Two sides of the same coin

(i.e. random thoughts on resummation and parton showers)

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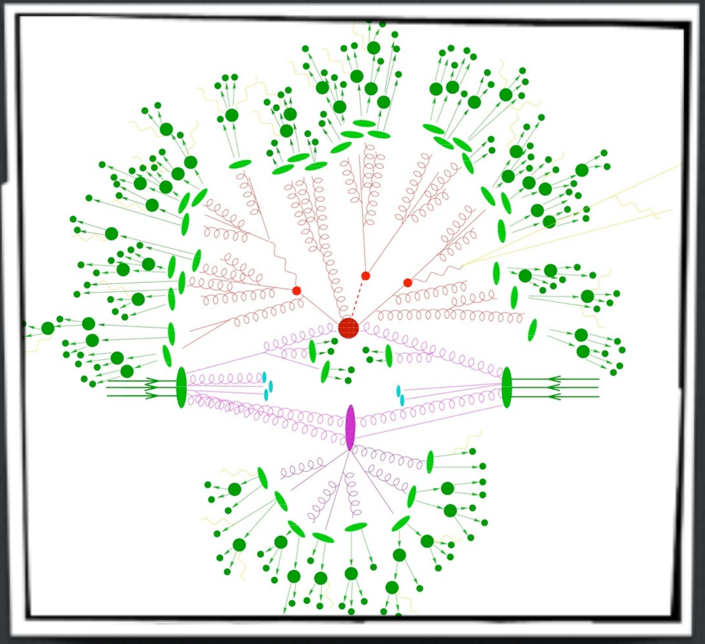
MC event generators vs analytic resummation

- powerful general-purpose tools
- provide fully differential events on which any observable can be measured
- interfaced with non-perturbative models to give a realistic description
- theoretical accuracy difficult to assess (often low)



$$\sigma_{res} = g_0 \exp[g_1(\alpha_s L)/\alpha_s + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots]$$

- feasible for a limited number of observables
- well defined and improvable accuracy
- state-of-the art (resummation + fixed order)
- can provide insights and understanding

Outline

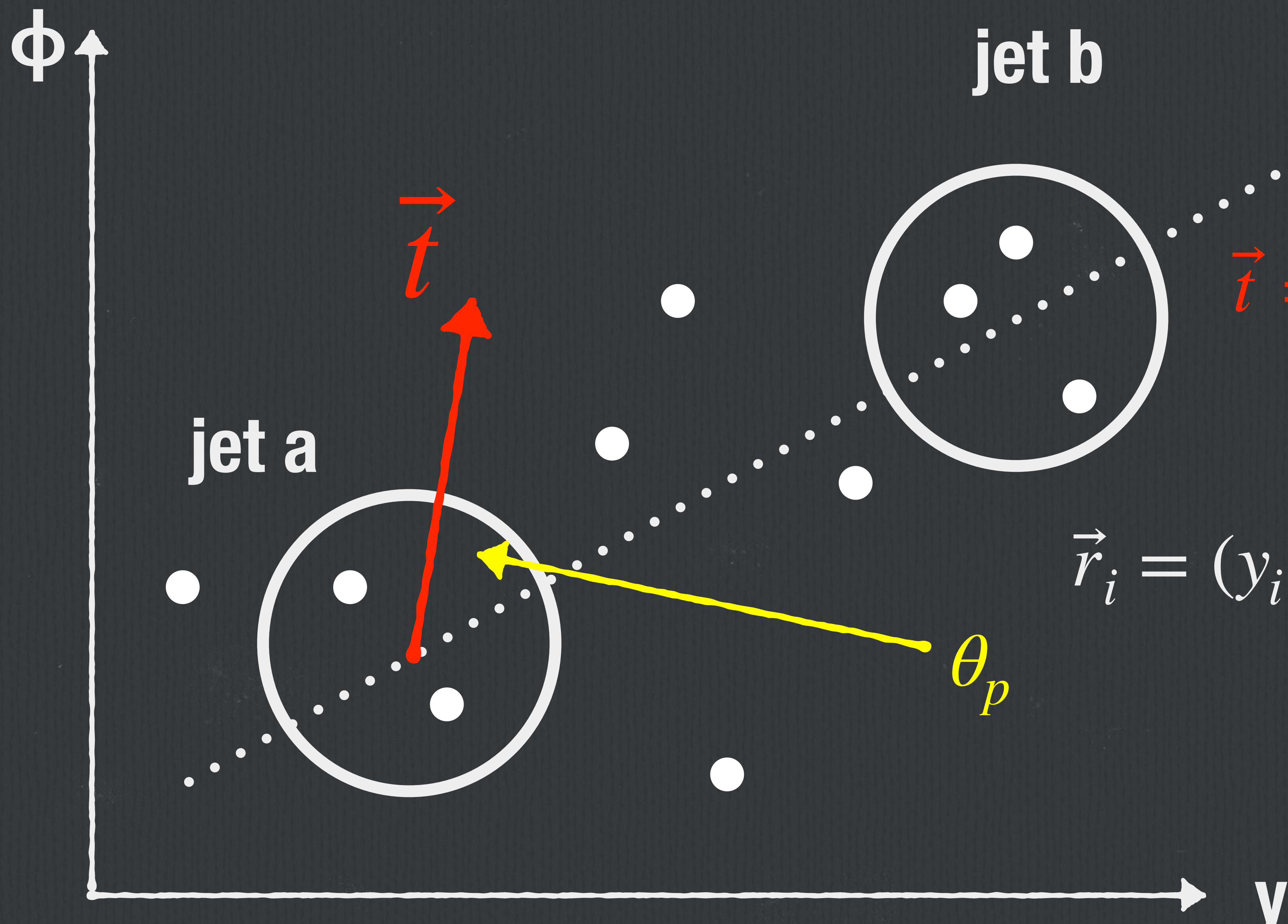
- What can analytic insights do for Monte Carlo event generators?
- What can Monte Carlo event generators do for analytic resummation?
- Conclusions

What analytics can do for MCs?

