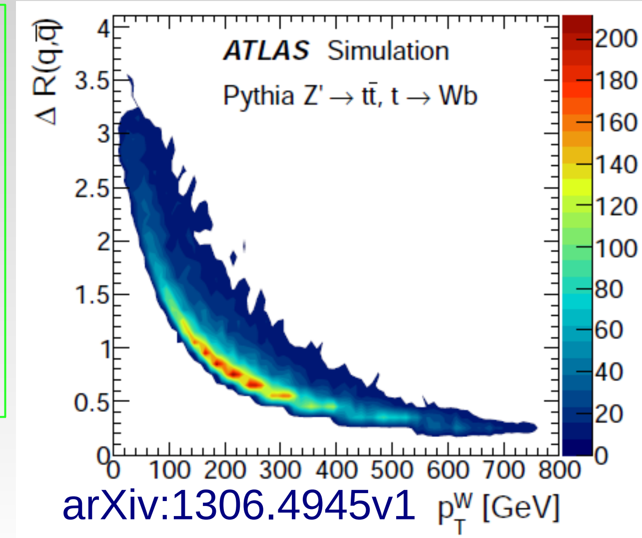
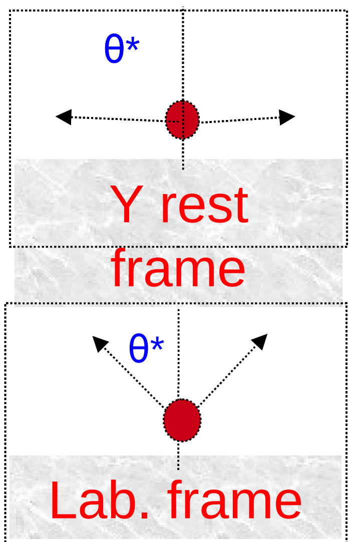
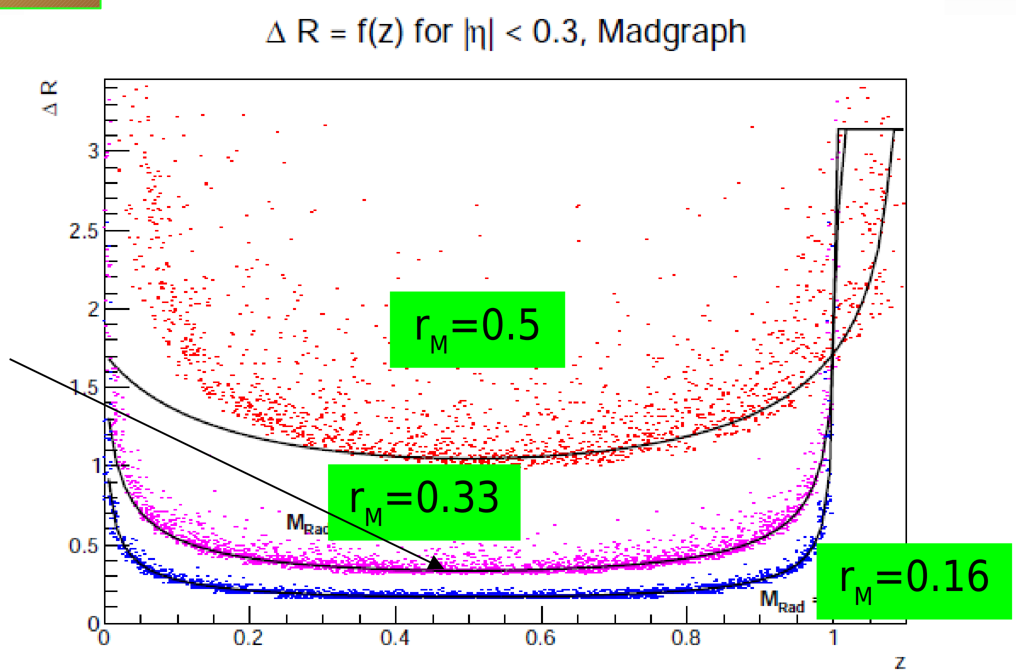


