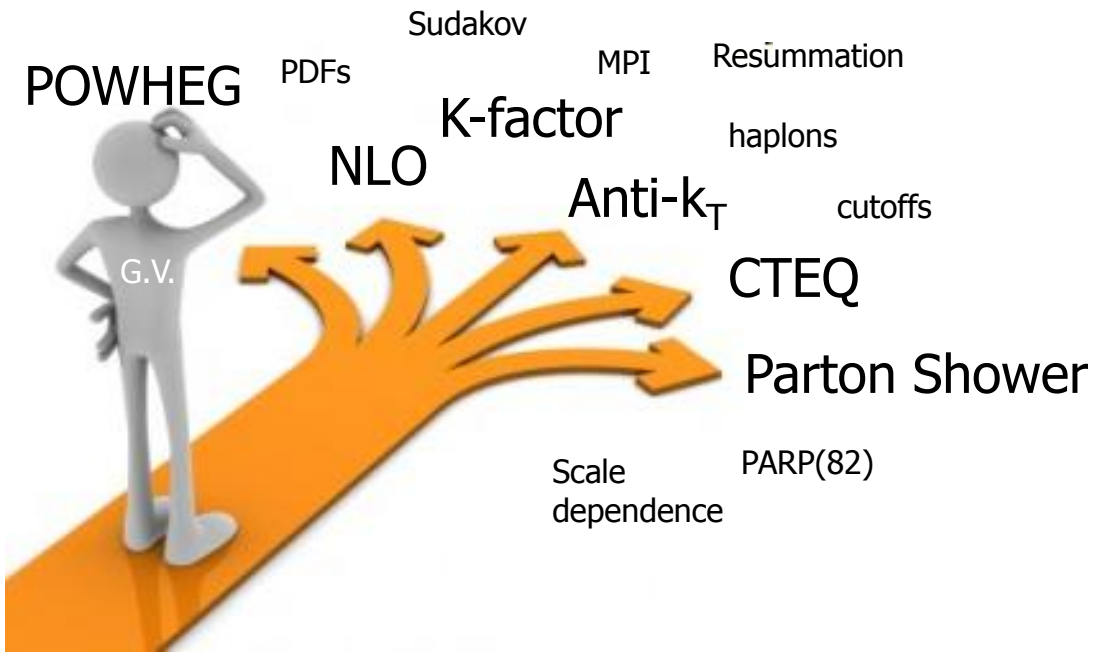
Summary of the discussions in the **Monte Carlo Working Group**

Gábor I. Veres (CERN)



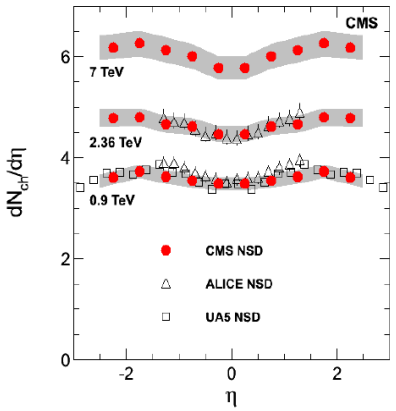
QCD… outline

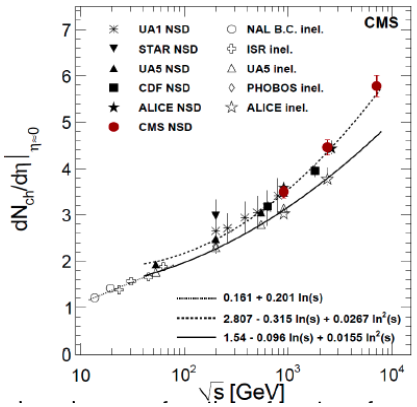
Quality - Cost - Delivery

- **Quality:**
  - How to estimate theoretical uncertainties?
  - Calculations to many perturbative orders
  - Parton showers, jet algorithms
  - How to deal with experimental backgrounds, UE, pileup…
  - Tuning MCs to data
- **Cost:**
  - Wish lists: what is realistic to calculate in finite time?
  - GPUs
  - Storage space for flexible event flies
- **Delivery:**
  - How to present experimental results most usefully?
  - How to prepare theoretical/MC results most usefully?

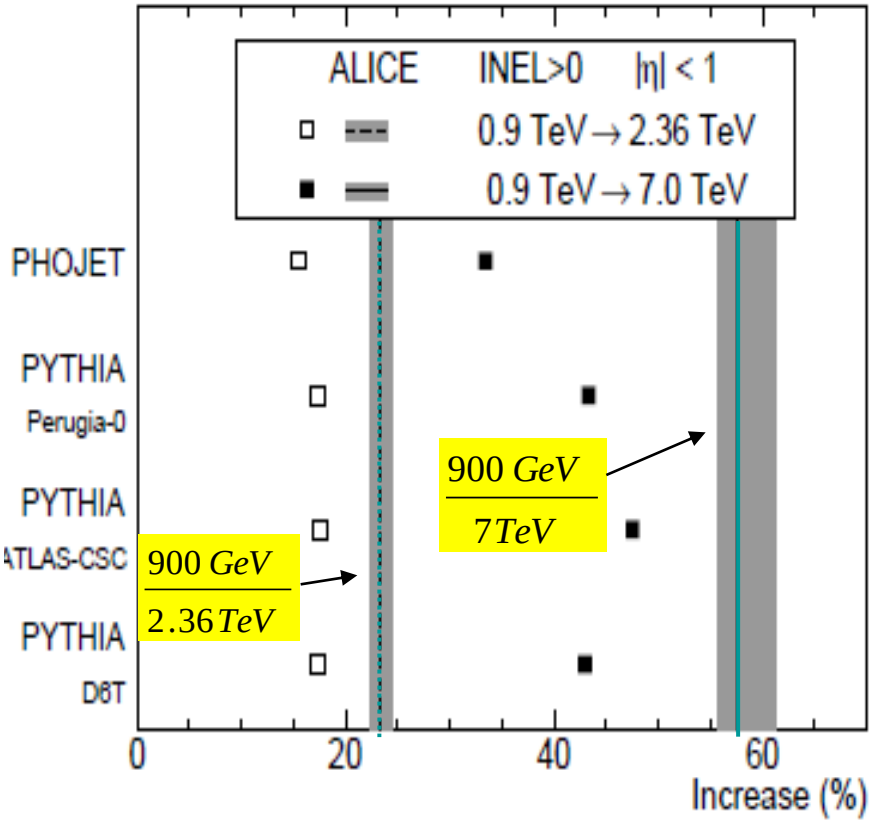
Soft particle production

- **dN/dη underpredicted by MCs**
  - But: most MCs are NOT aiming to describe it
  - Not infrared-safe
  - MCs do not implement diffraction reliably





Relative increase in $dN_{ch}/d\eta$



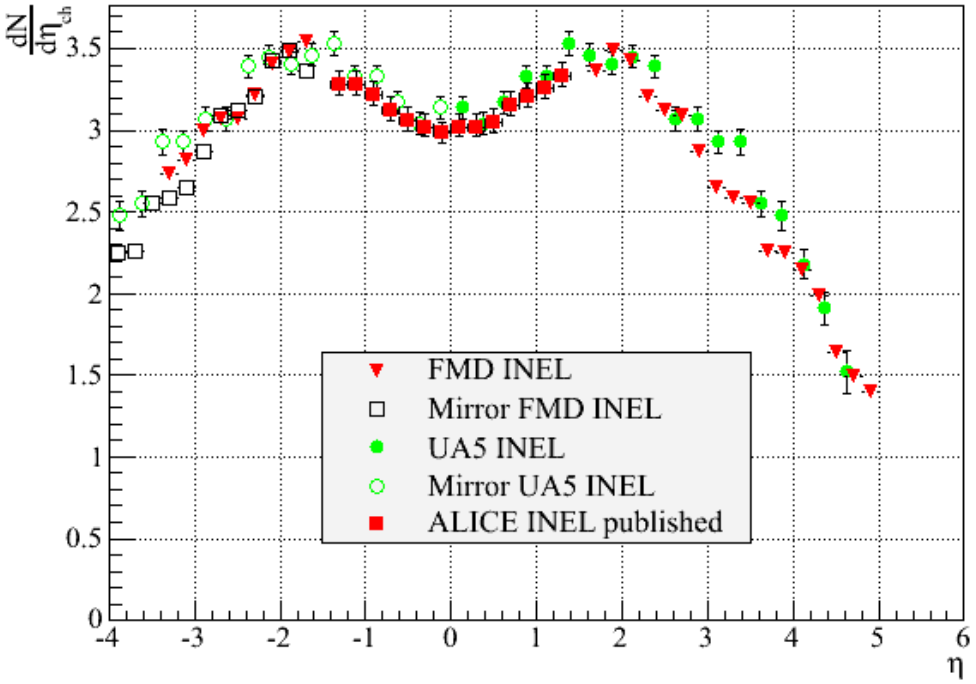
- none of the tested MC's (adjusted at lower energy) does really well
- tuning one or two results is easy, getting everything right will require more effort

(and may, with some luck, actually teach us something on soft QCD rather than only turning knobs)

Karel Safarik

Extremes: large η

- **Example: dN/dη from ALICE using the Forward Multiplicity Detector (prelim.)**
- **Extending up to η = 5**



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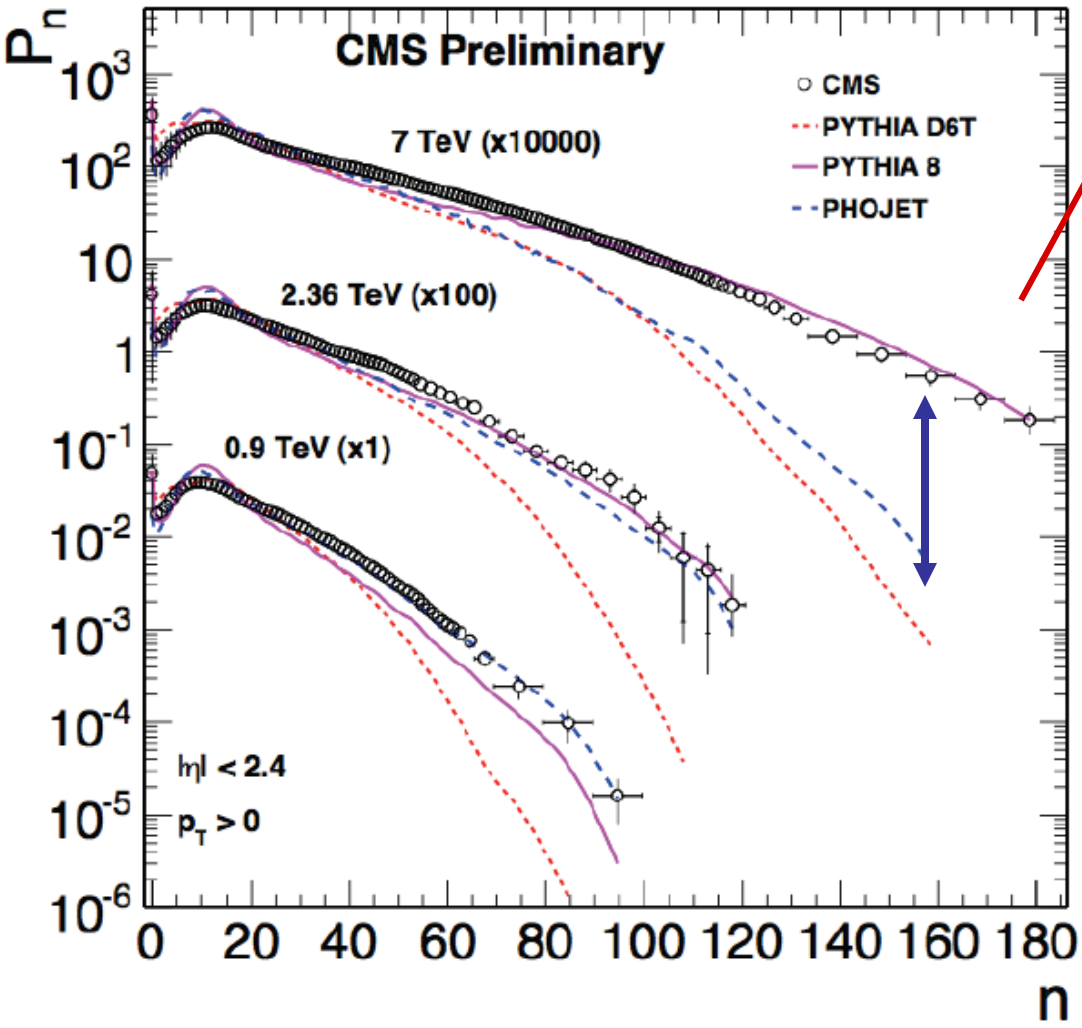
Extremes: very high multiplicity

