Colour Reconnection and Weak Showers

Jesper Roy Christiansen

Lund University

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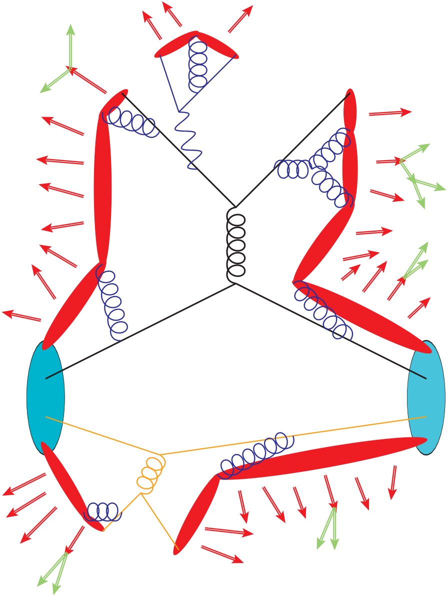
Science Coffee, Lund



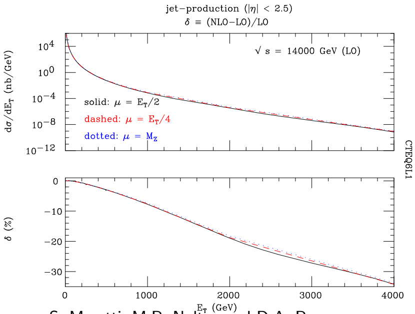
Weak showers

Motivation

- Effect of weak emissions in high $p_\perp$-jets.
- Possible to give a better description of the W/Z+jets production than the normal PS?
- Needed step to be able to recluster all PS histories in the merging/matching approach.

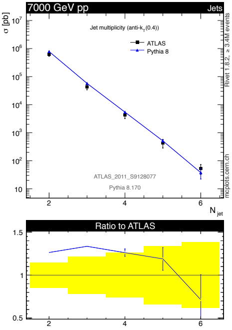
Motivation (W/Z in high $p_\perp - jets$)

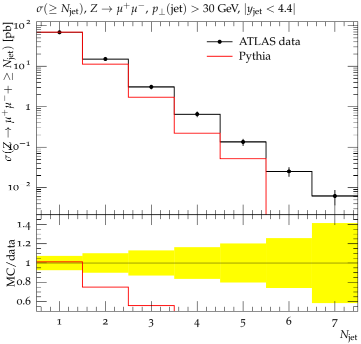
- Weak correction has a log enhancement of the form $\alpha_W \ln^2 \frac{\hat{s}}{M_W^2}$.
- Study the jet structure of jets with a weak boson inside it.



S. Moretti, M.R. Nolten and D.A. Ross, Nucl. Phys. B759 (2006) 50

Motivation for including weak shower (W/Z+jets)





Why does the PS do a relative good job describing QCD jets, but not W/Z+jets?

Implementation

- The implementation relies on ME corrections for ALL emissions.
- For FSR use the (massless) PS emission rate as overestimate:

$$\frac{dp_{\perp evol}^2}{p_{\perp evol}^2}\frac{N dz}{1-z} \qquad \text{with } N = 8$$

- For ISR use a modified shower emission rate to ensure it is an overestimate for the s-channel ME.

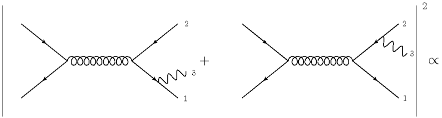
$$\frac{dp_{\perp evol}^2}{p_{\perp evol}^2}\frac{(1+(1+r^2)^2)dz}{1-z(1+r^2)} \qquad \text{with } r = \frac{m_W}{m_{dip}}$$

- Uses Z MEs even for W-radiation (except for coupling strength)
- Full CKM matrix for W-radiation.
- The mass of the W/Z-bosons are picked according to a Breit-Wigner distribution at each trial emission.
- The decay of the W/Z-boson is after full shower and matched to ME (e.g. $G \to u\bar{u}e^+e^-$) to get better angular distributions.