Symmetric - low ΔR



$$\Delta R = \frac{4M_Y}{M_X}$$



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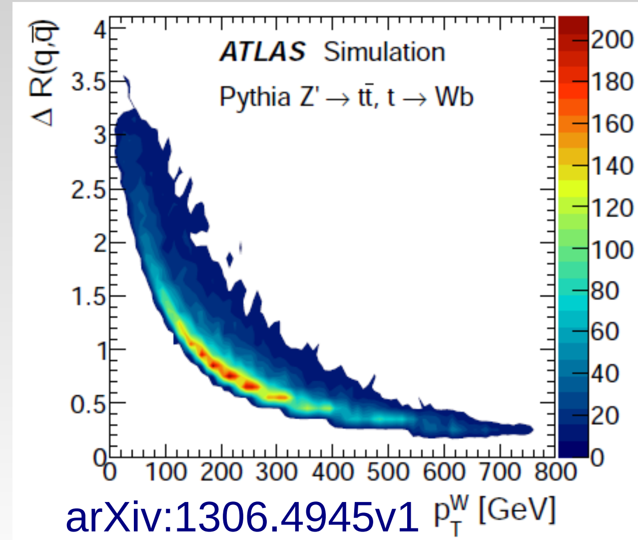
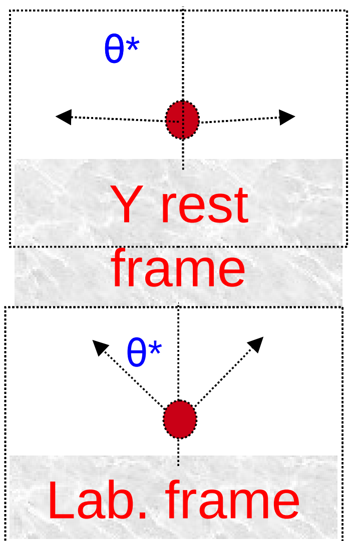


arXiv:1306.4945v1

Symmetric - low ΔR



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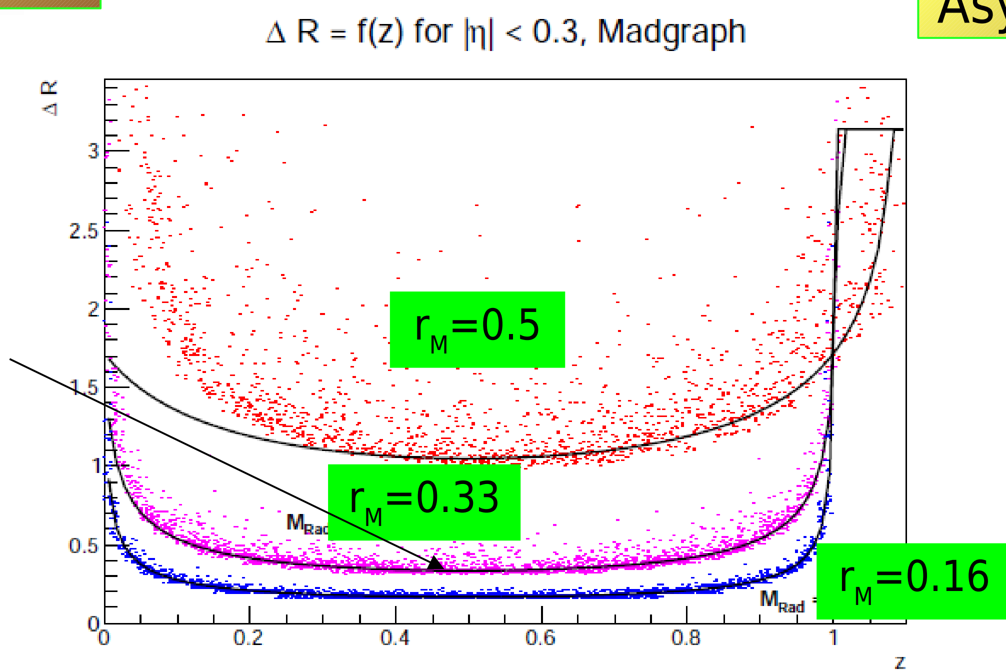
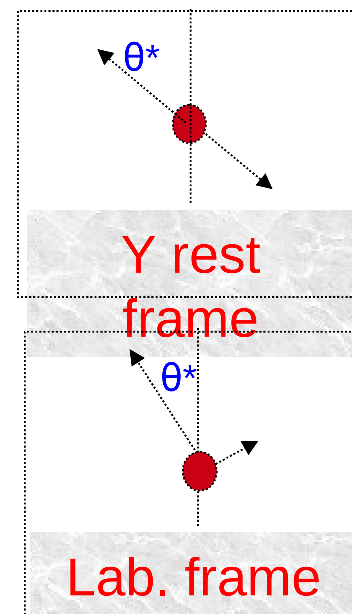