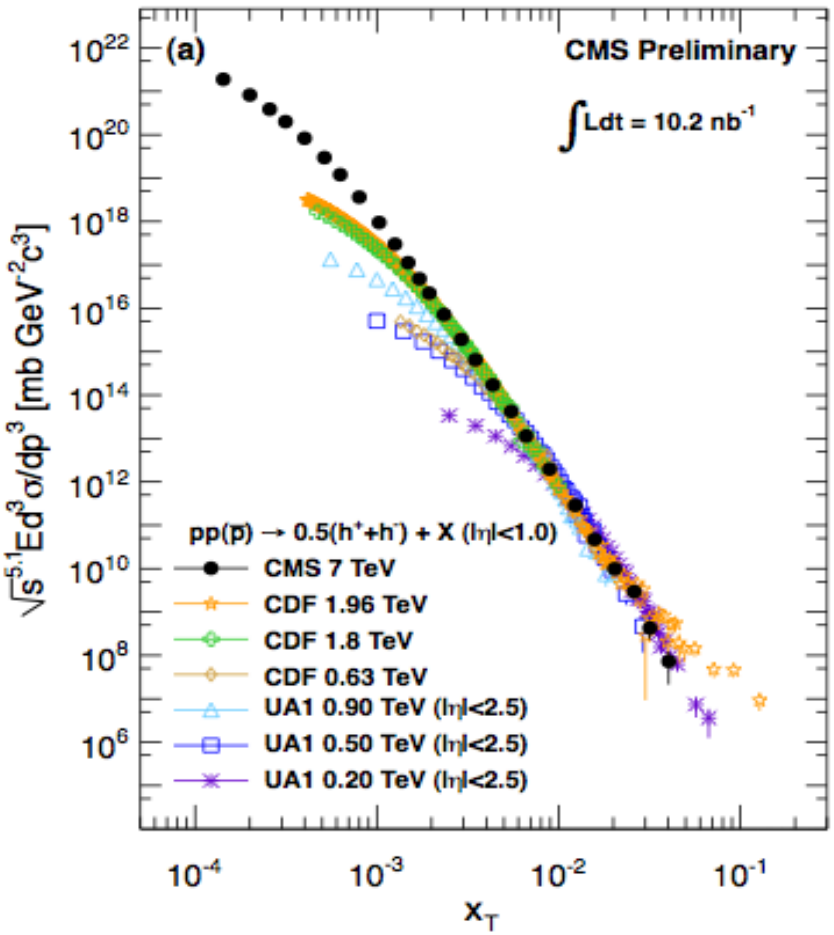


Large deficiencies in certain MCs for high multiplicity events (PYTHIA 6 D6T, PHOJET)

Will be possible to test KNO scaling, moments, MPI, …

G. Veres

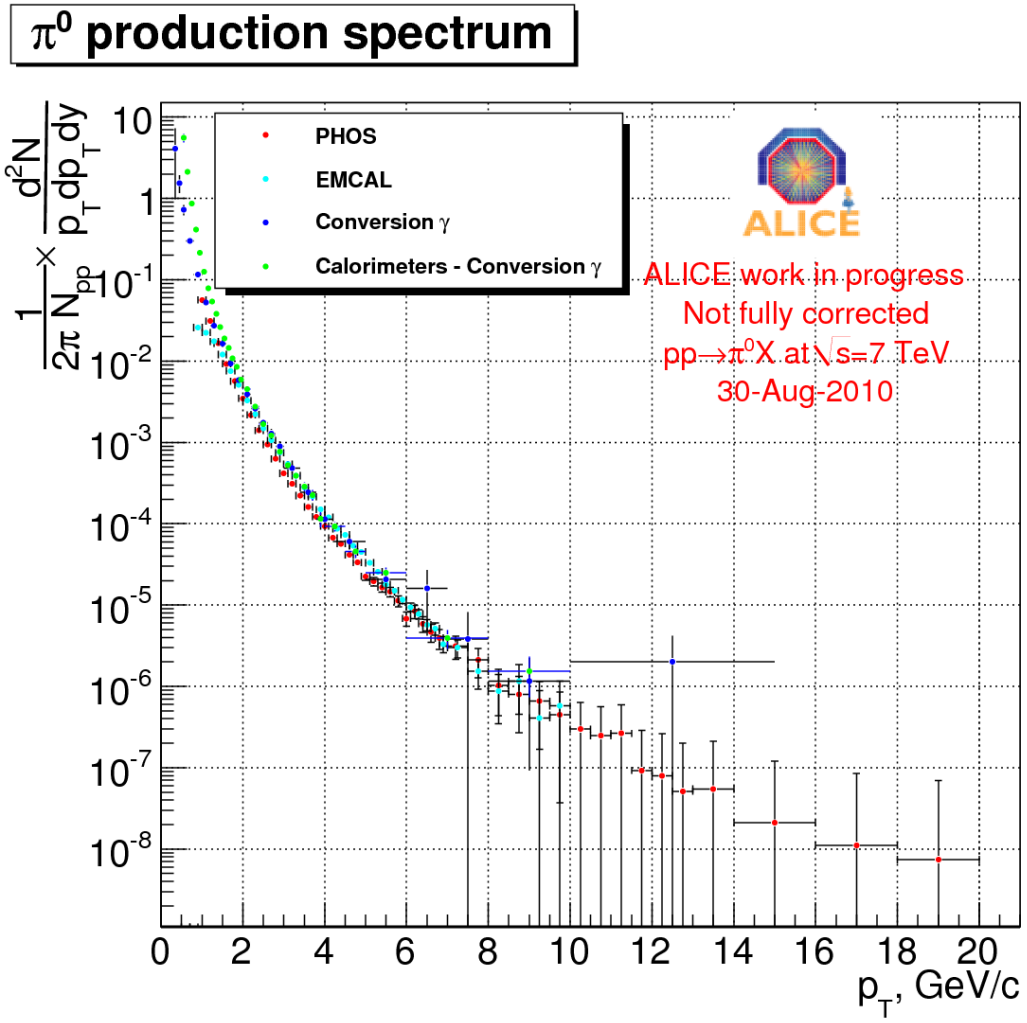
Extremes: high p_T, charged hadrons



- **Using jet triggers**
- **Merging various triggers with different E_T thresholds**
- **x_T scaling can be studied**

A prediction of pQCD hard processes is the power-law scaling of the invariant cross section with $x_T \equiv 2p_T/\sqrt{s}$

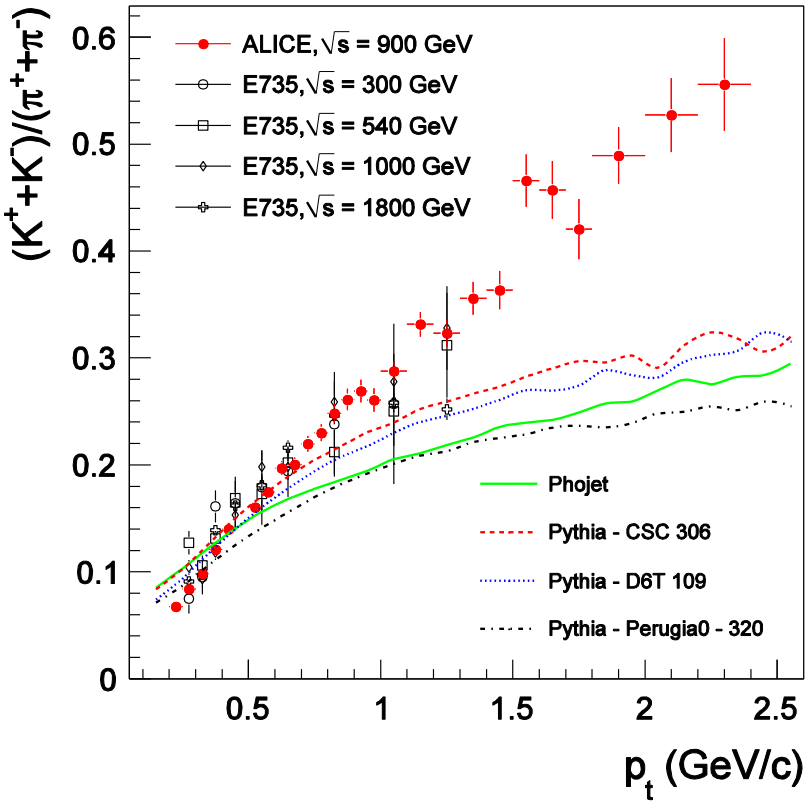
Extremes: high p_T, *neutral* hadrons

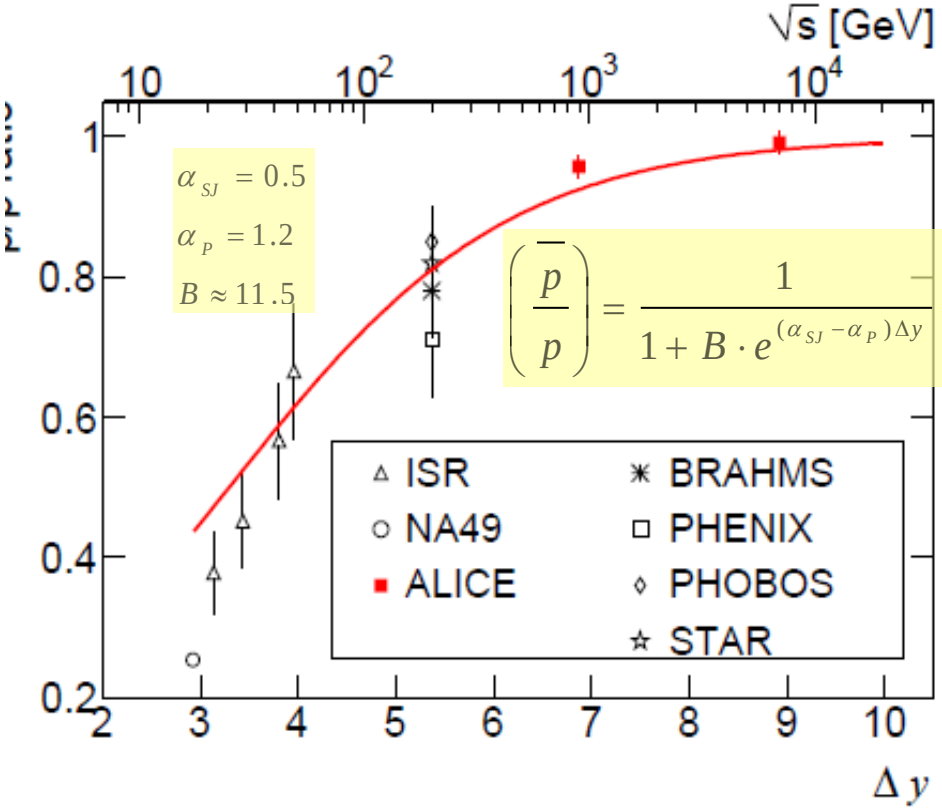


- **Using different experimental techniques**
- **Good agreement between methods and detectors**

Karel Safarik

Strangeness, baryon stopping





Strangeness underestimated by MCs
-More so for high p_T
-More so for large strangeness content
-But: φ meson is OK!

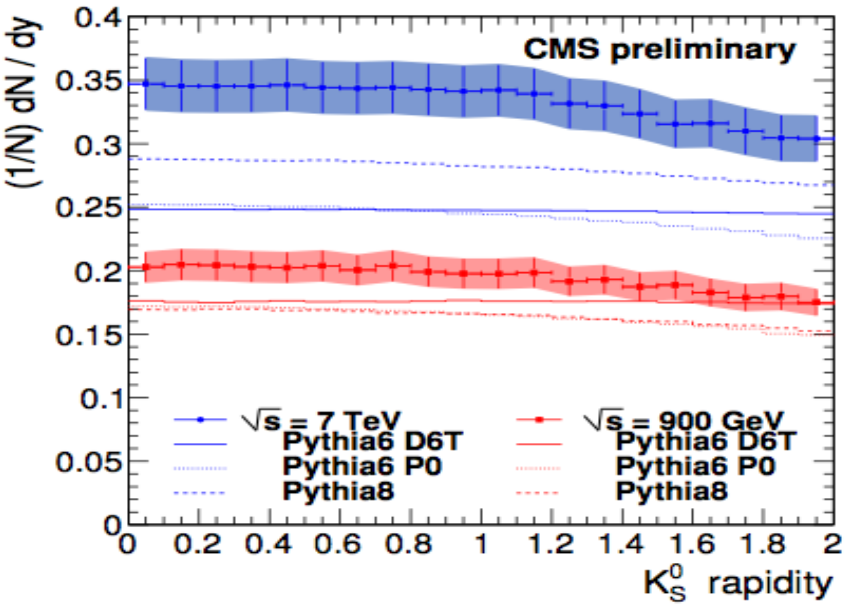
Discussion: how to address this in MC?
Tune consituent q mass?
strangeness suppression factor? (but it is more of an overall factor)

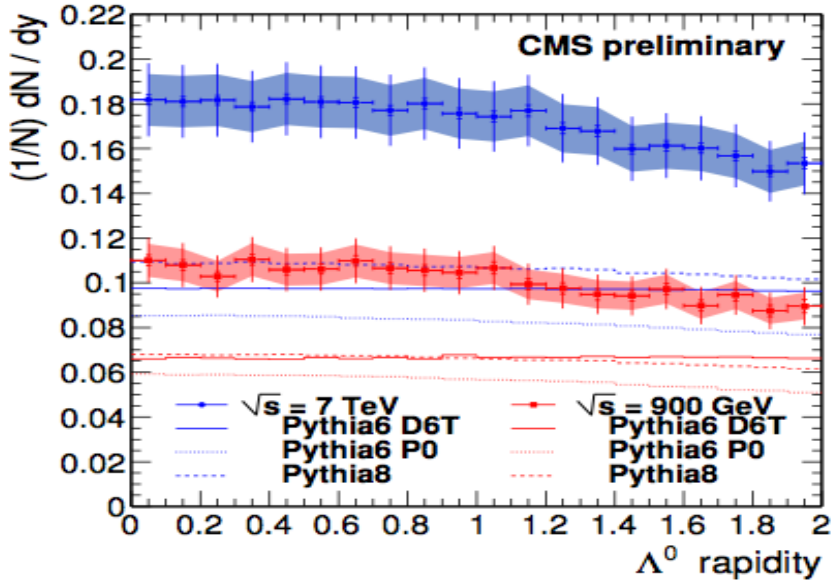
It is hard to stop a proton at LHC!