Implementation (s-channel)

- All 2-to-2 processes with a $q\bar{q}$-pair as outgoing particles uses the s-channel correction.
- The $g \to q\bar{q}$, $\gamma \to q\bar{q}$, $Z \to q\bar{q}$ and $W \to q\bar{q}'$ also uses the s-channel correction.
- Normal split of ME into ISR and FSR (i.e. no interferences included).

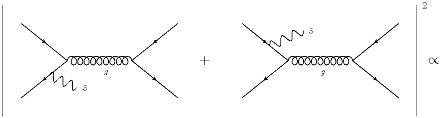
Final State Radiation



$$\frac{2r_3^4 + 2r_3^2(x_1 + x_2) + x_1^2 + x_2^2}{(1 - x_1)(1 - x_2)} - \frac{r_3^2}{(1 - x_1)^2} - \frac{r_3^2}{(1 - x_1)^2}$$

$$x_1 = \frac{2E_1}{E_{cm}}, \quad x_2 = \frac{2E_2}{E_{cm}}, \quad r_3 = \frac{m_3}{E_{cm}}$$

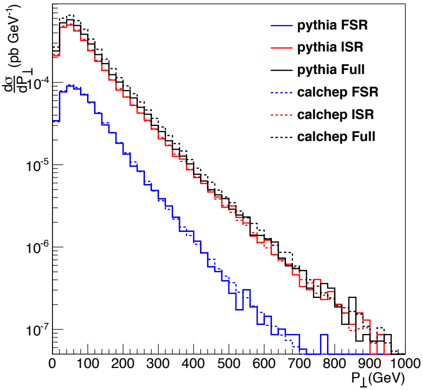
Initial State Radiation



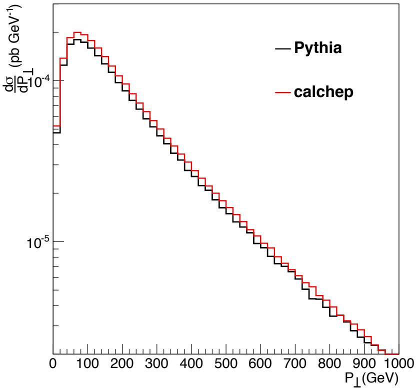
$$\frac{u^2 + t^2 + 2s(m_G^2 + m_3^2)}{ut} - \frac{m_G^2 m_3^2}{t^2} - \frac{m_G^2 m_3^2}{u^2}$$

Validation

s-channel:

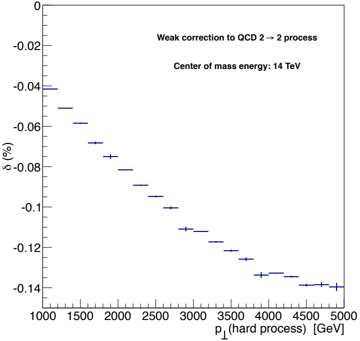


t-channel:



Di-jet Results

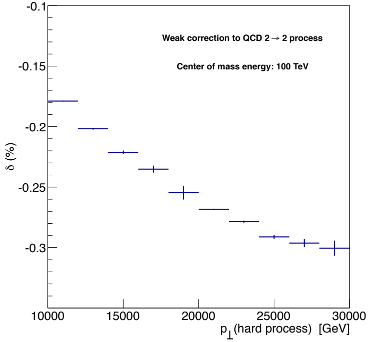
- Assume perfect detector and discard all events with W/Z boson.
- Effect is only of the order of 14 % even for very high $p_\perp$ events.
- Only includes $O(\alpha_W)$ corrections to $O(\alpha_s^2)$ 2-to-2 process.
- Misses $O(\alpha_s)$ corrections to $O(\alpha_s \alpha_W)$.