Asymmetric - high ΔR



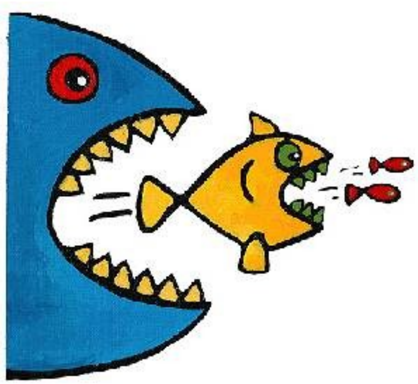
1.5) Jet clustering and substructure: role of the clustering order

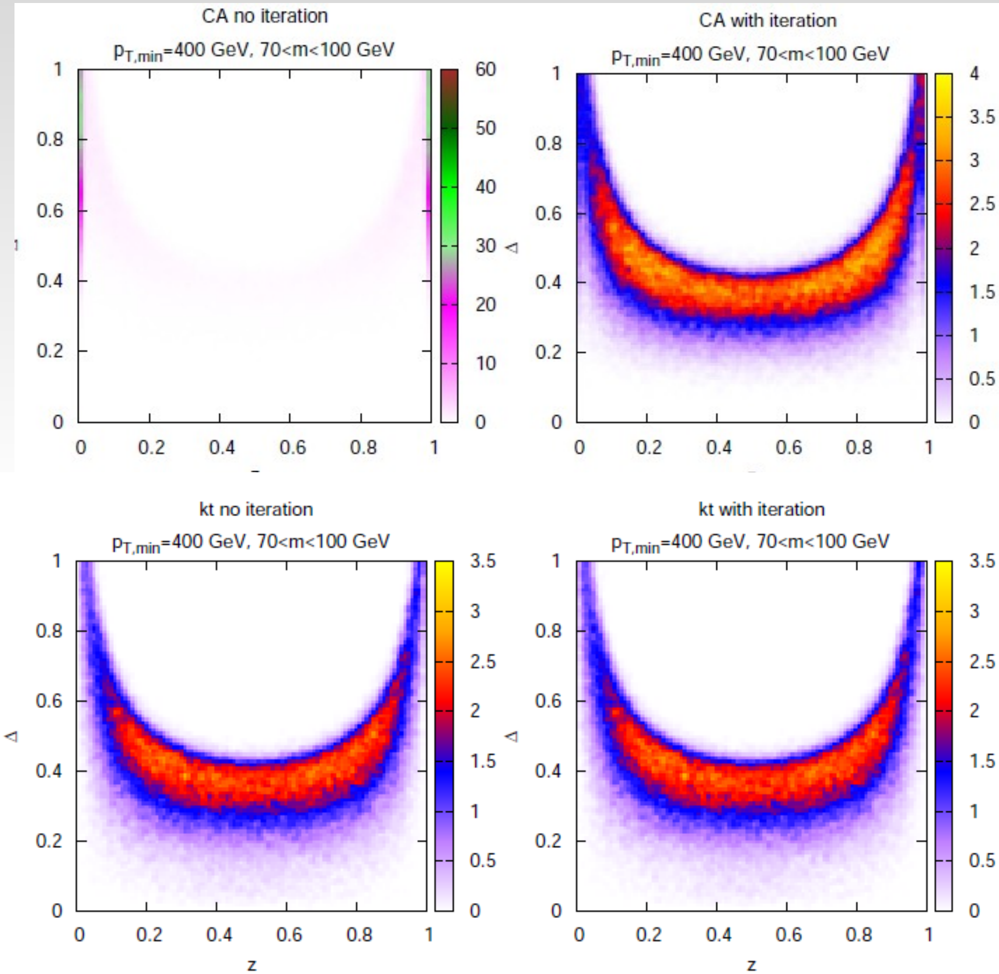
$$d_{ij} = min(k_{ti}^{n}, k_{tj}^{n})\Delta R_{ij}^{2}/R^{2}$$

N = 1: k_T – "Small fish eat first"

N = 0: CA - "Closest fish eat first"