'string junction' picture: $\alpha_{SJ} \approx 0.5$
little room for **<u>any</u>** additional diagrams
that transport baryon number over large rapidity gaps

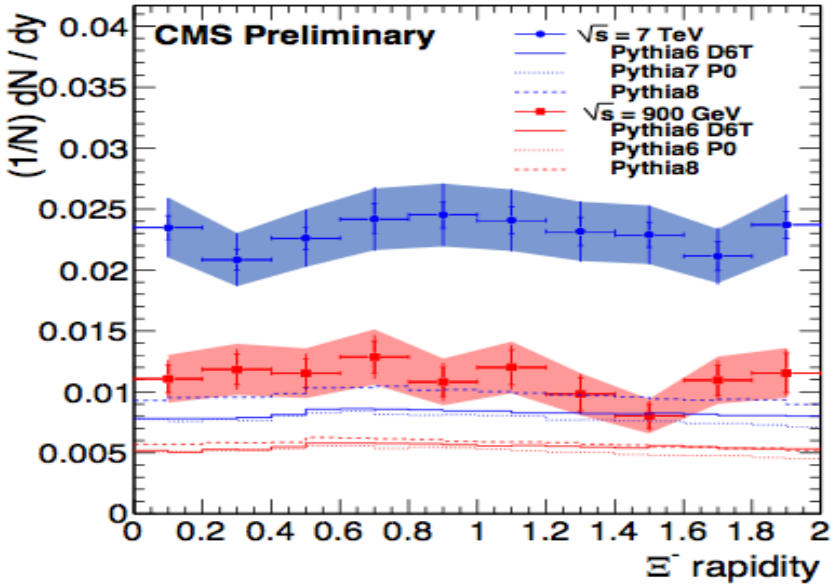
Karel Safarik

Dependence on strangeness content





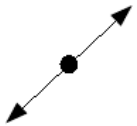
- **With increasing strangeness content, MC/data disagreement gets larger**

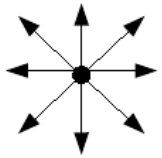


Mayda Velasco

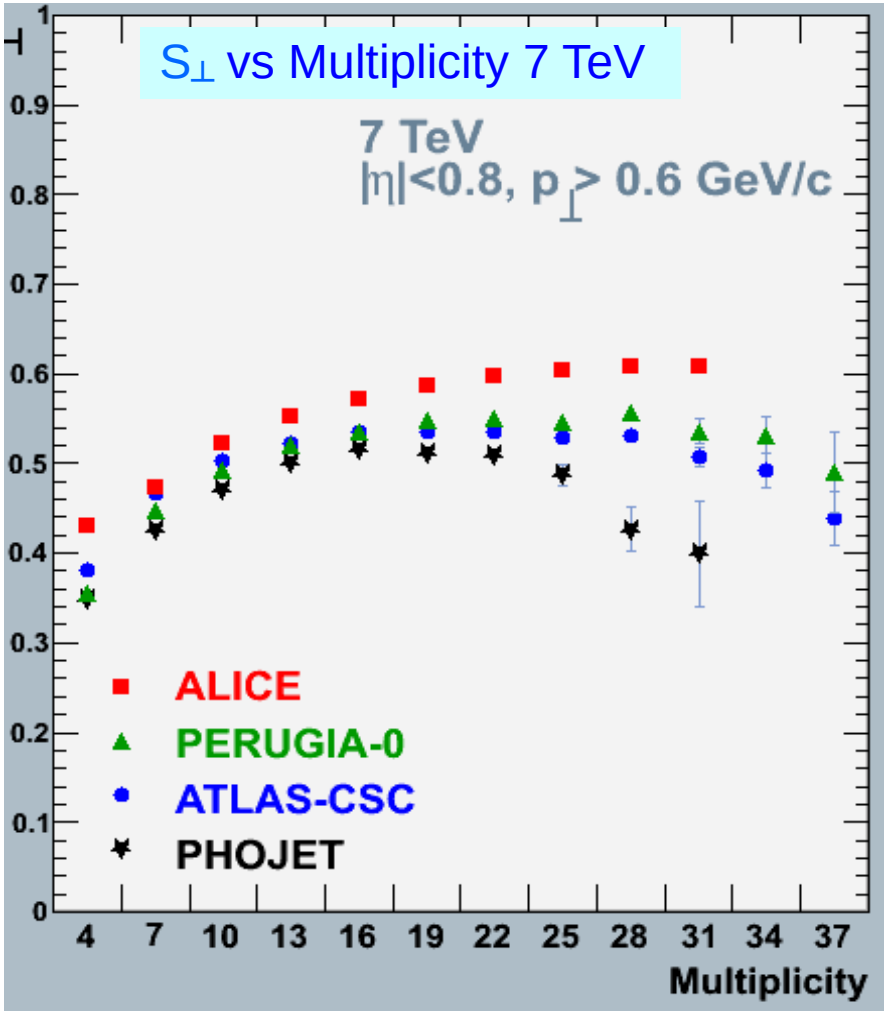
Minbias event shape/topology

- **Transverse sphericity**

small $S_\perp$: 

large $S_\perp$: 

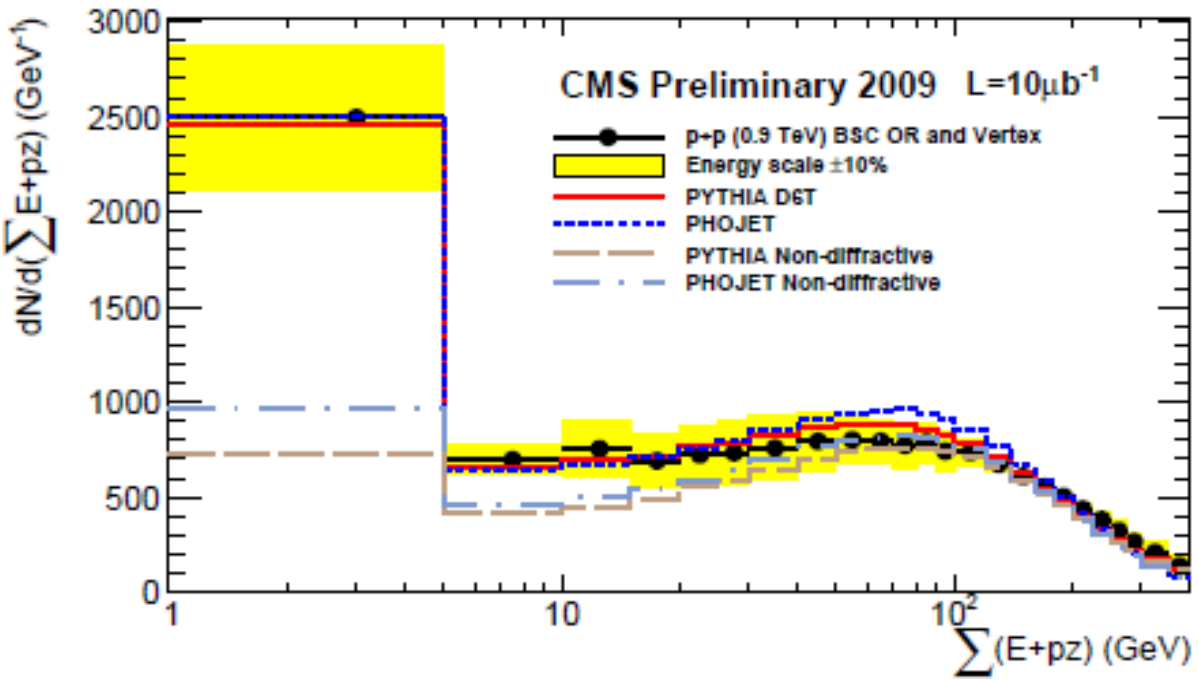
- Data appears to be more spherical than MC
- Work ongoing to study p_T-dependence



Karel Safarik

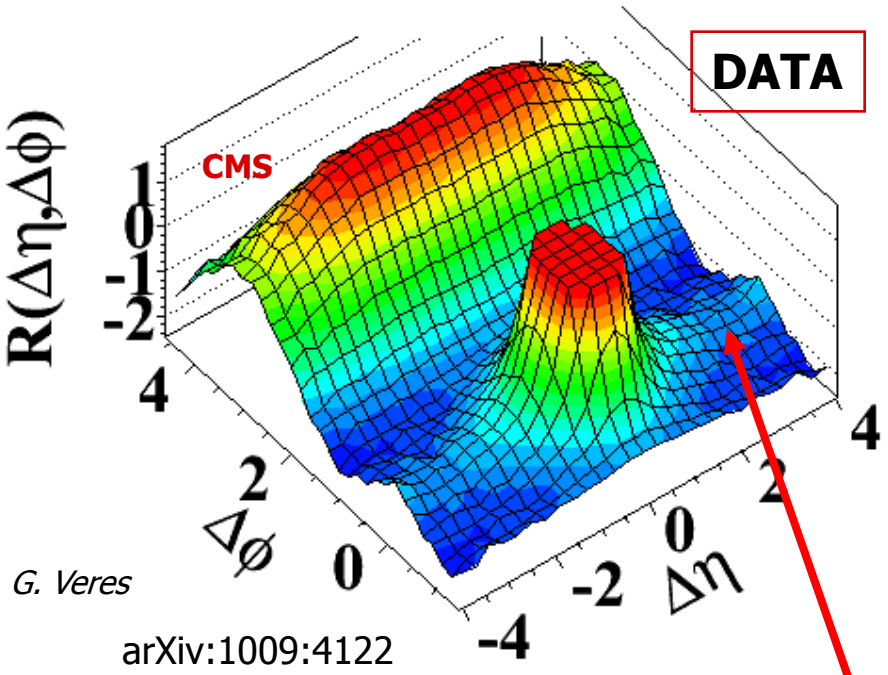
Diffraction

- **PYTHIA 6 is not very good in describing the diffraction (but quite good for non-diffractive events)**
- **PHOJET much better for diffraction (but not as good in nondiffractive events)**
- **But amusingly, all of them surprisingly close to data, given that they are NOT tuned for diffraction (i.e. it is often not even treated…)**