- Assessing the logarithmic accuracy of parton showers
- Improving the logarithmic accuracy of parton showers
- Assessing how parton shower algorithms deal with complex information, e.g. kinematics and colour

see Silvia's talk

Jet Pull



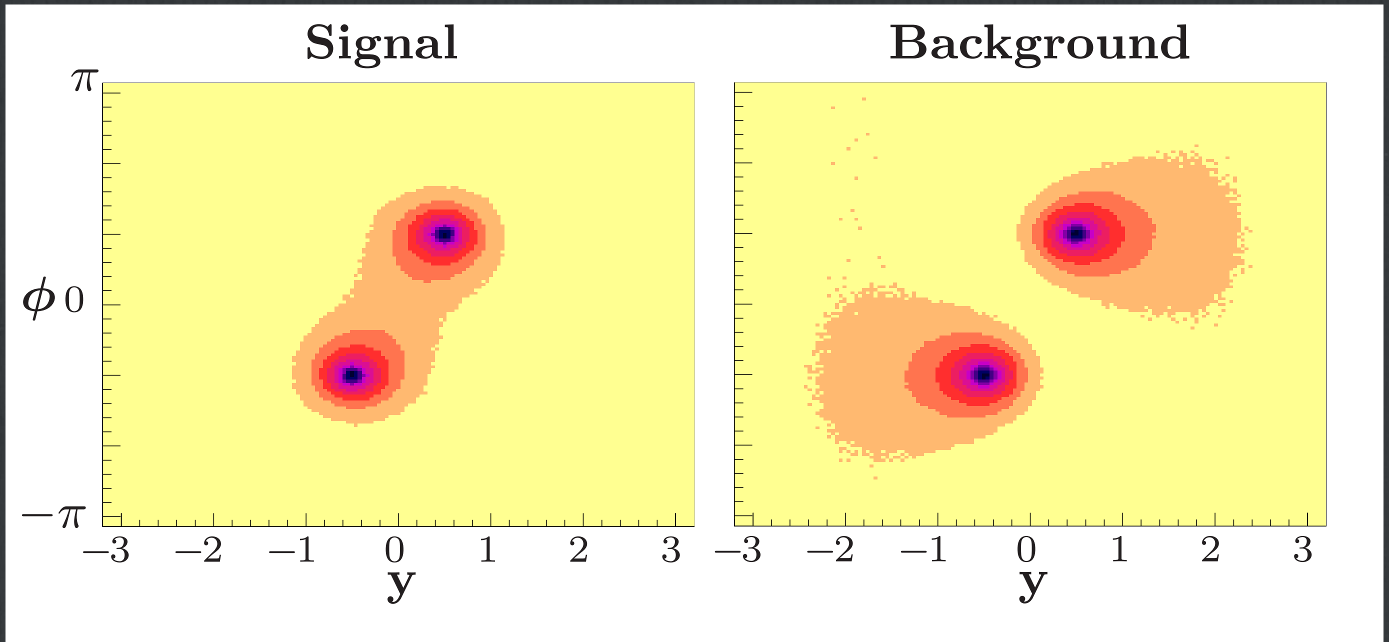
$$\vec{t} = \sum_{i \in jet\ a} \frac{p_{ti}}{p_t} |\vec{r}_i| \vec{r}_i$$

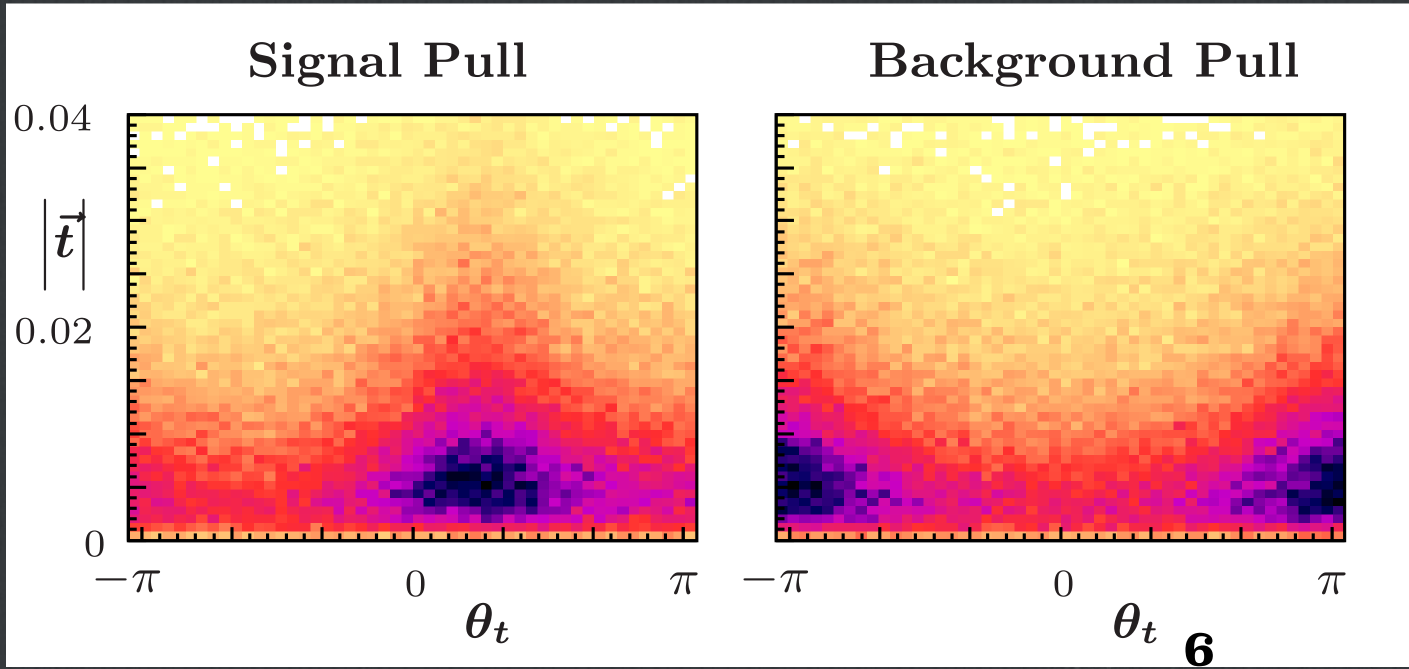
$$\vec{r}_i = (y_i - y_a, \phi_i - \phi_a)$$