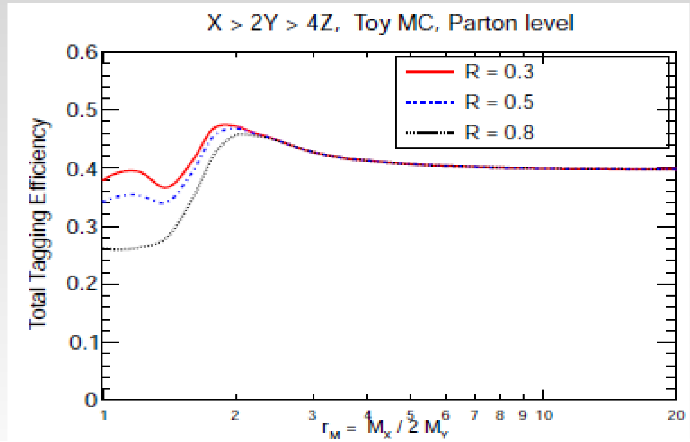
N = -1: anti-k_T "Big fish eat first"



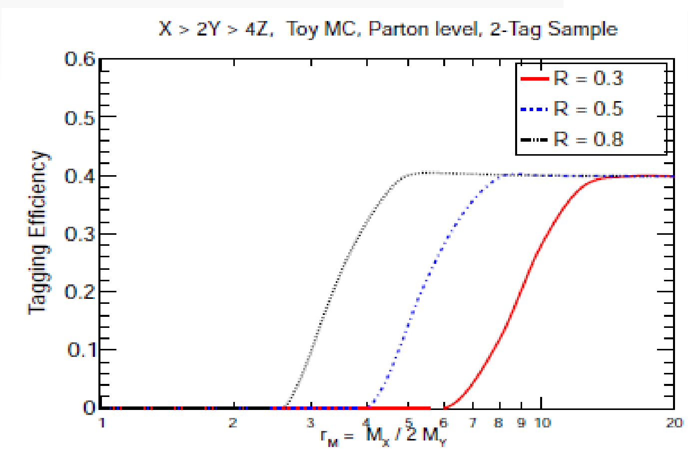


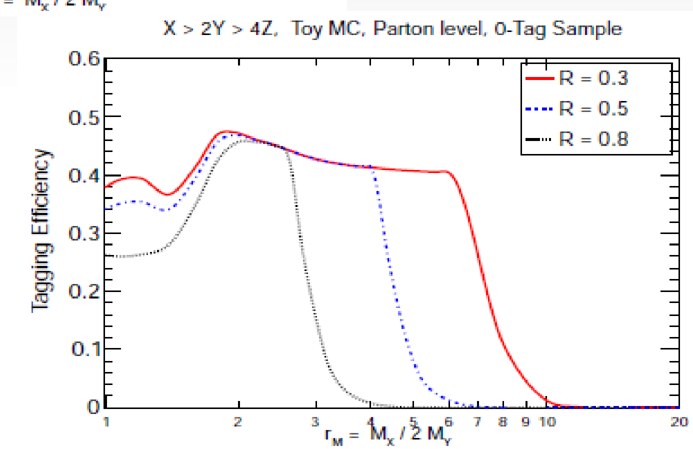
arXiv:1209.2858

1.5) Jet clustering and substructure: role of R



arXiv:1306.6219





- Pairing of jets (superstructure) or looking for subjets (substructure) is an equivalent activity! Fronter defined by R and M(V).
- You need jets to make sense in QCD and calibration.
- One can tune super/sub-structure cuts to have a smooth transition.

1.6) V-tagging in a nutshell

- Remove soft large angle radiation
- Remove PU and UE

GROOMING :
prunning, trimming, filtering

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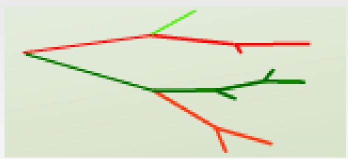
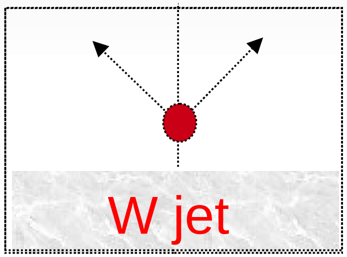
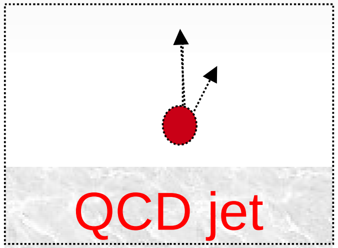


TAGGING:
N-subj.,
Splitting
scales...