Correlations – high multiplicity pp

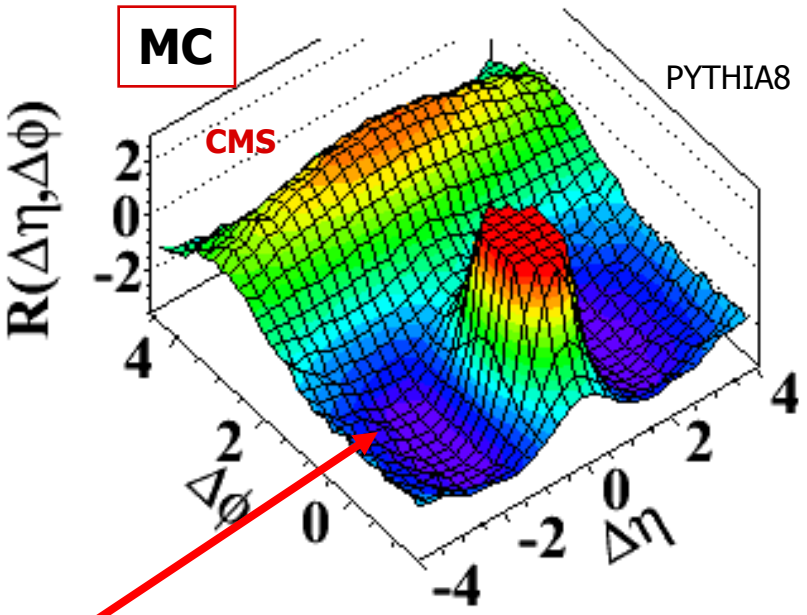
(d) N>110, 1.0GeV/c<p_T<3.0GeV/c



G. Veres

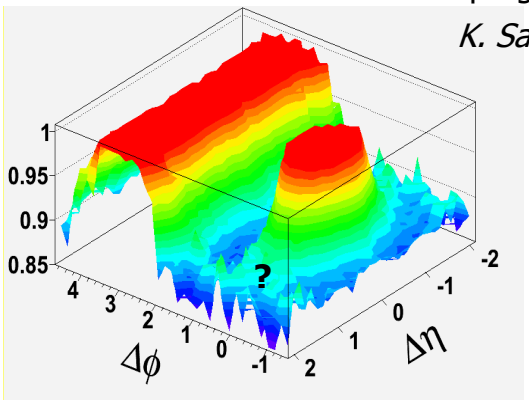
arXiv:1009:4122

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c



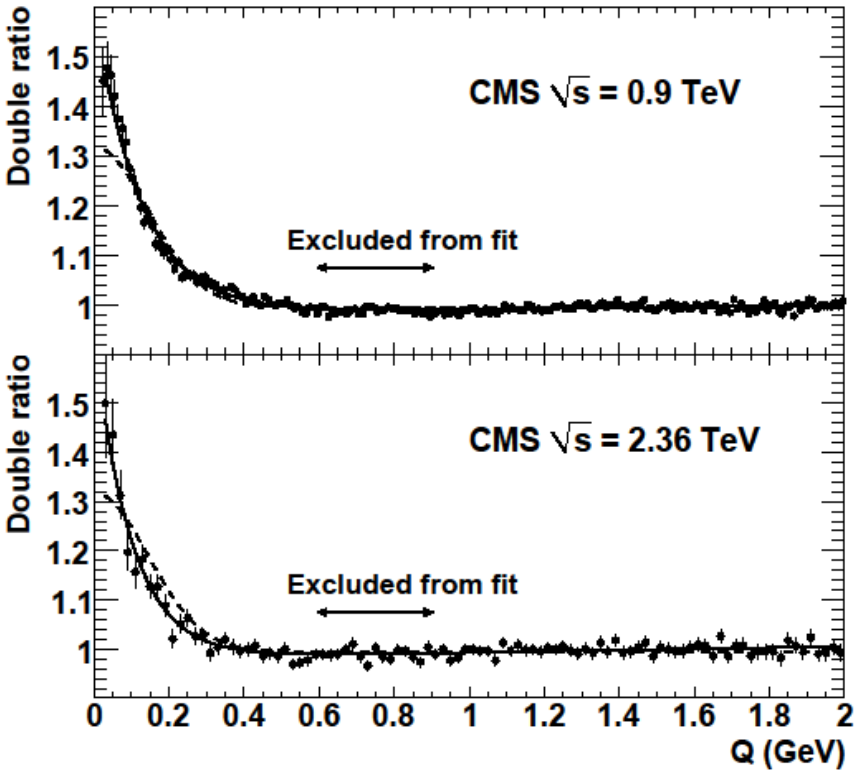
Qualitatively new correlation feature
not reproduced by various MC models
(HERWIG++, PYTHIA 8, PYTHIA 6, madgraph)

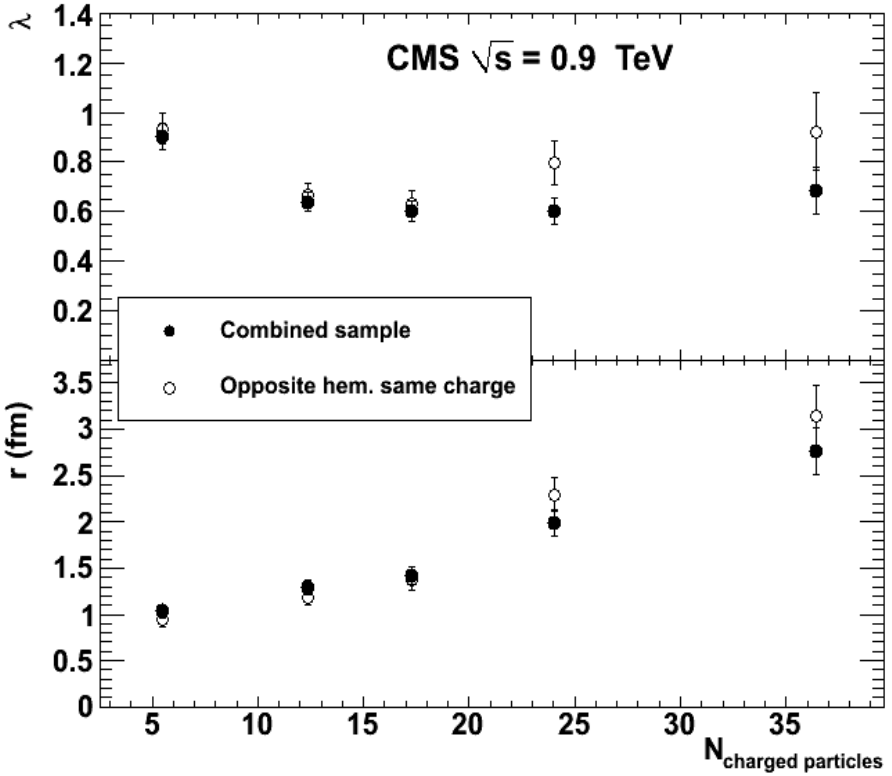
ALICE data
Work in progress
K. Safarik



Rick Field: This is a higher order effect that you can see in the 2→3 or 2→4 matrix elements, but it is not there if you do 2→2 matrix elements and then add radiation using a naïve leading log approximation (*i.e.* independent emission).

BEC





- **BEC is a Quantum Mechanics effect, well established**
- **Measured radius increases with multiplicity**
- **Not in the focus of MC models (intentionally)**

Monte Carlos – general remarks

- **Modelling MB and UE**
  - Complete view on events: total xsec, elastic, diffraction, inelastic
  - No single complete model
- **Why do we care?**
  - UE can pollute jet signatures
  - Can impact rapidity gap survival (Higgs: VBF, central exclusive)
- **Eikonal formalism:**

$$\sigma_{\rm tot}(s) = 2\int {\rm d}^2 b_\perp [1 - e^{-\Omega(s,\vec{b}_\perp)}]$$

Soft+hard eikonal: $\Omega_S(s,\vec{b}_\perp) + \Omega_{\rm H}(s,\vec{b}_\perp)$

The hard part: $\Omega_{\rm H}(s,\vec{b}_\perp) = \frac{1}{2}\,\rho(\vec{b}_\perp)\,\hat{\sigma}_{2\to 2}(s)$

PDF, α_s…

In PYTHIA: p_{T0} cutoff and its energy dependence

Changing any of these destroys the tune…

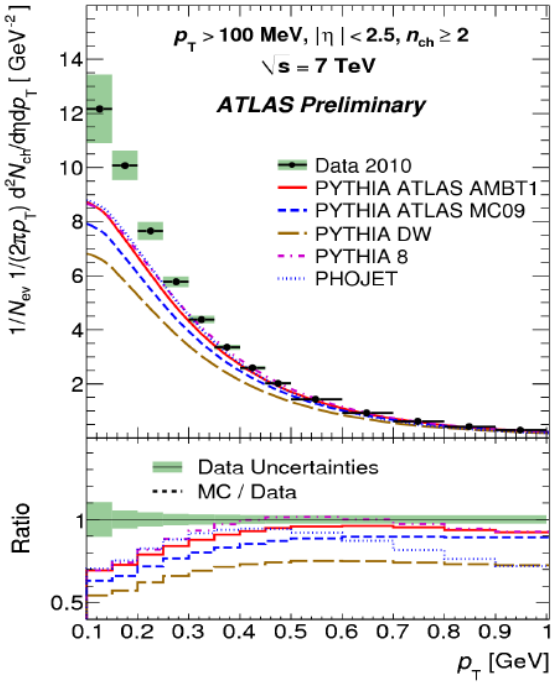
At low p_{T0}: partonic xsec> hadronic $\rightarrow$ Multiple parton scattering

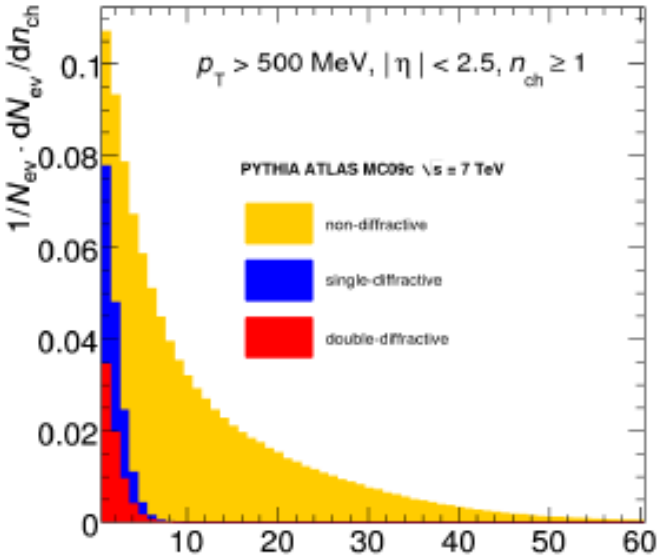
Frank Krauss

Difficulties at low mult/p_T

- **PYTHIA, HERWIG (hard eikonal): low multiplicity events, i.e. diffraction is just *out of their scope.***
- **Requring:**
  - More than 6 particles
  - A hard scale present

  improves the data/MC agreement!
- **Requring p_T>0.1GeV/c, 2 tracks:**
  - MC: too few low-p_T particles
  - Multiplicity under-estimated

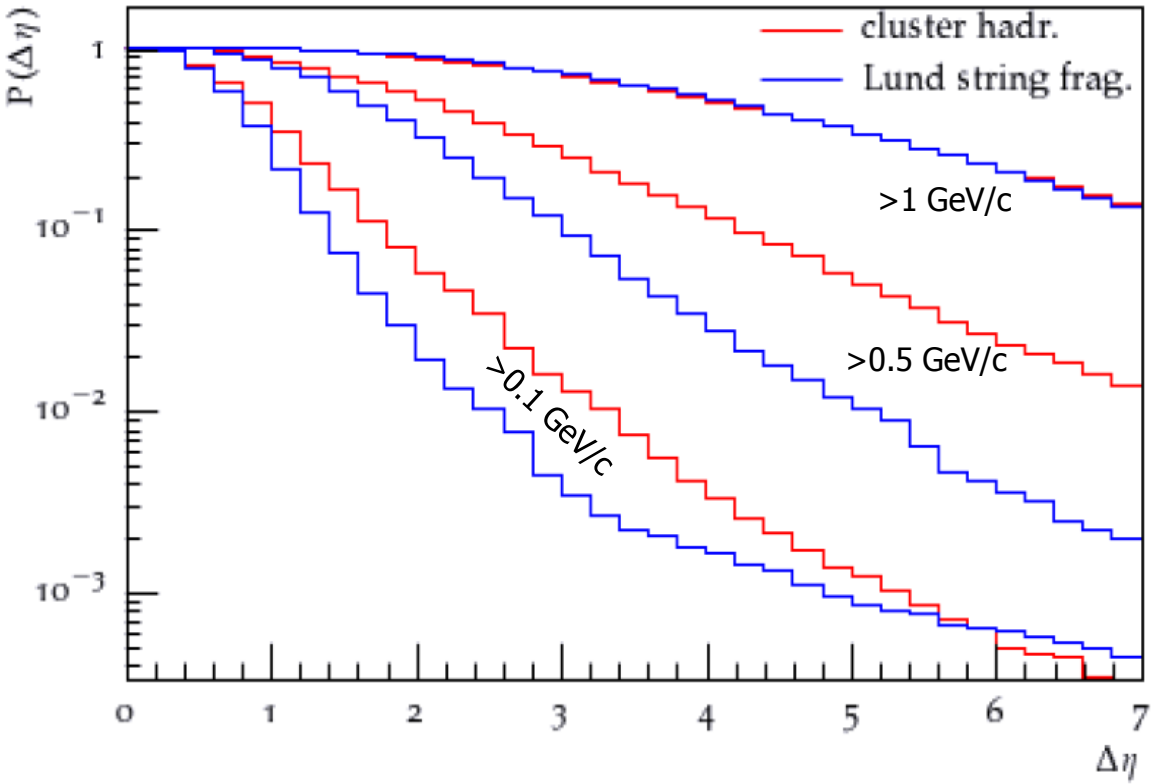




Frank Krauss

Difficulties with diffraction

- **Diffractive xsec's not negligible, ~10 times below inel**
- **Fluctuations in hadronization**
  → inel. events can look like diffractive ones!
- **Rap. gap not too stable.. example:**
  - Sherpa+Lund string and cluster fragm.
  - Lund better at LEP, cluster is better for DIS@HERA
  - Large uncertainties in the probability to find a gap with low p_T cuts!
  - Large influence of fragmentation



Frank Krauss

How to best present data?