Gallichio and Schwartz (2010)

H→bb vs g→bb

- consider radiation pattern of a colour singlet (signal) vs colour octet (background)
- simulation shows dominant colour-connections:
- between the two b's for the singlet
- between each b and the initial-state for the background

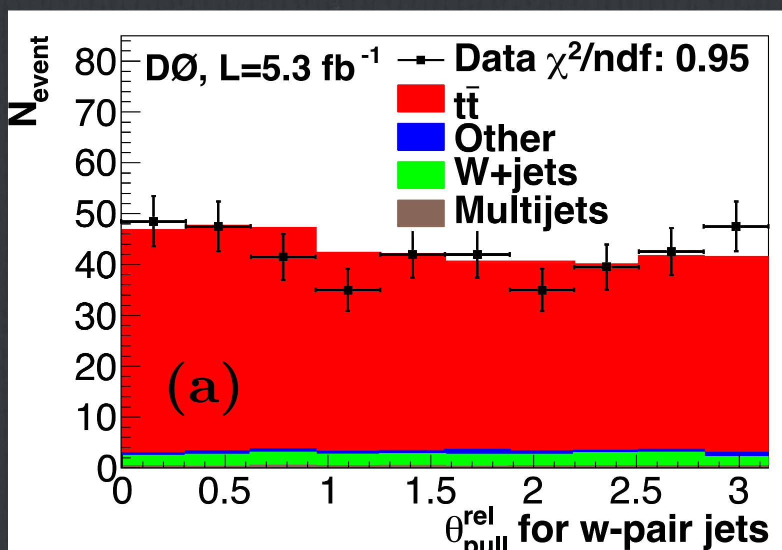




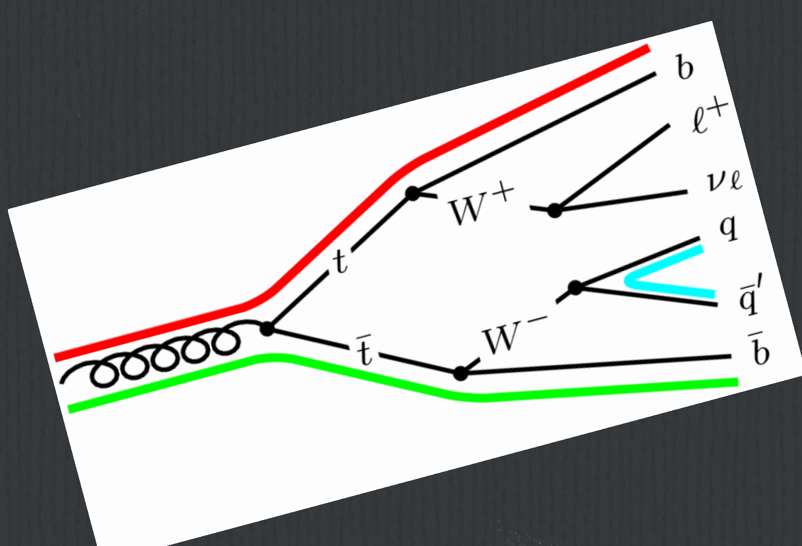
- pull angle shows much more sensitivity to colour flow than the pull magnitude

Gallichio and Schwartz (2010)

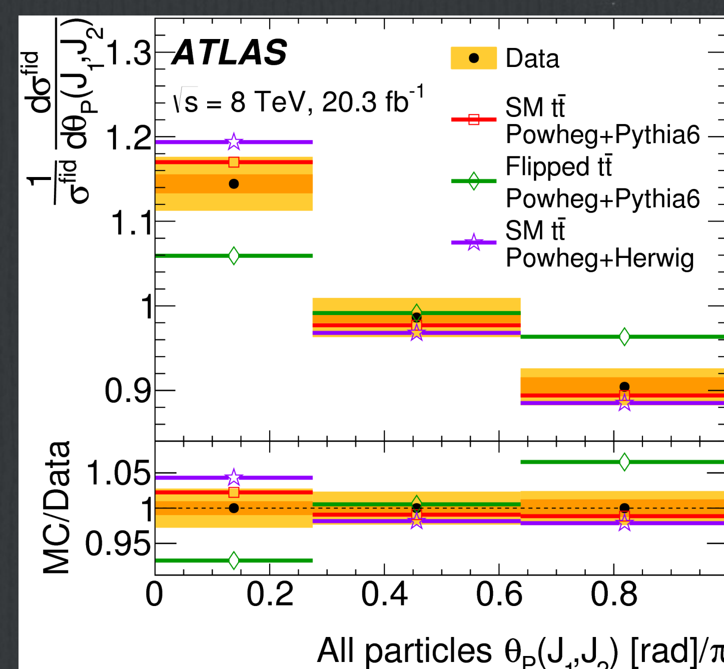
Experimental measurements



Phys.Rev. D83 (2011) 092002



- abundant production of top quarks offer nice lab for these studies
- pull angle can be measured on different types of colour connections