Di-jet Results (100 TeV)

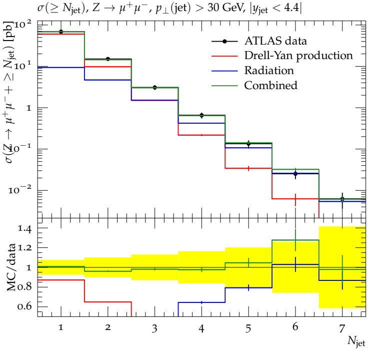
At what energies does the effect become important?

- To study the effect at even higher center of mass energies, we can consider a 100 TeV pp collider.



Z/W + jets results

- The Pythia distributions are normalized such that first bin fit the data.
- The shower starting scale is $\hat{s}$ for Drell-Yan and $p_\perp$ for QCD $2 \to 2$.



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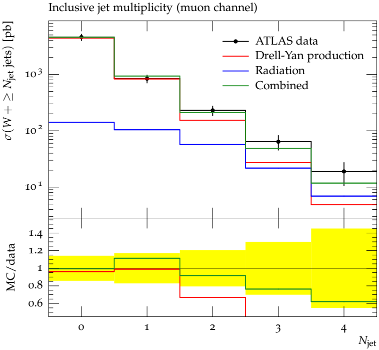
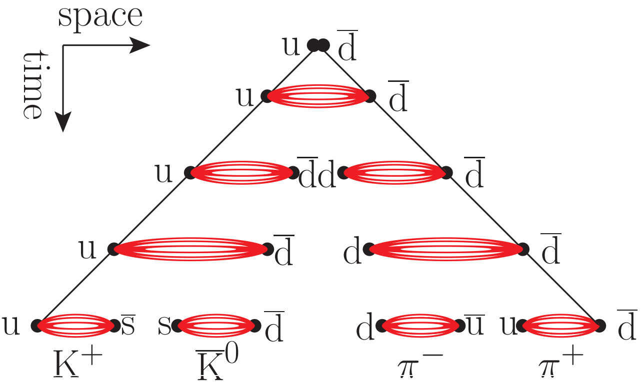


Conclusion

- I have described the implementation of a weak shower within Pythia.
- I have shown that the effect on exclusive di-jet production is in the region of $4 - 14\%$ at 14 TeV.
- I presented a first study of jet substructure with weak radiation inside the jet, but the effect is minimal.
- I have shown that it is possible to describe inclusive $Z/W +$ jets data only using a PS approach.

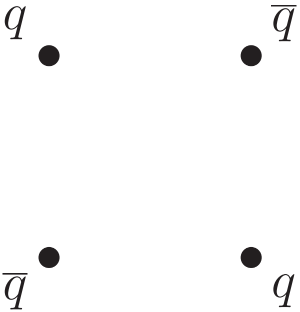
Colour Reconnection

Hadronization



Multiple strings

- What happens for multiple strings?
  - QCD quadropole? We have no idea how to hadronize this
  - Instead use several dipoles!
  - Multiple possible pairings $\Rightarrow$ Colour reconnection!



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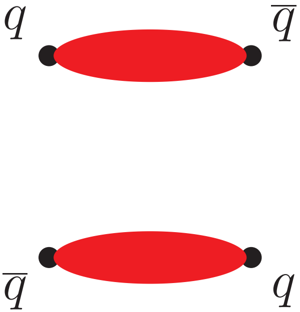

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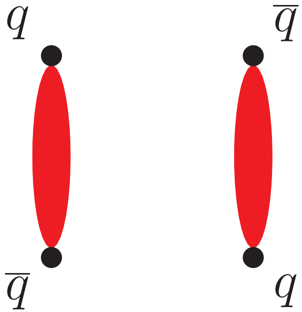
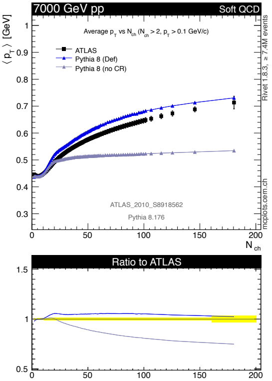
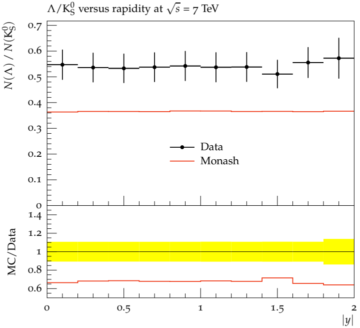


Motivation

Why study CR at pp colliders?