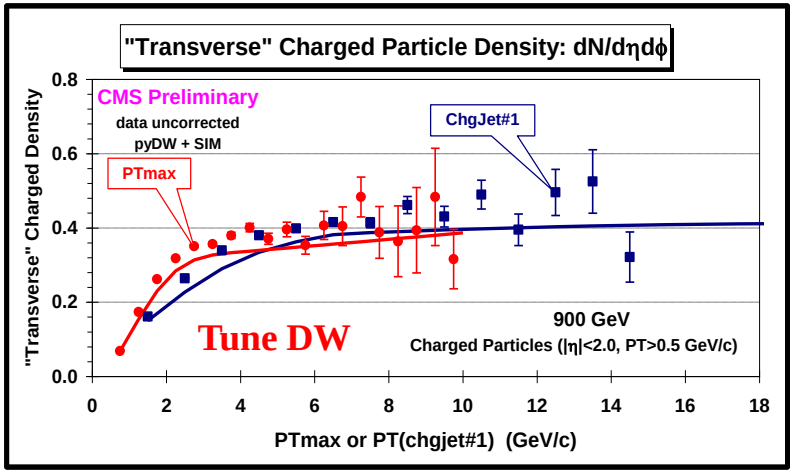
- **Corrected for detector effects** → But in some cases ($p_T \to 0$) they overlap…
- **Do not use extrapolations** → Or at least publish both w/ and w/o it.
- **Well defined cuts**
- **Numerical values to HEPDATA**
- **Include to RIVET if possible**

- **The MBUE tuning story is not over!**

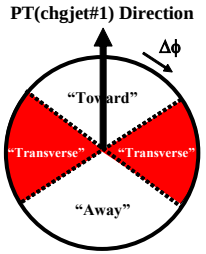
Frank Krauss

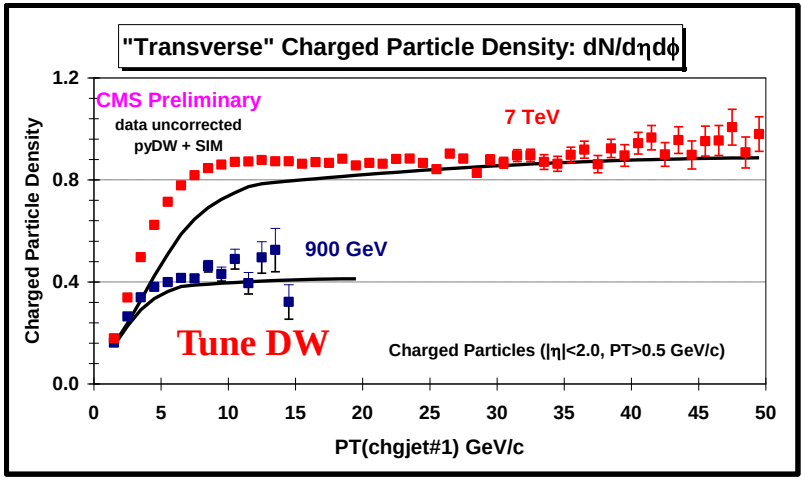
Underlying Event & MC tunes

- **The "underlying event" at 0.9 and 7 TeV are close to expectations! Only a little tuning needed.**
- **MC Tunes predicted UE behavior surprisingly well; even if this is soft QCD.**
- **Minimum Bias is a different story, more complicated due to diffraction.**



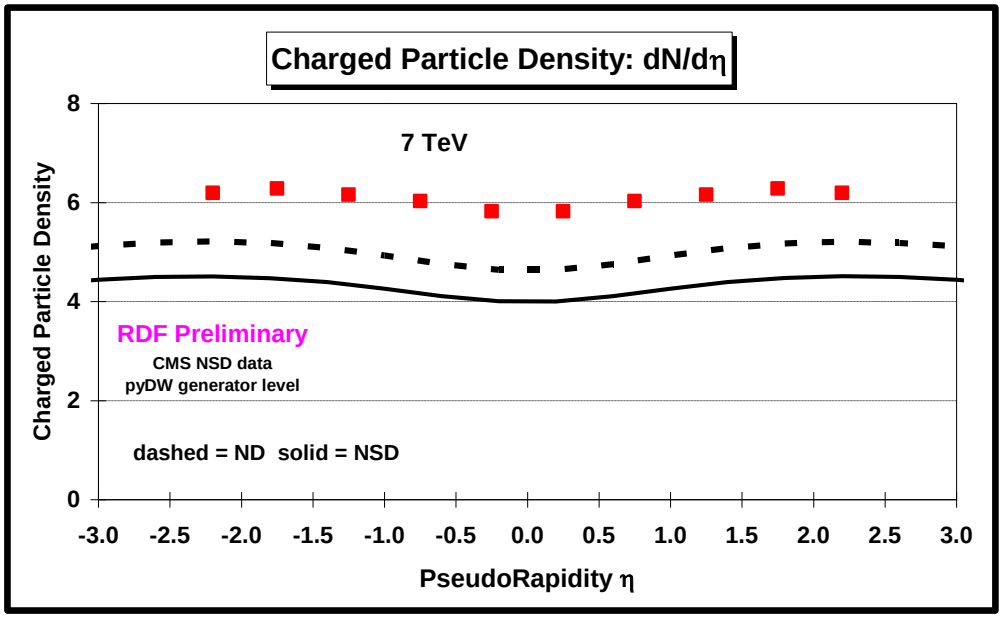
Notes:
- p_T>0.5 GeV/c is used
- with a hard scale present, MC/data agreement is good





Rick Field

In the absence of a hard scale…



dN/dη (all p_T). NSD and ND from Tune DW compared to CMS NSD data.

Off by 50%!

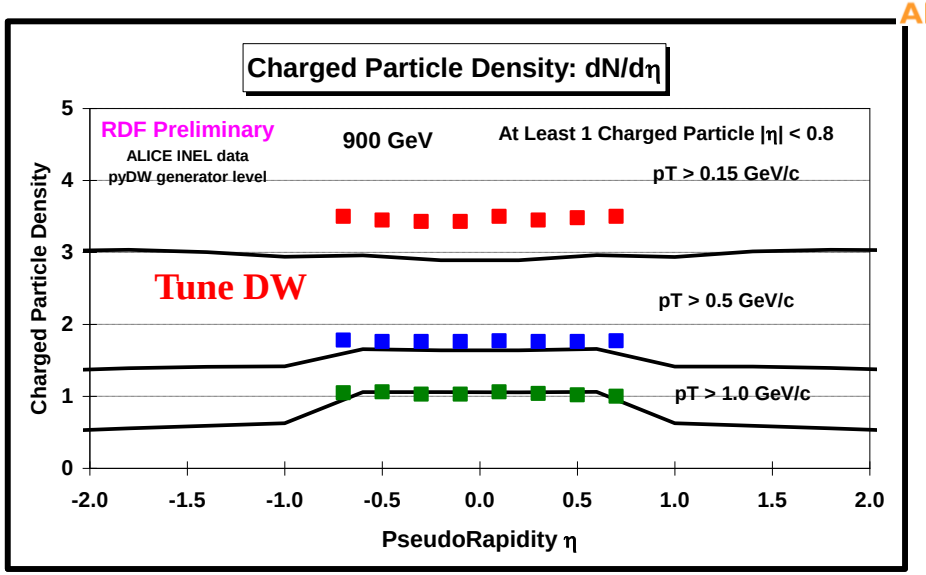
We can try to tune the Monte-Carlo to fit the data!

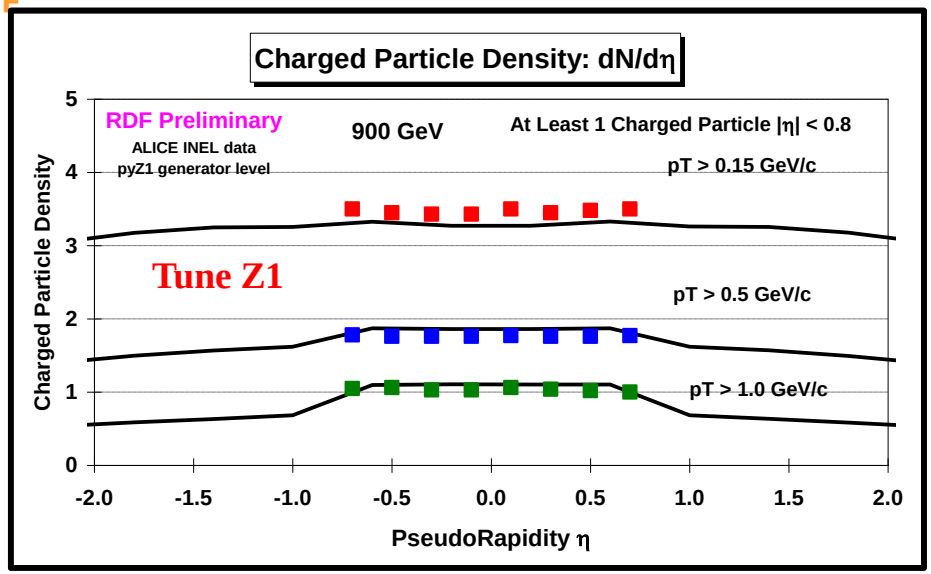
B.U.T.

Be careful not to tune away new physics!

Rick Field

Role of the hard scale





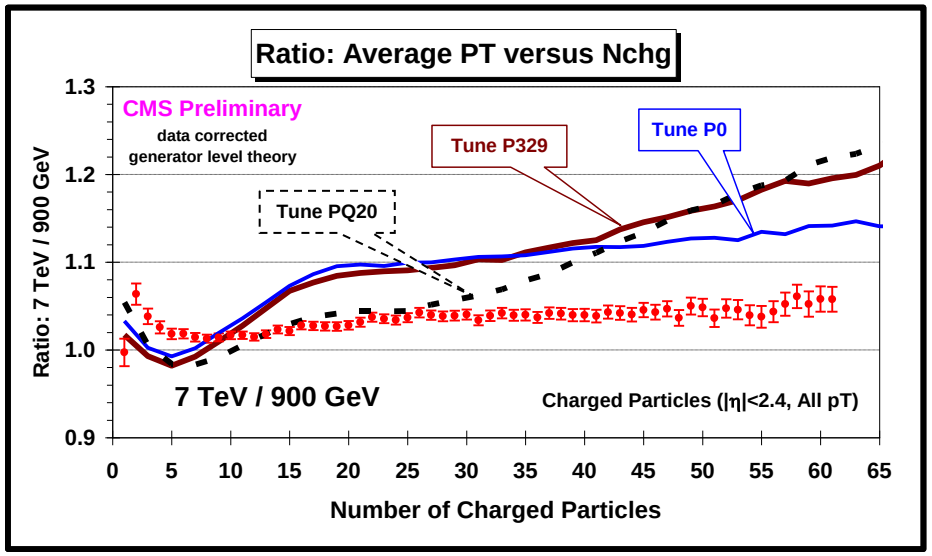
- **ALICE inel. dN/dη, 900 GeV ($p_T > P_{Tmin}$) for events with >=1 charged particles with $p_T > P_{Tmin}$ and $|\eta| < 0.8$.**
- **Compared with PYTHIA Tune DW and Z1**

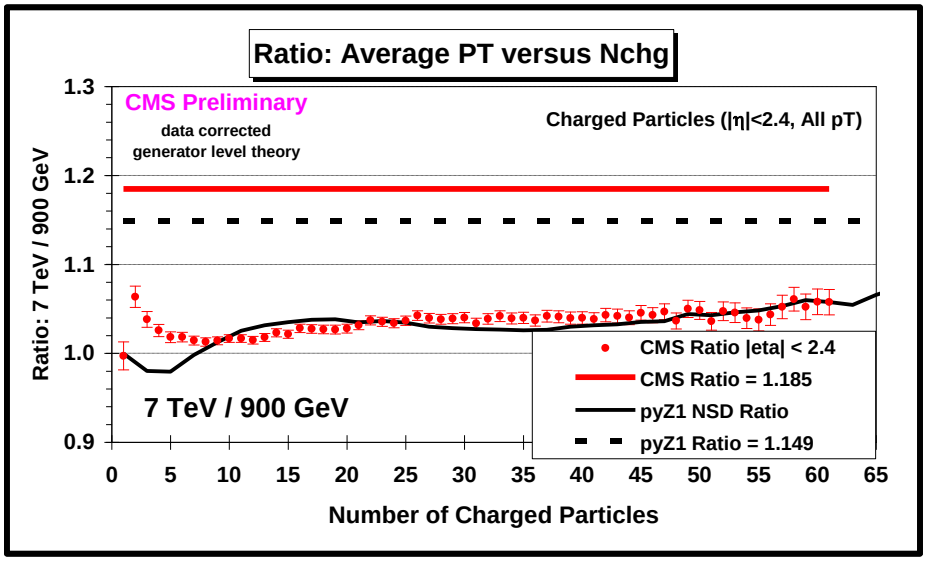
Many other successes of Z1 tune presented! Both UE and MB.

Tune Z1: Started from the parameters of ATLAS Tune AMBT1,
- changed LO* to CTEQ5L
- varied PARP(82) and PARP(90) to get a good fit of the CMS UE data
i.e. MPI cutoff and energy extrapolation

Rick Field

Something fundamental?





CMS NSD $\langle p_T \rangle$ vs N_{ch}, 7 TeV/0.9 TeV, compared with Tune P0, PQ20, P329.

Tune Z1!