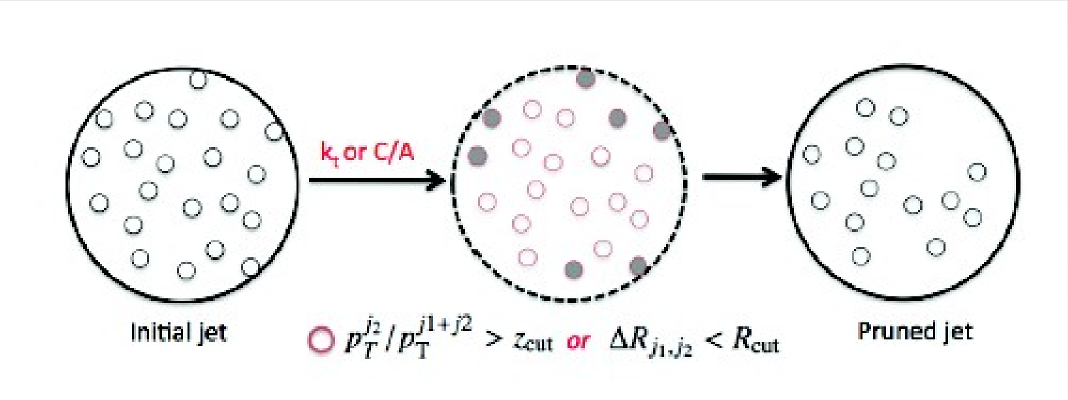




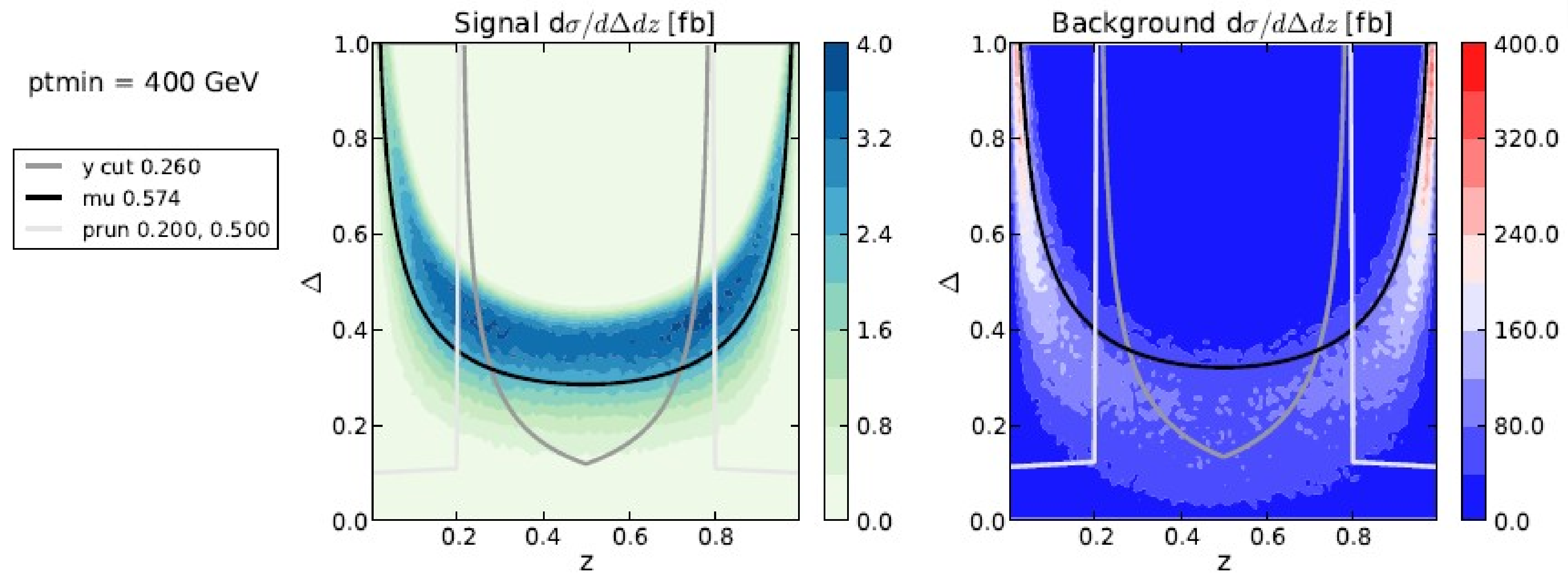
TAGGING :
Jet mass,
Mass drop...