Why study CR right now?

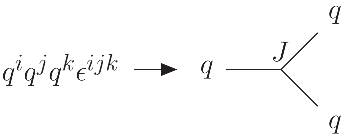


The new CR model

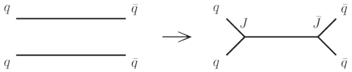
The new CR model reshuffles the colours just prior to hadronization based on three main principles:

- Use the SU(3) colour rules to determine if two strings are colour compatible
- Use a simplistic space-time picture to tell if the two strings coexist
- Minimize λ string-length measure to find which colour configurations Nature prefers

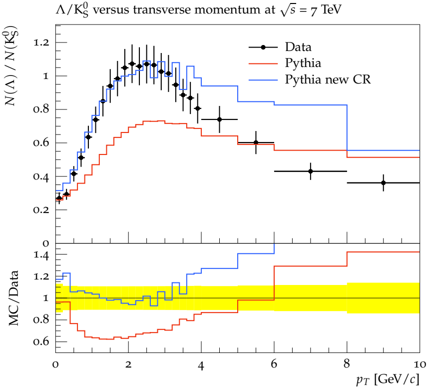
- Colour epsilon tensor corresponds to a junction structure

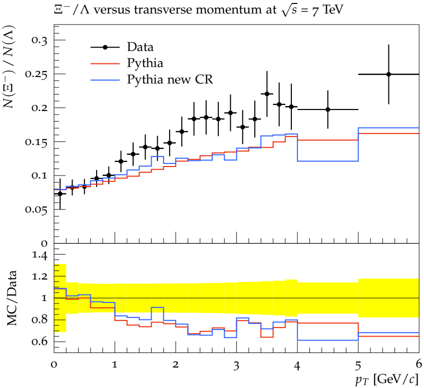


- New type of reconnection



Tests - Λ/K_s and Ξ/Λ

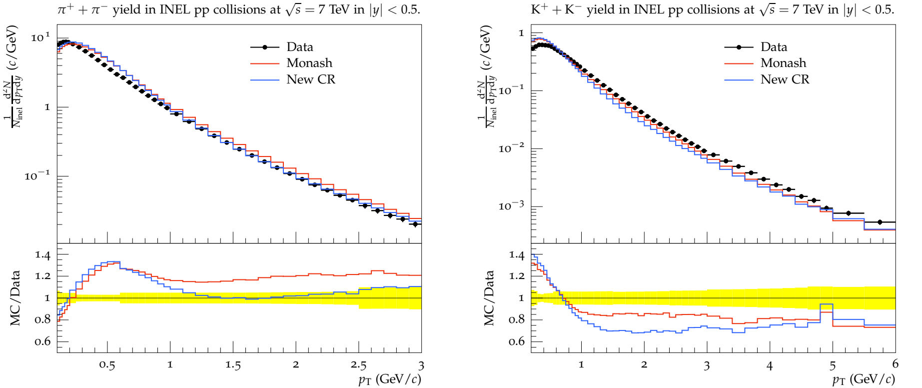




- Λ/K_S is better described by the model (overall yield is tuned)
- (No rate change in e^+e^-)
- Ξ/Λ is the same as old model - no strangeness enhancement