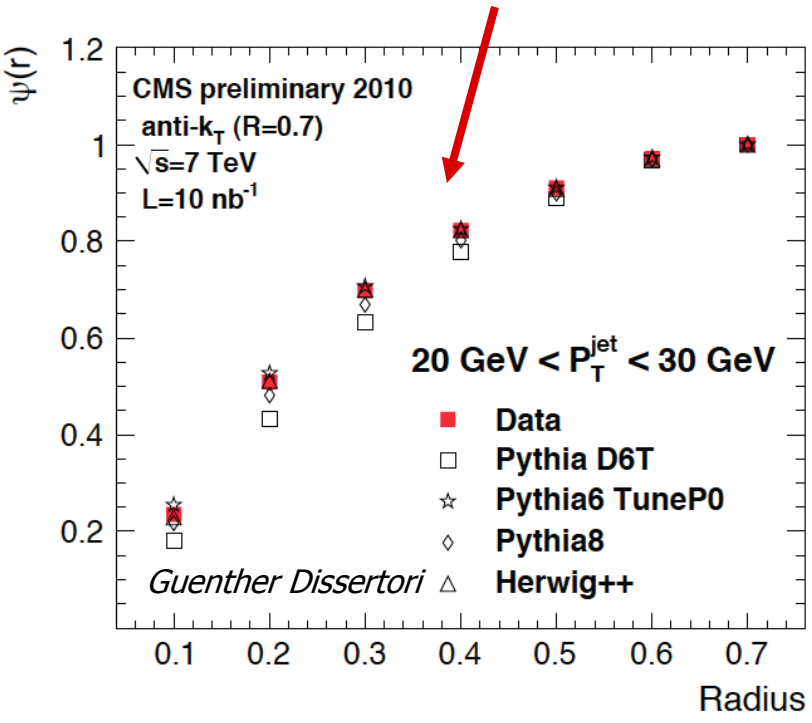
The increase in mean p_T between 0.9 and 7 TeV is BARELY more than just:
- Increasing multiplicities 0.9 $\rightarrow$ 7 TeV
- Increasing mean p_T vs N_{ch} (which is almost energy-independent!)

Looking for such 'scaling' features may be a very good and instructive direction to go

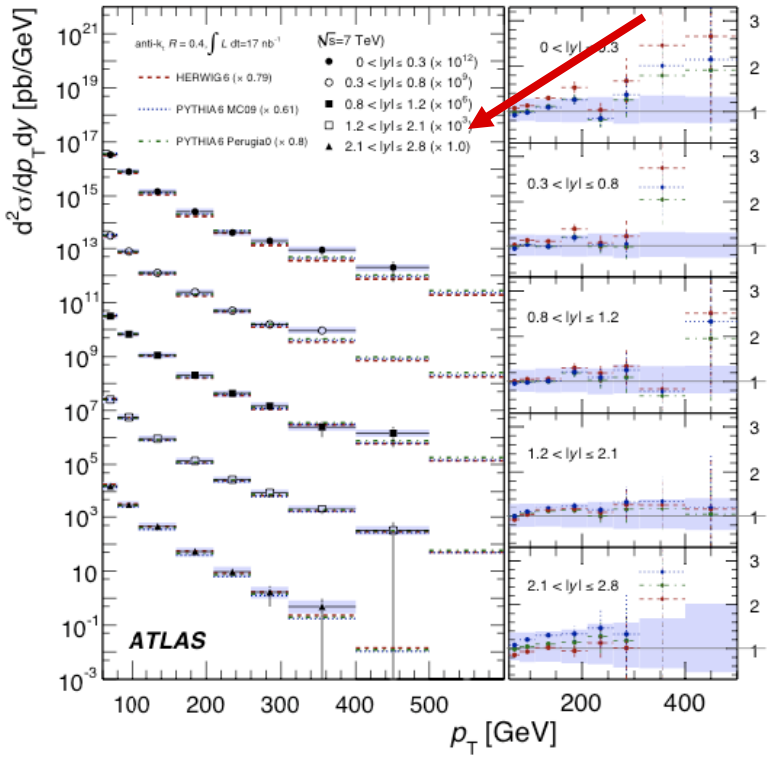
Rick Field

ATLAS results and MC Tunes

- **Note on ATLAS tunes for MC09:** **ATL-PHYS-PUB-2010-002**
  - For UE and minbias.
  - PYTHIA and HERWIG+JIMMY used MRST LO* PDFs
  - Also CTEQ6.6 PDFs used with MC@NLO, and JIMMY was tuned for them
- **ATLAS: jet-xsec and jet shapes well described by PYTHIA**
- **Also: jet shapes in CMS: well described at high-p_T but not so at low p_T**



Discussion on K-factor (ATLAS):
less than 1 required to agree with data?
UE event may be responsible



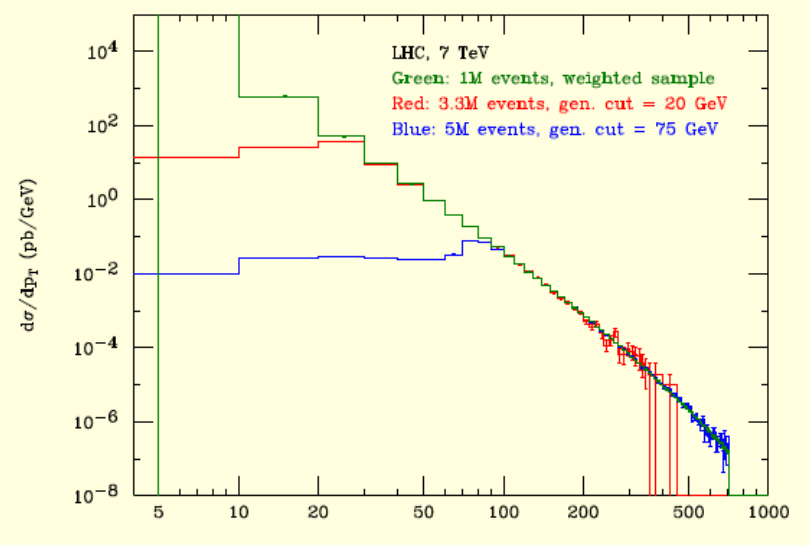
Positive Weight Hardest Emission Generator

- Method (not a program) that interfaces NLO calculations with Parton Shower
- Formulation: 2004
- POWHEG BOX: 2010. Fortran framework to implement NLO processes into POWHEG.
- POWHEG compares well to MC@NLO (few exceptions)
- Completely separates hardest radiation generation from the following shower.
- One can implement NLO calculations (POWHEG BOX) as NLO+PS that can be interfaced to any shower program.
- Z+jet and dijet is now available in POWHEG at NLO
- Implementation of new processes proven to be quick
- Generates user event file in the Les Houches format

Paolo Nason

Jets in NLO+PS

- **Generation cut needed: minimum k_T**
- **Jet k_T should be set higher in any analysis**
- **Possible to paste together samples with different $k_T$min**
- **Or weighting by** $k_T^2/(k_T^2 + p_{T\,\mathrm{supp}}^2)$
- **Dijets: POWHEG agrees with NLO**
  - Asymmetric E_T cuts for the two jets work better
- **With shower by PYTHIA: data is well described**
- **Extensive data/MC comparison presented**
- **POWHEG is a viable tool for NLO jet physics**



Paolo Nason

NLO wishlist

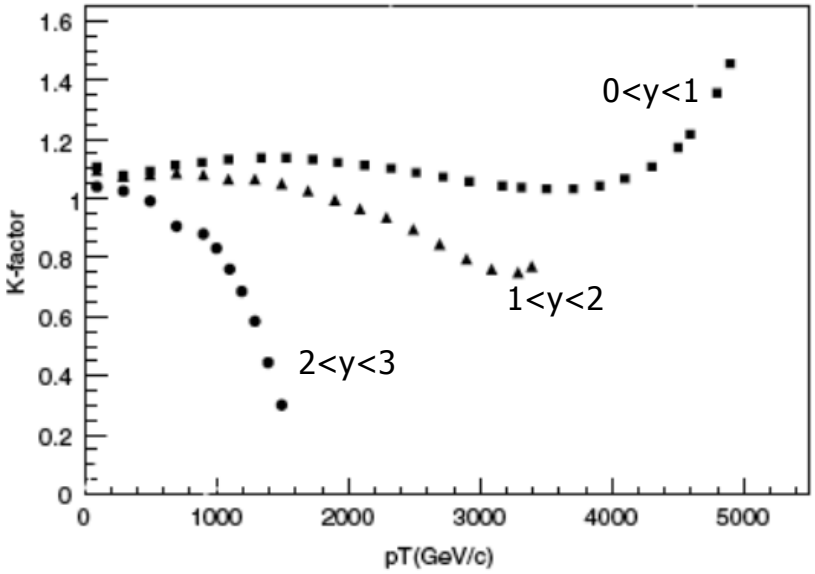
- **Developed in 2005, Les Houches**
- **Both 'doable' and important for LHC**
- **Useful to include final particle decays too**
- **Best: NLO partonic level calculations interfaced to shower/hadronization**
- **Would be nice to automatize inclusion of new processes**
- **Flexibility important: i.e. ROOT ntuples at parton level, user can cluster the jets, variable sizes/cuts**

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Joey Huston

K-factors (NLO/LO)

- **LO parton shower MCs… but would like to know the impact of NLO corrections**
- **K-factor can depend on PDFs used at LO, NLO; scales**
- **NLO corrections can result in a *shape change***
- **Inclusive jet production:**
  - wide x,Q2 range
  - Varying gg, gq, qq mixture
  - PDF uncertainties larger at high p_T



K-factor for yet cross section

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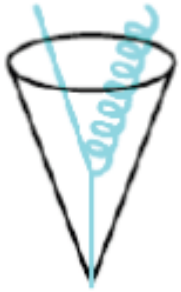
Jet algoritms - NLO

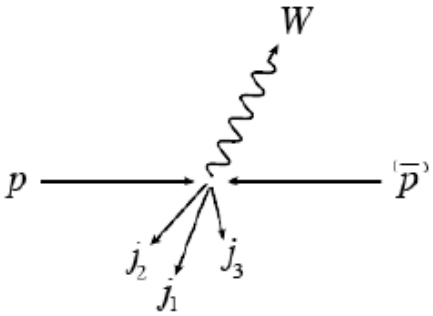
- **At NLO, more than one parton in a jet**
  - How to cluster them? Jet algo's.
- **W+3j xsec: jet size dependence smaller for NLO**
- **Scale choice: E_T^W is not fortunate at LHC; total E_T can be much larger than E_T^W, i.e. E_T^W is too small to describe the process well**
- **H_T works well at LO and NLO**

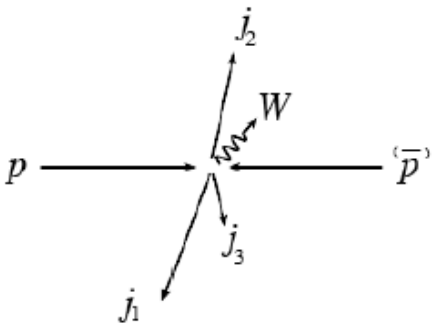


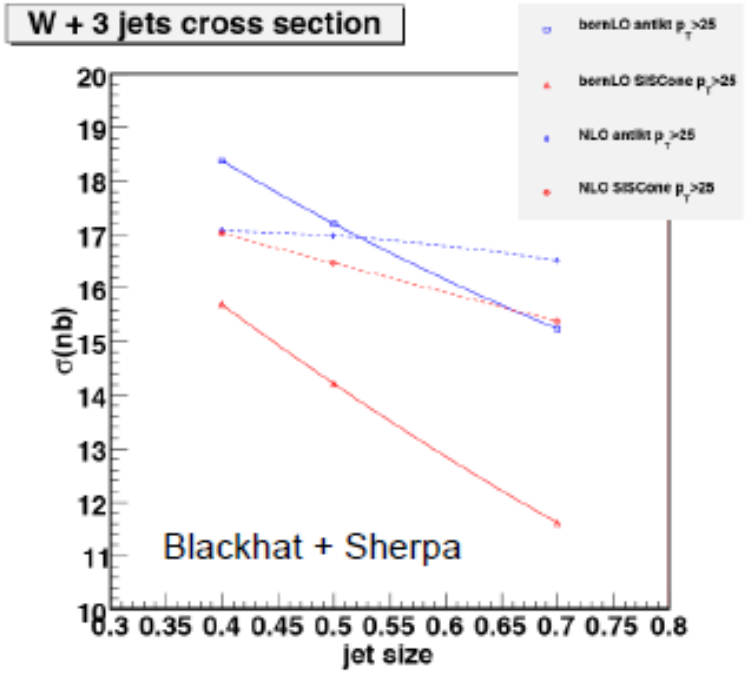
$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{ii} = p_{T,i}^{2p}$$

p=0; C-A
p=1: k_T
p=-1 anti-k_T







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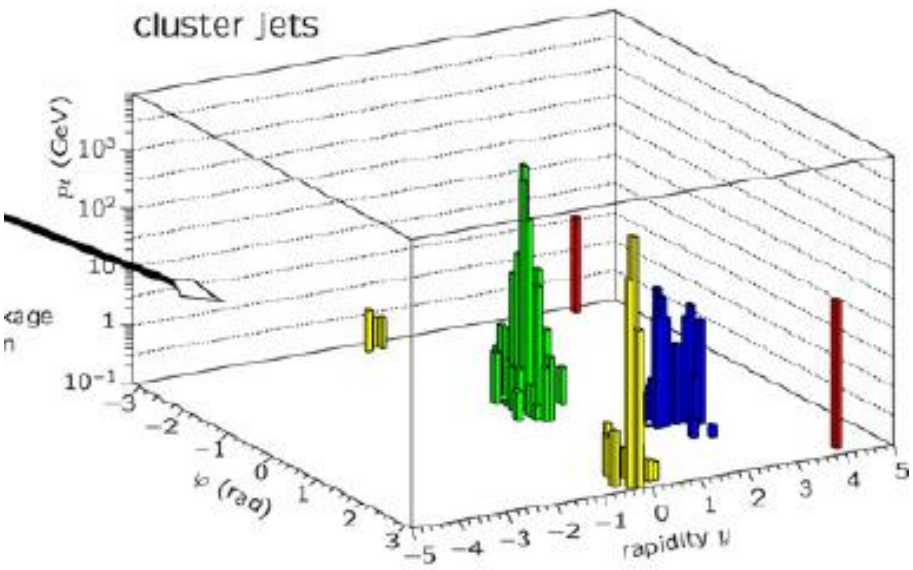
Jet algorithms