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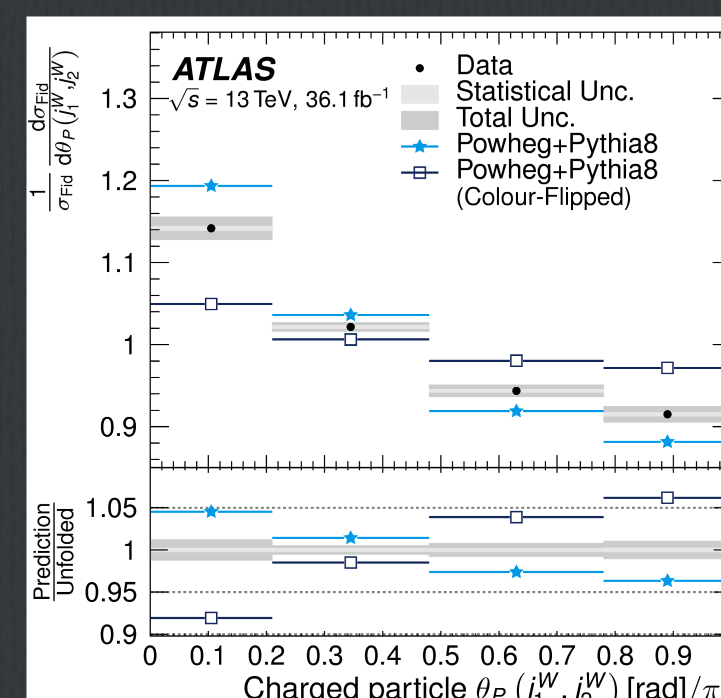
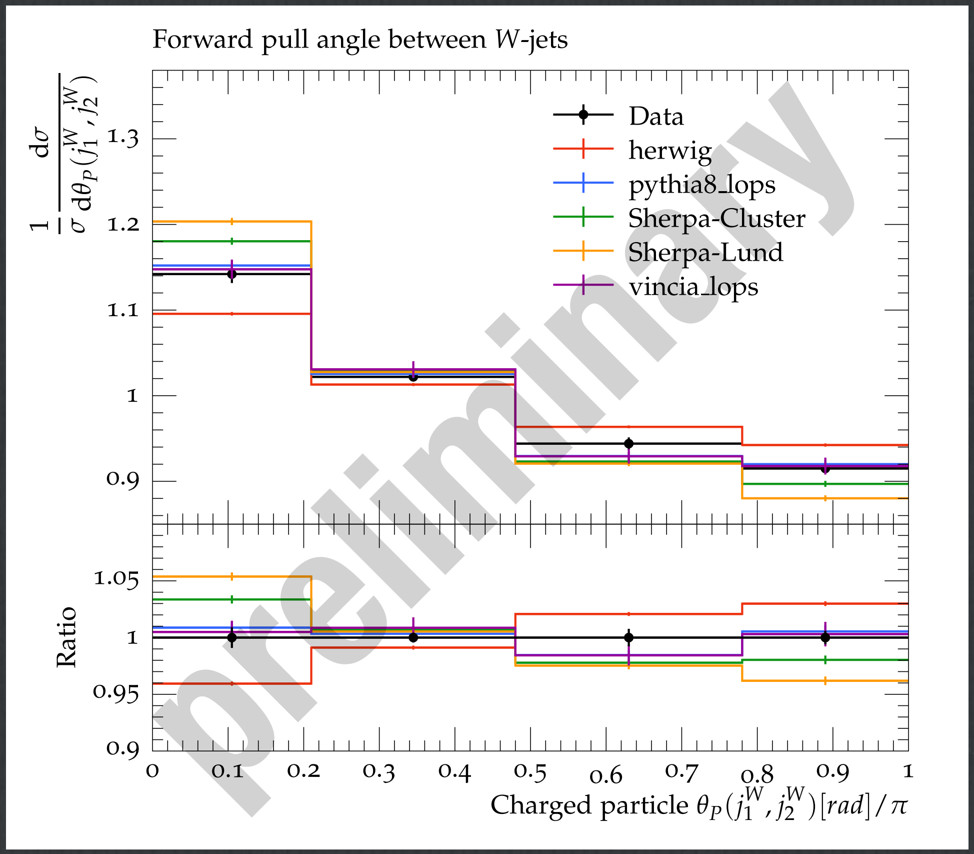


Eur. Phys. J. C 78 (2018)