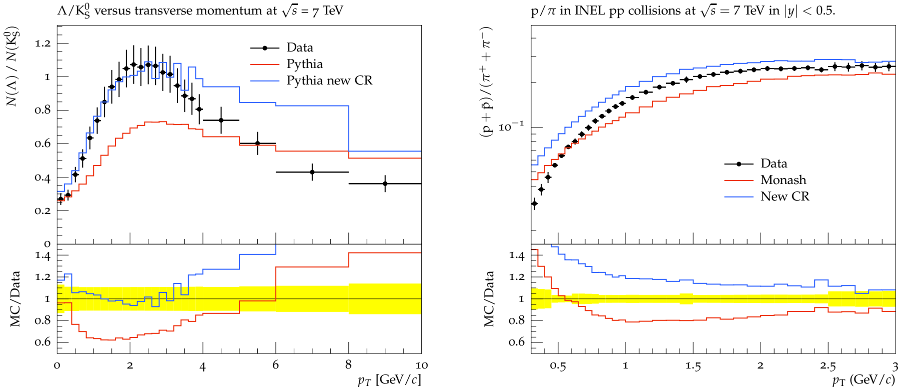
Tests - Individual $p_\perp$ spectra

- Individual $p_\perp$ spectra not well understood.



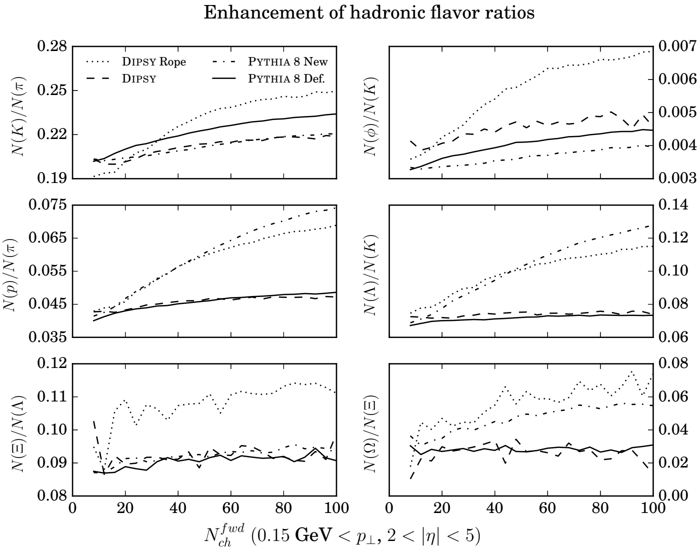
Tests - p/π enhancement needed?

- New model predicts enhancement of protons. Experimentally needed?



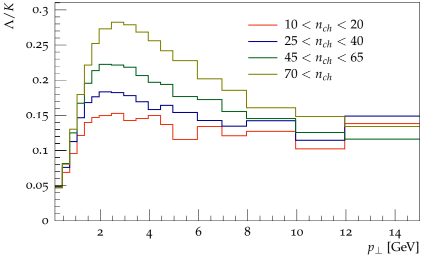
- No definite answer yet.

Multiplicity dependent particle ratios



CR and Flow-like effects

- Flow-like effects observed in *pp* is potentially connected with CR
- Repeat typical HI observable: Λ/K as function of $p_\perp$ separated into different multiplicity intervals (or centrality)
- Qualitative similar effect seen in the model as in HI collisions



CR in $e^+e^- \to W^+W^-$

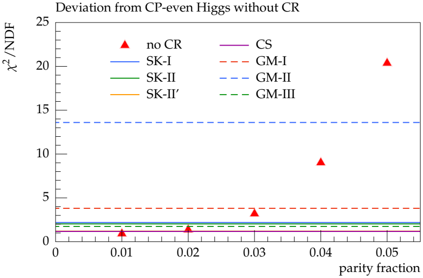
- Clean environment to test CR effects
- CR established at 2.8 σ
- Turn table around and use precision studies to constrain CR (e.g. W mass measurement, see table)
- Dedicated angular studies in fully hadronic WW
- Multiplicity comparisons between semi-leptonic and fully hadronic WW

Model	$\langle \delta \overline{m}_{\mathrm{W}} \rangle$ (MeV)		
	170 GeV	240 GeV	350 GeV
SK-I	+18	+95	+72
SK-II	-14	+29	+18
SK-II'	-6	+25	+16
GM-I	-41	-74	-50
GM-II	+49	+400	+369
GM-III	+2	+104	+60
CS	+7	+9	+4

Table : Systematic W mass shifts at three different center-of-mass energies.