- **Jet sizes: better to use smaller size for multijet events**
  - Also reduces pileup/UE effects
- **But too small R: hadronization effects**
- **Scale uncertainty for n-jet final state can depend on jet size**
- **(50 GeV incl. jet:) Uncertainty due to scale dependence minimal if jet size ~0.7**
- **ATLAS: uses jets in a dynamic manner, multiple jet algo's, parameters, substructure**
  - similar to situation in hadron level MC



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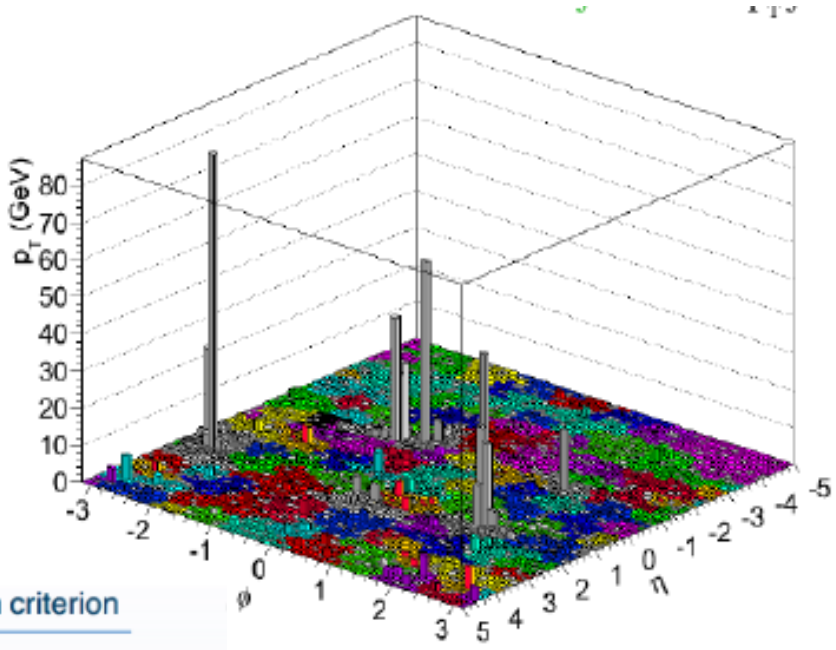
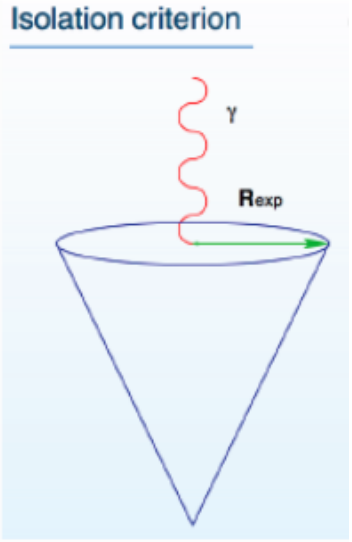
UE and isolation

- **Area-based correction:**
  - Find low p_T jets
  - average/median p_T density
  - Use area A of signal jets to correct: $p_{T corr} = p_T - \rho A$
- **Photon isolation**
  - Frixione: allowed energy depends on the distance from the photon
  - But large UE contribution
  - Work ongoing





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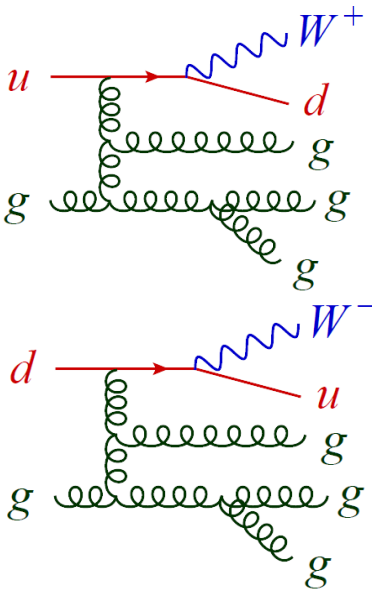
Perturbative stability… what to measure?

- **Approach: measuring certain *ratios* can be much less sensitive to shower and non-perturbative effects, but sensitive to *new physics***
- **Example:** $R^{\pm}(n) \equiv \dfrac{\sigma(W^+ + n \text{ jets})}{\sigma(W^- + n \text{ jets})}$
  - Very small experimental systematics
  - (N)NLO QCD corrections quite small, 2% or less
  - → Intrinsic theoretical uncertainty very small.
  - PDF uncertainty also ~1-2%. Driven by PDF ratio $u(x)/d(x)$ in well-measured valence region of moderate x.
  - Sensitive to new physics (or Higgs, or top quark pairs) that produces $W^{\pm}$ symmetrically
  - Fraction of new physics in sample is:

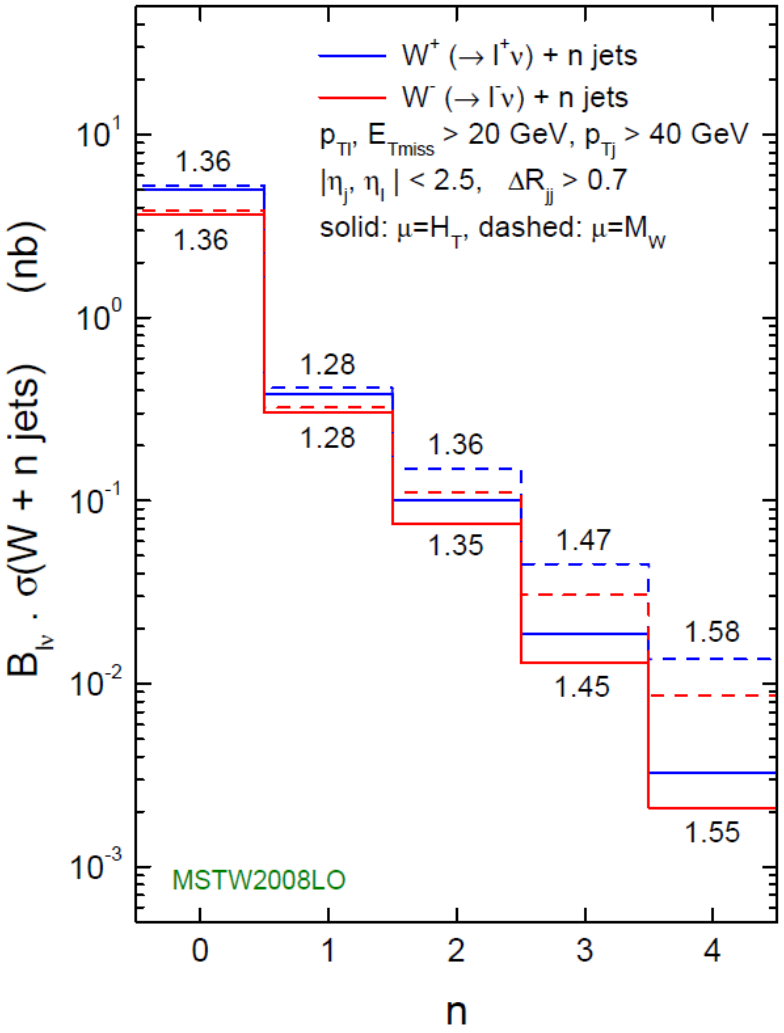
$$f_{\text{NP}} = \frac{2(R^{\pm}_{\text{SM}} - R^{\pm}_{\text{exp.}})}{(R^{\pm}_{\text{SM}} + 1)(R^{\pm}_{\text{exp.}} - 1)}$$

n	QQ	Qg	gg
0	100	0	0
1	18	82	0
2	21	73	6
3	23	70	7
4	25	67	8

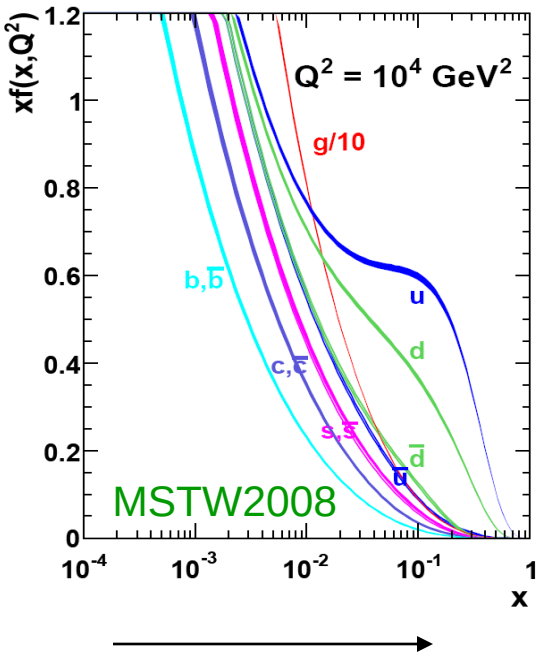


Lance Dixon

W+/- ratio: high accuracy



- **Huge scale dependence at LO cancels in ratio**
- **Increases with *n* due to increasing *x***

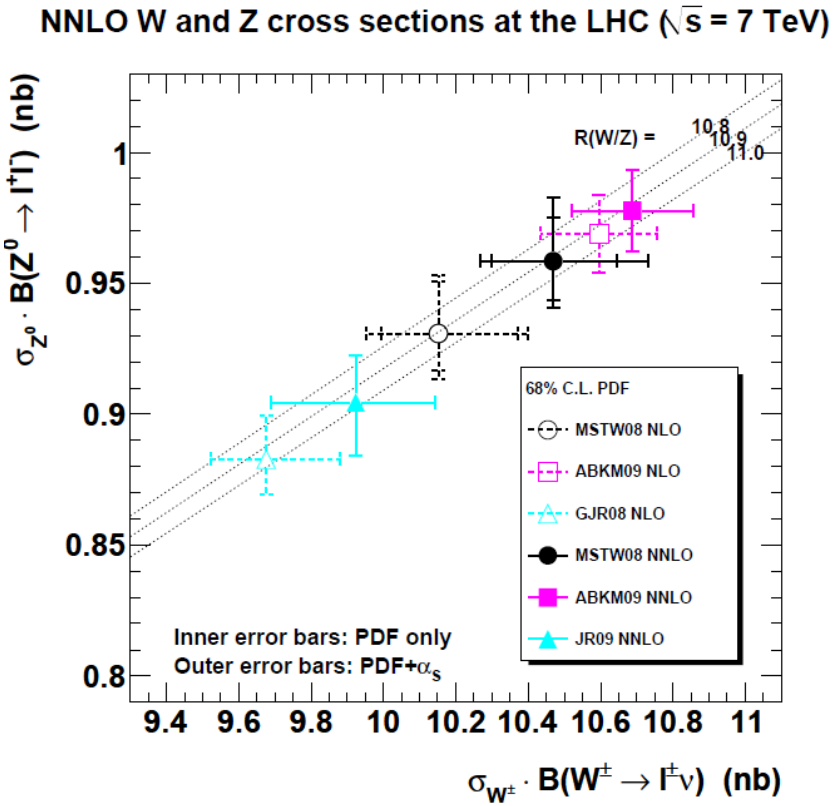


Many jets. u/d increases
Lance Dixon

W/Z ratios

$$R^{W/Z}(n) \equiv \frac{\sigma(W^+ + n \text{ jets}) + \sigma(W^- + n \text{ jets})}{\sigma(Z + n \text{ jets})} \frac{\text{Br}(W \to \ell\nu)}{\text{Br}(Z \to \ell^+\ell^-)}$$

- Stable against perturbative nonperturbative QCD effects, since $M_W \approx M_Z$
- In inclusive case ($n = 0$) it's a precision observable, computable at NNLO, also including experimental cuts
- Not as clean experimentally as W^+/W^-, because W and Z selections are not identical, top background is different



Lance Dixon

Jet production ratios

Adding one more jet reduces the cross section by a constant factor (which depends on jet definition), i.e. uniform jet emission probability r.