Les Houches studies



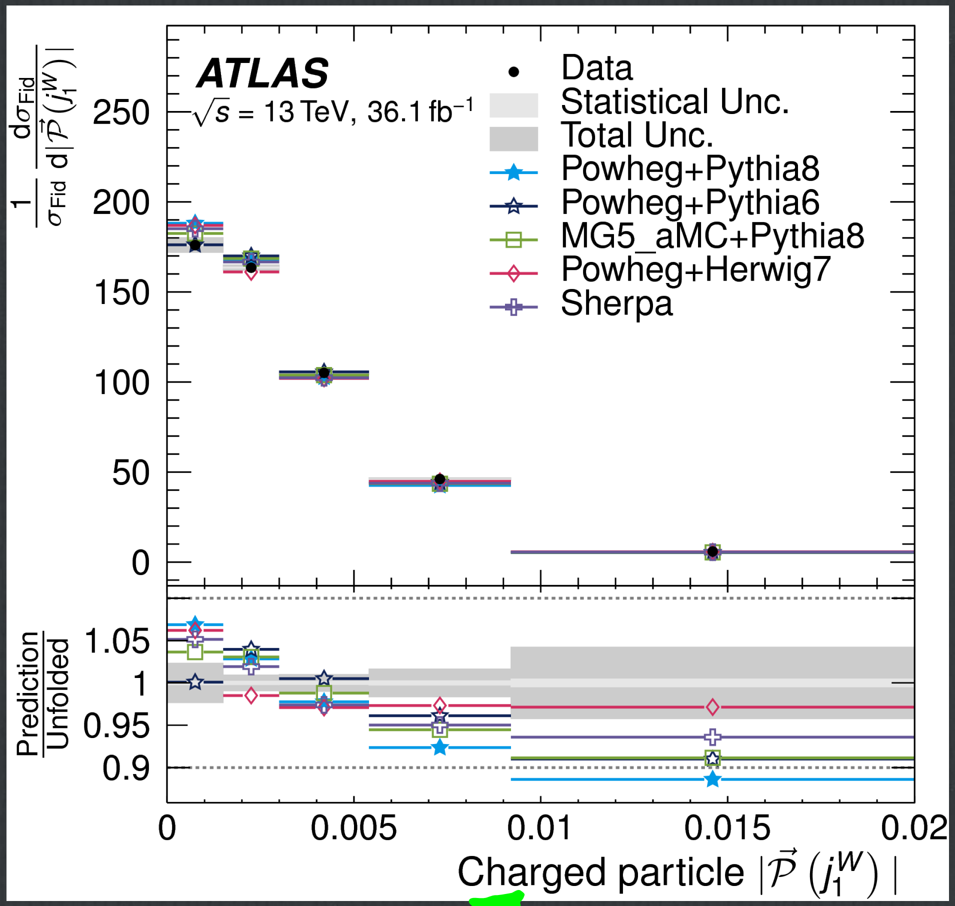
courtesy of Helen Brooks

- astonishing precision of 13 TeV data allows for stringent test of different MC tools
- on-going study started at LH 19 aimed at understanding this observable better
- intricate interplay of different ingredients:
    - spread in parton shower modelling is comparable (if not bigger) than spread due to non-perturbative contributions

- we hope to achieve a clearer picture for the proceedings!

Can we make firmer theory predictions?

- besides MC study we can try and understand jet pull with analytic calculations
- we aim at a description that matches together fixed-order and resummed prediction
- let's look at next-to-leading log (NLL)
- pull magnitude is IRC safe:
  - if two emissions p_1, p_2 become collinear, we are only sensitive to p_1+p_2
  - if emission p_1 becomes soft $p_{t1} \to 0$ and it does not contribute to the magnitude
- we can calculate this distribution in perturbation theory!



not quite IRC safe!

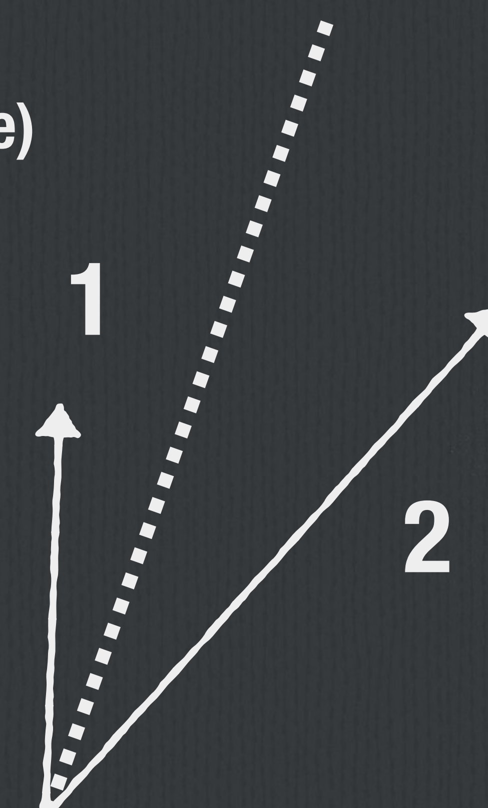
Resummation of the pull magnitude

- we consider the resummation of the magnitude of a 2-D vector:

$$t = |\vec{t}\,| = \left| \sum_{i \in jet\, a} \frac{p_{ti}}{p_t} |\vec{r}_i| \vec{r}_i \right|$$

- situation very similar to well-known Q_T-resummation (but in the final state)
- we we work in a conjugate Fourier space
- on the other hand, its scaling properties are the similar to the jet mass

$$t = |\vec{t}_1 + \vec{t}_2| \simeq |z(1-z)^2 - (1-z)z^2|\,\theta_{12}^2$$
$$= |z(1-z)(1-2z)|\,\theta_{12}^2$$



NLL resummation

- in the collinear limit, i.e. up to term of $O(R^2)$ the all-order behaviour is

$$\frac{1}{\sigma_0}\frac{d\sigma}{dt} = \int_0^\infty db\, b\, J_0(bt)\ \exp\left[L f_1(\lambda) + f_{2c}(\lambda)\right] S_{ng}(\lambda)$$