CR in $H \to W^+W^-$

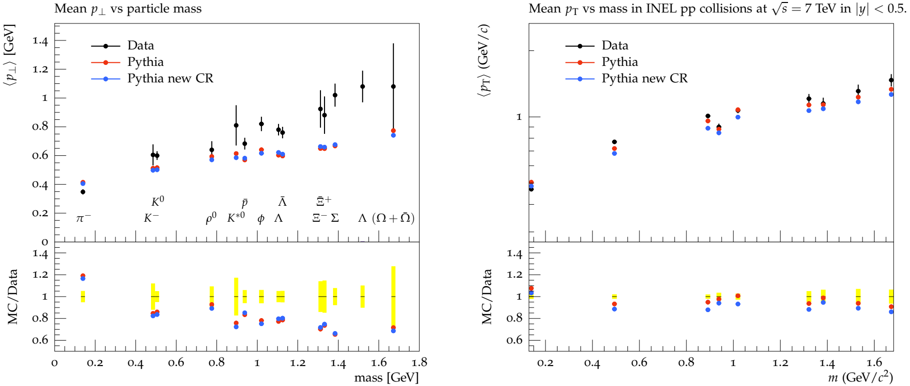
- Need to include CR as an uncertainty
- Example: Higgs Parity measurement in $\mathrm{WW} \to \mathrm{q\bar{q}q\bar{q}}$
  - Select events with four jets
  - Compare interjet angles using a simple χ^2 test
  - Compare between different CR models and different amount of CP-oddness in the Higgs
  - The analysis contains room for improvements



Conclusion

- I presented a new CR model able to describe the Λ/K_s ratio
- Identified particle ratios as a function of multiplicity is an excellent probe to test CR models
- Similarity between CR and flow-like effects in pp was presented, more studies still needed
- CR in $\mathrm{e^+e^-}$ collisions both provides constraints and needs to be included as an uncertainty
- All the CR models are publicly available in PYTHIA 8.210
- For more details see: arXiv:1507.02091, arXiv:1506.09085, arXiv:1505.01681

Tests - $p_\perp$ boosts



- Expected larger boosts for heavier particles - no effects for new model
- Discrepancy largest at low CM energies

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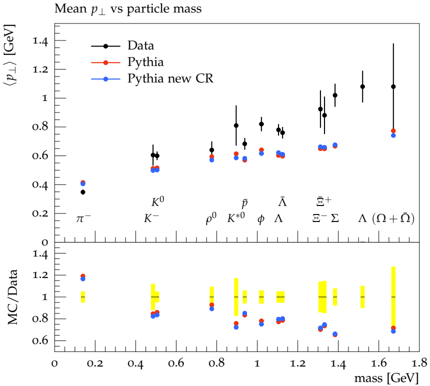

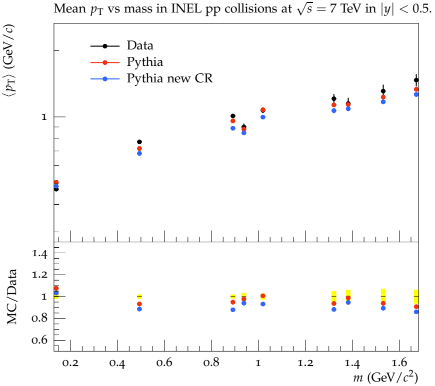

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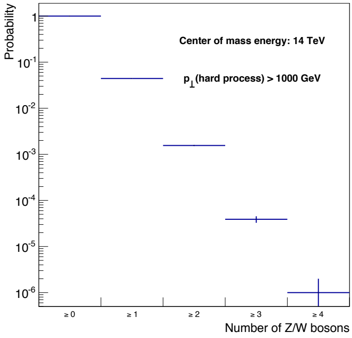
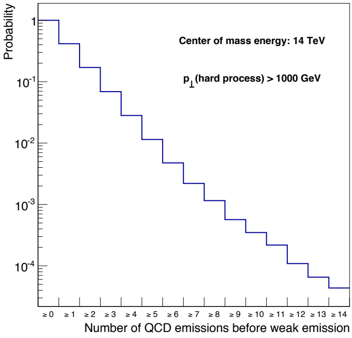
Results

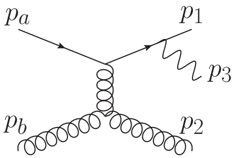
How important is resummation and competition between QCD and weak emissions?