- Use taggers to decide if the jet looks like a “rather symmetric massive dipole” or “hard parton with a soft/collinear radiation”.
- Could be done after or before grooming.
- Need to account for possible FSR in V production.
- For example: Jet mass works well only after grooming;
Pruning can degradate N-subjettiness by removing asymmetric W;

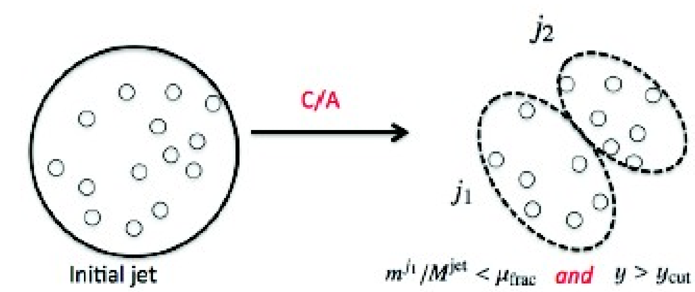
1.7) Algos: Prunning algorithm



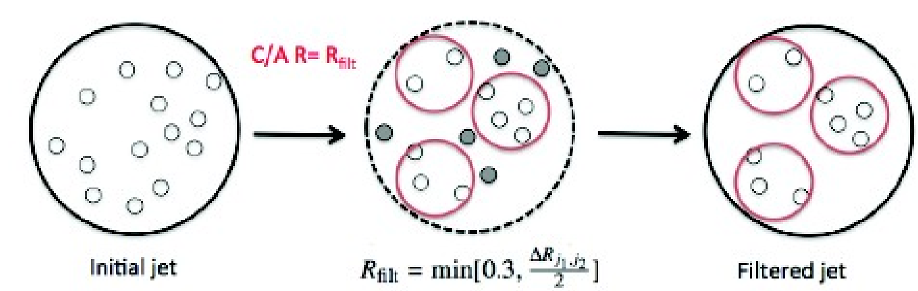
arXiv:1209.2858



1.8) Algos: Mass drop + Filtering



(a) The mass-drop and symmetric splitting criteria.