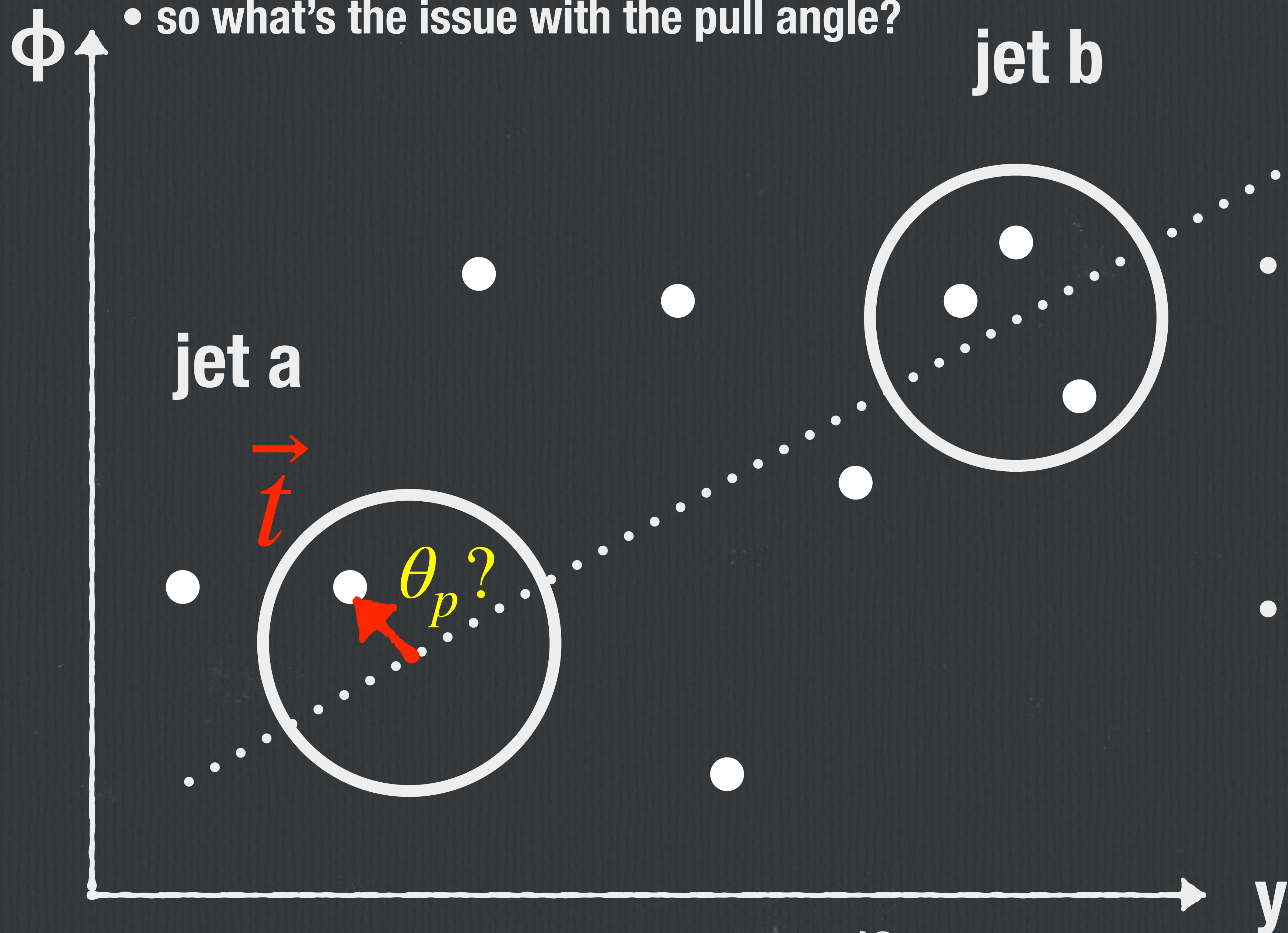
$$\lambda = \alpha_s \beta_0 \log\left(b\frac{e^{\gamma_E}}{2}\right)$$

- remarkably, the f_1 and f_{2c} have the same function have the same functional form as for the jet mass distribution

- S_{ng} accounts for non-global logarithms

Pull angle: IRC un-safety

- so what's the issue with the pull angle?



- if particle i is soft, its contribution to the magnitude vanishes but its pull angle is undefined

- equivalently: in order to define the pull angle we need two emissions

aside: Sudakov safety

- we know of other observables that suffers from similar problems (ratio of angularities, soft-drop momentum balance)
- we can make sense of these observables if we are able to resolve the singularities with the help of a (safe) companion variable
- we say that the IRC unsafe variable u is Sudakov safe if there exists an IRC safe observable s such that

$$p(u) = \int ds \, p(u \,|\, s) \, p(s)$$

- p(s) must be calculated to all-orders in order to (Sudakov) suppress the s=0 singularity

Larkoski, Thaler (2013)
Larkoski, SM, Thaler (2015)

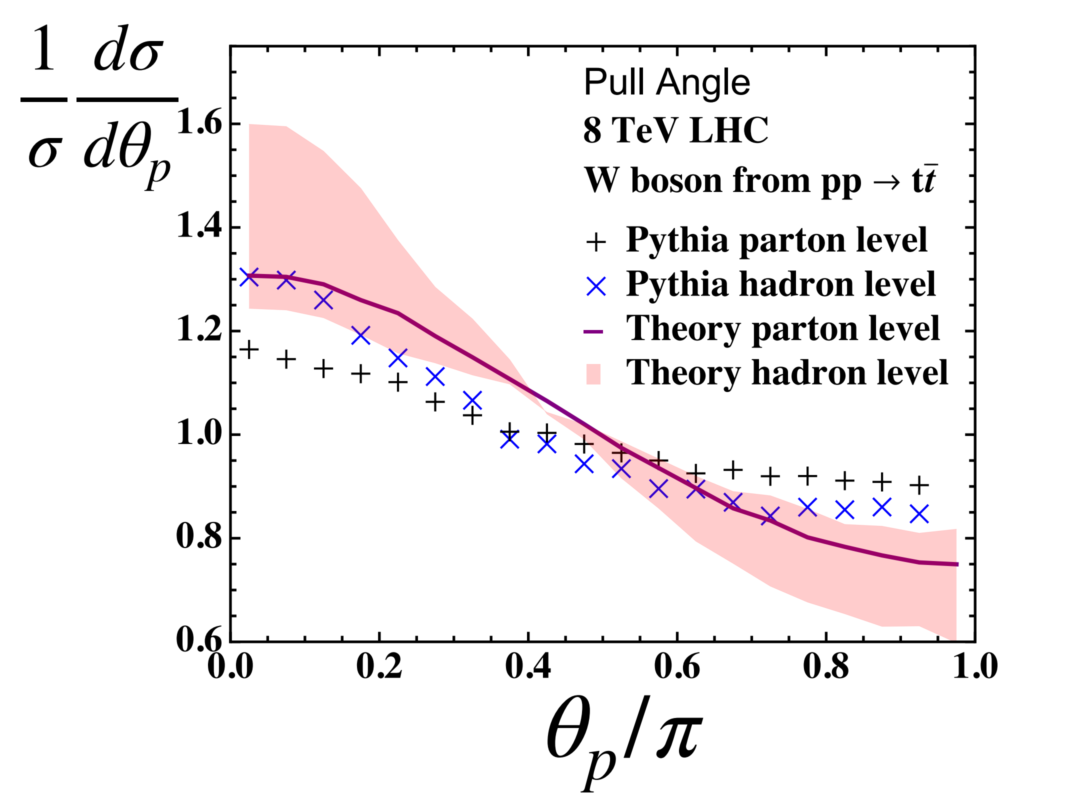
Perturbative calculation

- our natural candidate for the safe companion is the pull magnitude itself

$$\frac{1}{\sigma}\frac{d\sigma}{d\theta_p} = \int dt\, p(\theta_p\,|\,t)\, p^{res}(t)$$