Implementation (t-channel)

- s-channel ME for t-channel processes → does not work, instead need correct ME for t-channel.
- Three different cases: $ug \to ugZ$, $ud \to udZ$, $uu \to uuZ$.

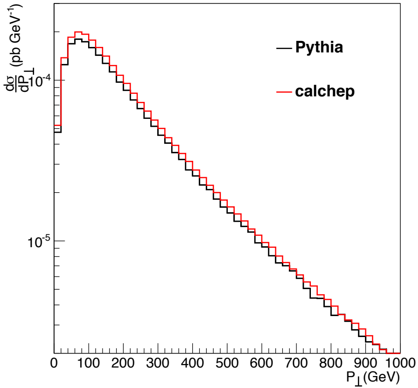


- Split between ISR and FSR done by multiplying with:

ISR: $\frac{\frac{1}{(p_a - p_3)^2}}{\frac{1}{(p_a - p_3)^2} + \frac{1}{(p_1 + p_3)^2}}$ and FSR: $\frac{\frac{1}{(p_1 + p_3)^2}}{\frac{1}{(p_a - p_3)^2} + \frac{1}{(p_1 + p_3)^2}}$

- For $ug \to ugZ$ it is trivial to identify the radiating quark.
- For $ud \to udZ$, the ME used was with the d-Z coupling set to zero.
- For $uu \to uuZ$, the same ME as for $ud \to udZ$ was used. Need to figure out which incoming u quark correspond to which outgoing u quark. This is done by comparing $\hat{t}$ and $\hat{u}$ in the 2-to-2 process.

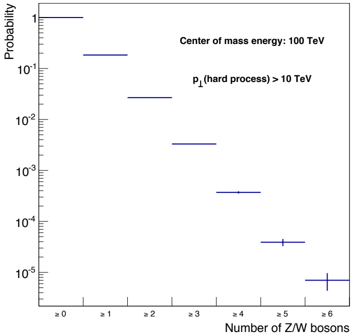
t-channel validation

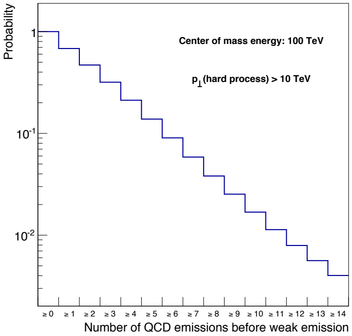


- Comparison of $uu \to uuZ$ between Pythia and CalcHep
- $p_\perp(u) > 1000$ GeV, $M(u, u) > 1500$ GeV and fixed scales at m_Z
- PS is not always an overestimate of the ME.

Results

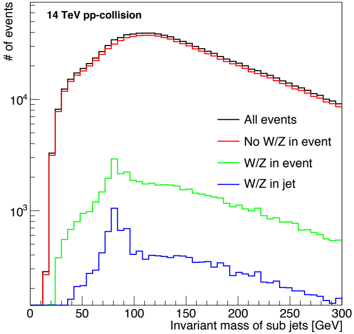
What is the effect on resummation and competition at higher energies?





Jet substructure

- Calculate invariant mass of sub jets inside jet with $R = 1$ and $p_\perp > 1\,\text{TeV}$.
- Sub jets found by using trimming and are required to have $p_\perp > 50\text{GeV}$ and $R_{trim} = 0.2$.



Jet substructure (II)

- Is it possible to see the effect of weak emissions inside the jet?
- Only statistical MC errors are shown.
- 1 million events $\sim 77 \text{ fb}^{-1}$