$\sqrt{s} = 7$ TeV
anti-k_T, $R = 0.5$
$p_T^{\text{jet}} > 25$ GeV

no. jets	LO $W^- \; n/(n-1)$	NLO $W^- \; n/(n-1)$
1	$0.164^{+0.044}_{-0.031}$	0.159
2	$0.277^{+0.051}_{-0.037}$	0.236
3	$0.235^{+0.034}_{-0.025}$	0.216
4	$0.221^{+0.026}_{-0.020}$	0.211

Using W + n jets at NLO for n=1,2,3,4 we can test this scaling at NLO parton level.

- **State-of-art NLO V + 2,3,4 jet results are still at parton level, not embedded in a shower Monte Carlo**
- **Best use may be via ratios – aids to data-driven analysis of backgrounds.**
- **W^+/W^- ratio in presence of additional jets is nontrivial, well-determined, sensitive to new physics**
- ***(W + jets)/(Z + jets)* also interesting, but a bit harder experimentally.**
- **"Jet production ratios" are less uncertain than individual multi-jet rates.**

Lance Dixon

Model building: composite weak bosons

- **Standard model: two types of mass generation**
  - Confinement (QCD), Mp=E(gluons, quarks)/c^2
  - Weak boson mass: spontaneous symmetry breaking
- **Alternative: mass of weak bosons generated by confinement? Composite W. Analogy with $\rho^{+,0,-}$.**
- **Binding via gauge interaction: QHD (for *haplons*)**
- **Mass scale: Λ_h. M_W = const x Λ_h**
- **Gauge group: SU(n)**
- **New excited states below 1 TeV**
- **W' -> W+Z; W'' -> W+Z+Z etc**
- **Estimate: in 1e-5 of LHC events: QHD interaction**
- **Dimuon resonances estimated about m ~ 0.4 TeV**
- **LHC can address all this, if true**
- **Discussion:**
  - parity violation may already give limits
  - do haplons serve the economy (as QCD quarks are)?
  - Gluon-scalar scattering would give a limit? (scalar inside q)

$$W^+ \quad \bar{\beta} \quad \alpha$$

$$W^- \quad \bar{\alpha} \quad \beta$$

$$W^0 \quad \frac{1}{\sqrt{2}}(\bar{\alpha}\alpha - \bar{\beta}\beta)$$

Harald Fritzsch

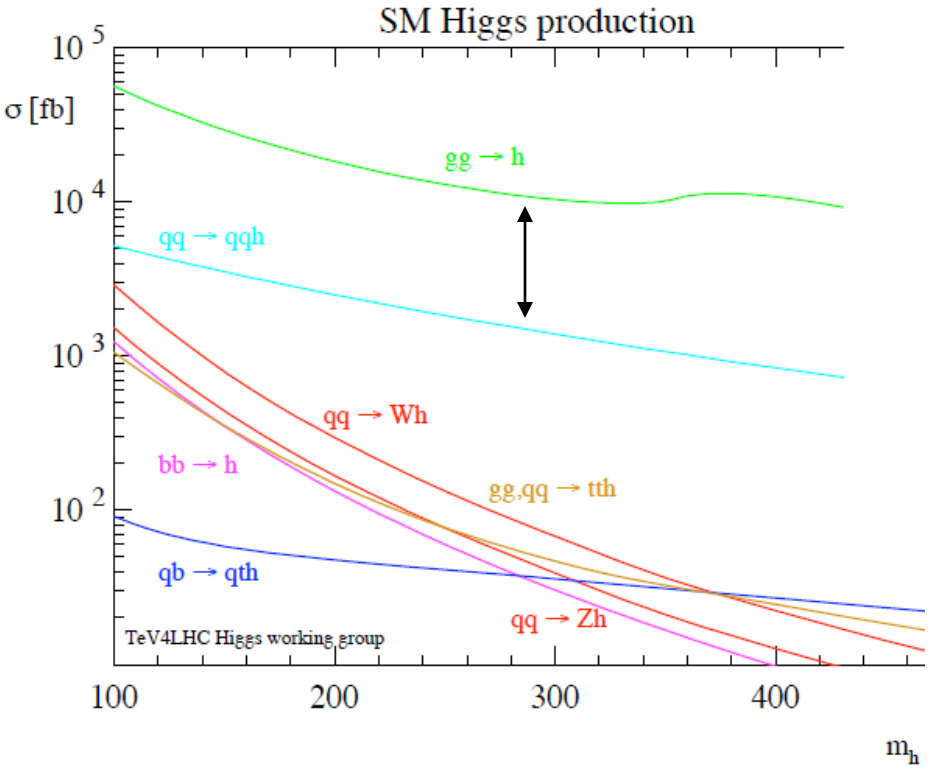
Status of MCs – general remarks

- Enormous progress recently: W+n jet calculations speeding up; pp → ttH, ttbb, VV, VVV....., GPUs, automatic NLO matching, automation of POWHEG method…
- We could imagine in one or two years from now: NLO+PS will be available for any process of interest, together with some key NNLO processes.
- Recommendations/discussion points:
  - **(If available) use MC@NLO/POWHEG for any analysis (w/NLO PDF for the hard scattering and LO for the showering/UE)**
  - **How should exps use a total cross section/resummed result?**
  - **How should experimentalists present their results on ttbar,Z, W, WW, ZZ, Higgs?**
  - **How should the uncertainties related to the MC/TH should be evaluated ?**

Fabio Maltoni

Interference

- VBF cross section is 10% of ggH. With central jet veto's and consider p_T shapes it can go up to ~20%.
- So VBF is actually a more important effect in ggH than any QCD/EW correction....
- How should experimentalists use a total cross section/resummed result?



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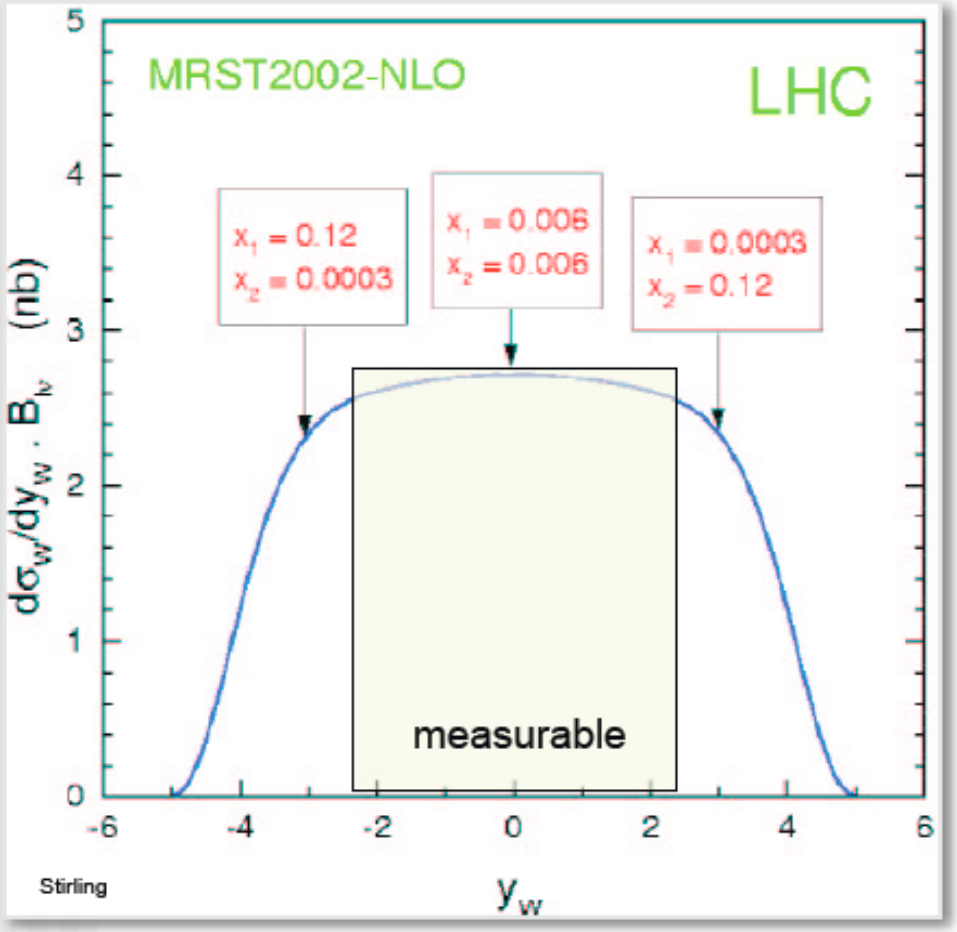
How to present measured xsec?

- Example: W or Z production



- Again, is a convolution of the acceptances for the leptons
- **Do we really want to correct for acceptance?**
- **Pros:**
  - The cross section measurement can be directly compared to other (corrected) measurements, from other exps
  - The measurement can be compared to theory predictions which cannot be obtained for arbitrary acceptance
- **Cons:**
  - The measurement becomes model dependent
  - we introduce a systematic error, eg. because of uncertain extrapolation to full acceptance

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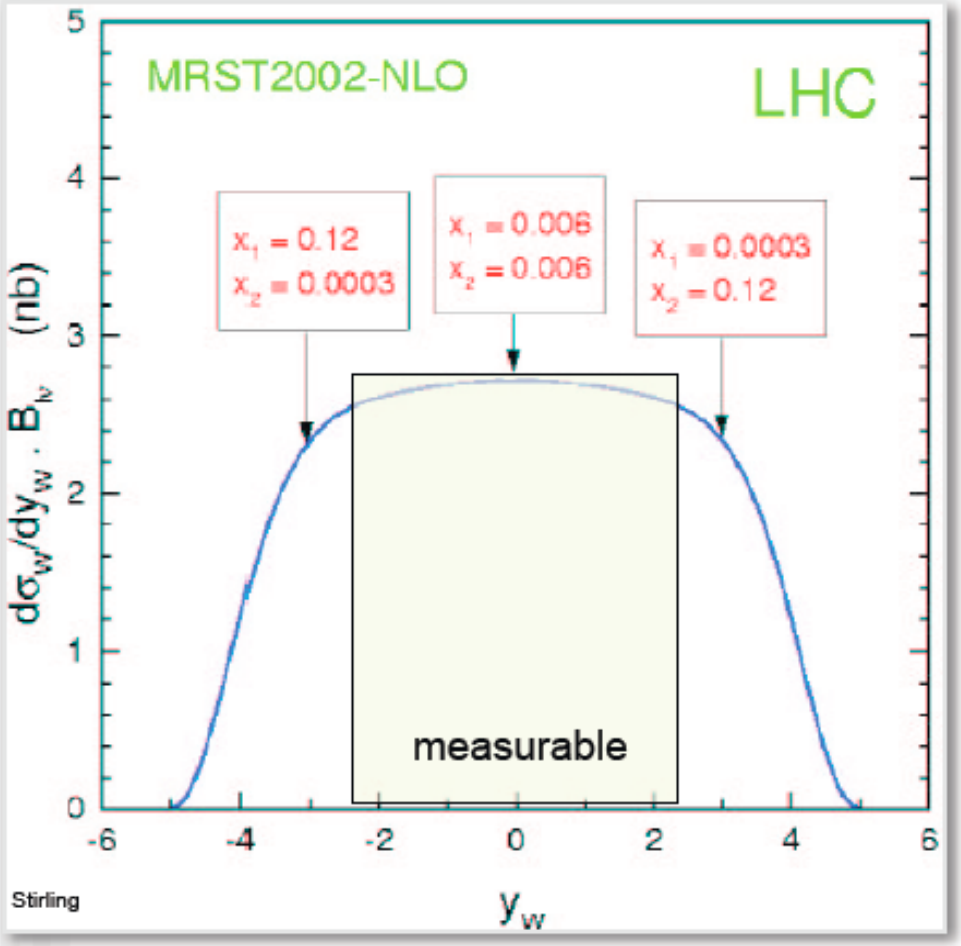
Guenther Dissertori

How to compare to calculations?

- Example: W or Z production



if we want **precise measurement** of Luminosity or some parameter in hard-interaction cross section, it is essential to have HO calc.

restricted to measurable acceptance

⇒ avoid **extrapolation errors**

eg. from extrapolation to large y_W where uncertainties from pdfs are large!

... fortunately, nowadays more and more fully differential calculations are available.... thus it becomes possible to calculate "EXACTLY" what is measured....

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Conclusions

- **Wide range of discussions**
  - Data for MC tuning
  - How to present data that is best useful for MC comparisons
  - New developments in perturbative QCD, manybody processes, generator codes, parton showers
  - How to use PDFs in MCs
  - How to present theoretical results to be best useful for experiments
  - How to generate/share generated event data (which format?)
  - What to measure to be more theory-independent and more background-independent
  - Wish lists for processes to be calculated
  - Jet algorithms, UE subtraction, photon isolation
  - Model building
  - Tuning to UE and MB, fragmentation, diffraction, limits of MC

VERY IMPORTANT TO KEEP UP DISCUSSIONS BETWEEN EXPERIMENTAL AND THEORY/MC COMMUNITIES!
A LOT TO LEARN FROM EACH OTHER.
This workshop was an excellent example.