computed at fixed-order

resummed at NLL in the collinear limit (but with no non-global logs a the moment)



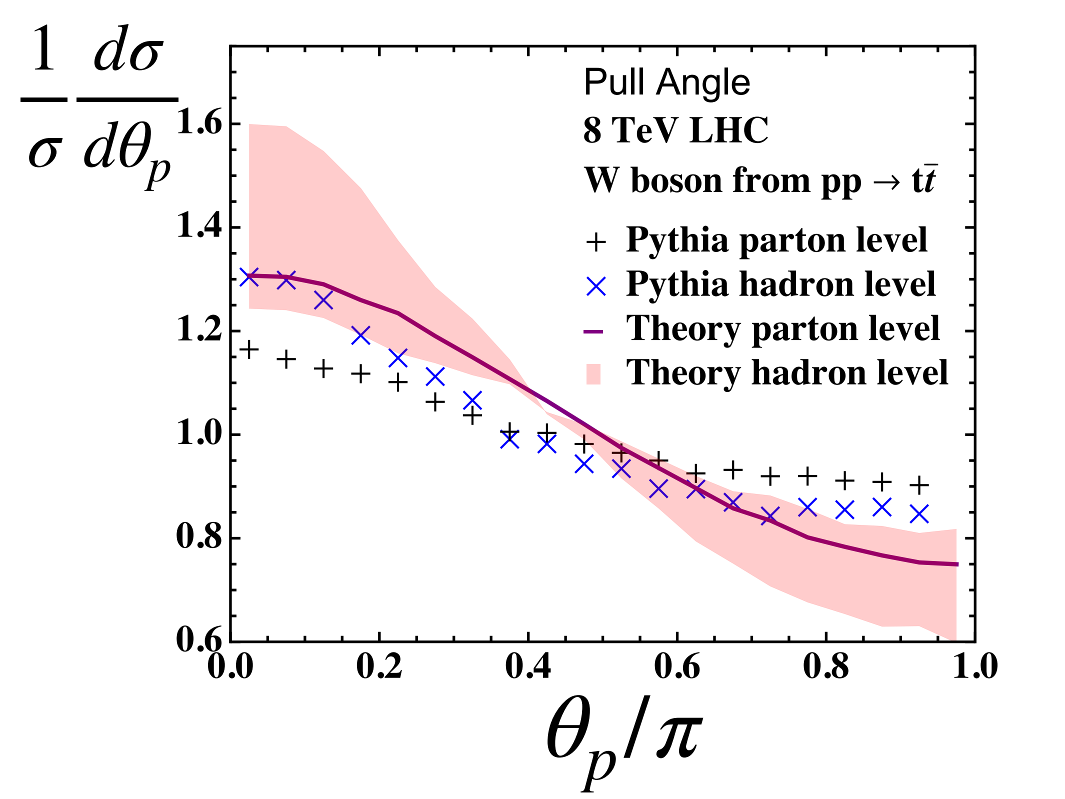
Non-perturbative effects

- for IRC safe observable we can make relatively strong statements about the scaling of non-perturbative corrections
- for Sudakov safe observable we do not have such luxury
- we make some rough estimate

$$p_{np}(t,\theta_p) \propto \tanh\left(\frac{1}{a\theta_p(2\pi-\theta_p)}\right)\delta\left(t-\frac{\Omega}{E_J}\right)$$

$$\Omega \simeq \Lambda_{QCD}\,, \quad 0 \leq a \leq 0.25$$

uniform to peaked in ϕ_p=0



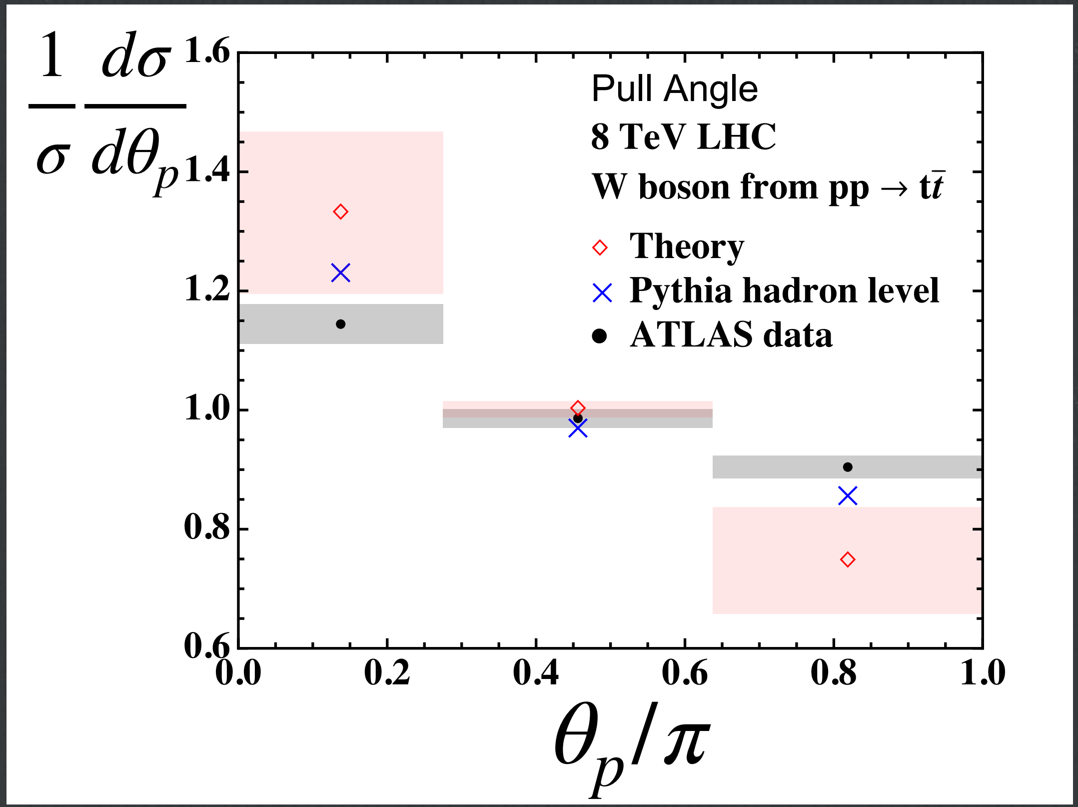
$$p_{tot} = p_{np} \overrightarrow{\otimes} p_{pert}$$