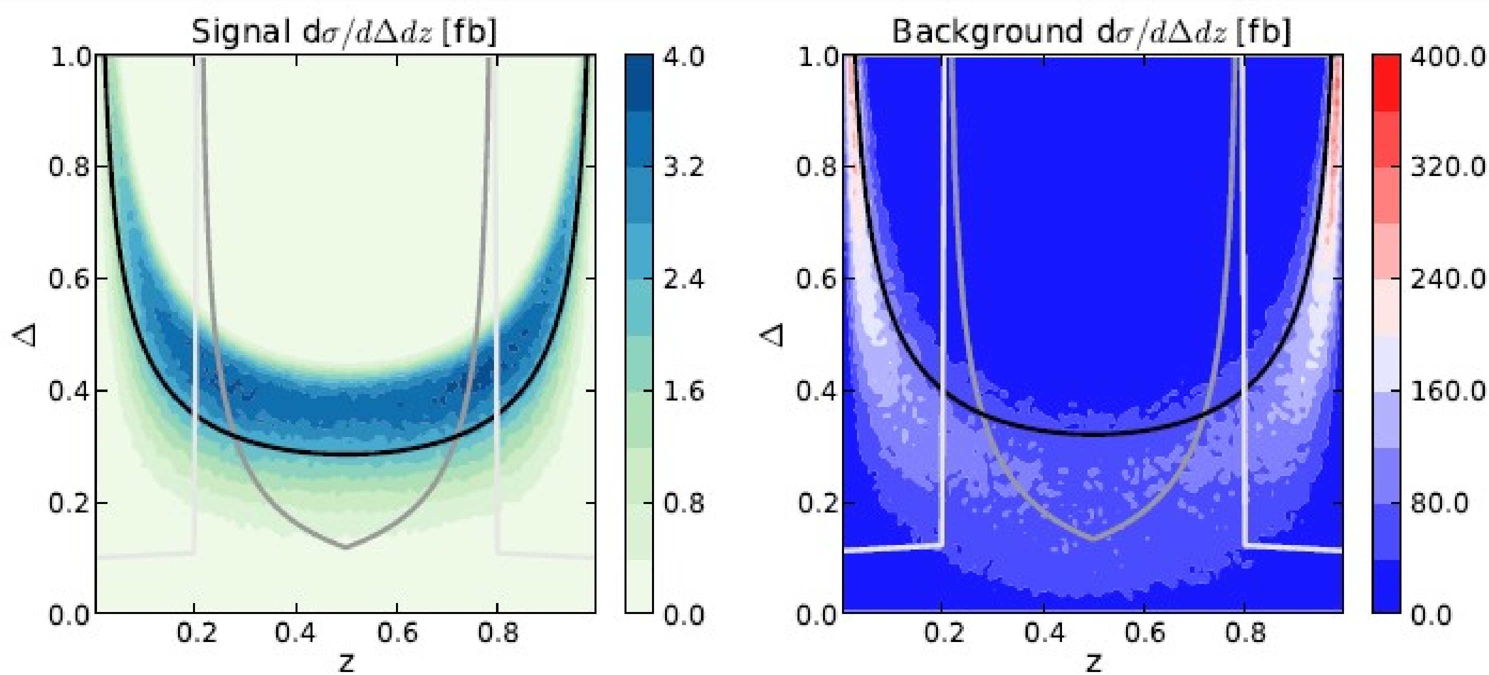


(b) Filtering.

Allow up to 3 subjets to account for FSR.

ptmin = 400 GeV

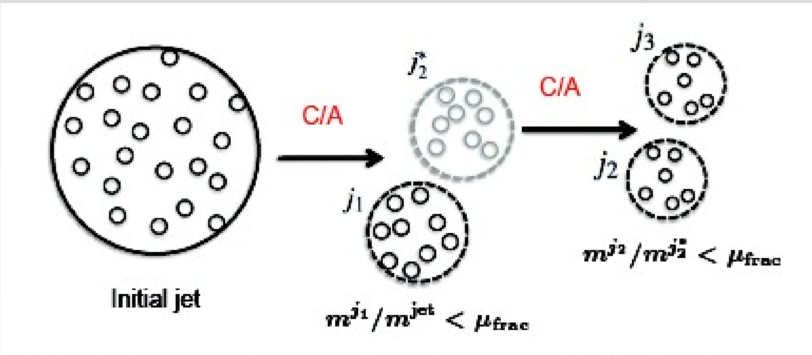
y cut 0.260
mu 0.574
prun 0.200, 0.500



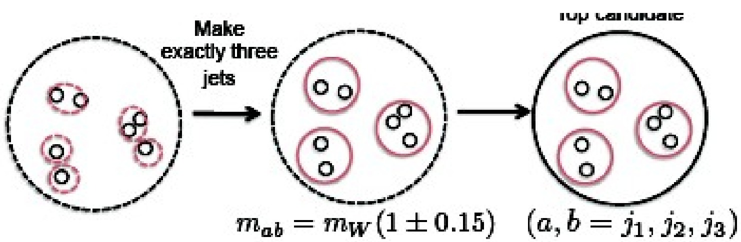
arXiv:1209.2858

1.9) Top tagging: generalisation

Filtering + mass drop generalisation



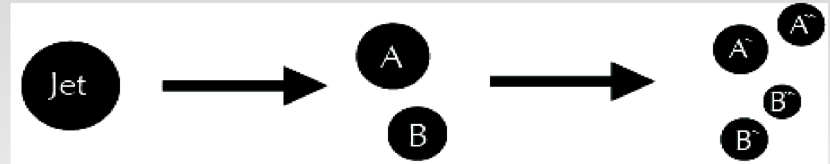
Iteratively produce N subjets without no « substructure »



Recluster into few bricks (5) to allow some QCD radiation.
Then combine into 3 groups using W and top mass constraints.

Atlas : HEP TOP TAGGER
arXiv:1306.4945v1

Prunning generalisation



Iteratively uncluster up to 4 subjets: symmetric splittings and not too far away.

- Momentum fraction criterion: $p_T^{subjet} > 0.05 \times p_T^{jet}$
- Adjacency criterion: $\Delta R(C_1, C_2) > 0.4 - 0.0004 \times pT(C)$

Select events where subjets and jet satisfy W and top mass constraints.

CMS/JHU tagger :
arXiv:1204.2488