Comparison to the data

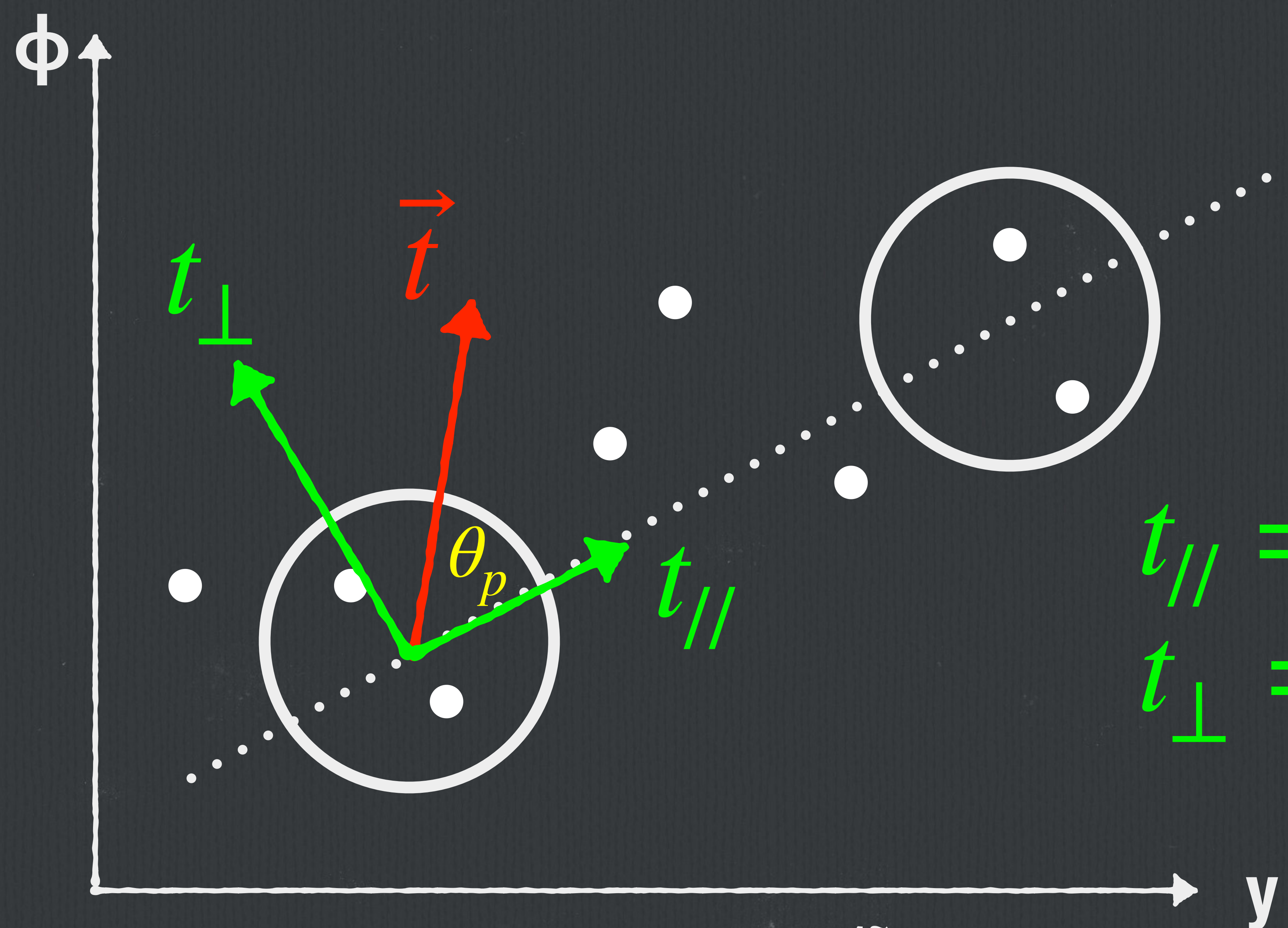
- we can now compare to the Run I measurement by the ATLAS collaboration
- our calculation is in fair agreement with the data (similar to the Monte Carlo prediction)
- however it suffers from large theory uncertainties

- perturbative uncertainties: Sudakov safe observables do not admit standard expansion in terms of Feynman diagrams: we have to combine fixed-order and resummed ingredients (and several questions remain open)

- non-pert. uncertainties: lack of IRC safety prevents us from clearly separating perturbative and non-perturbative regions



Safe use of jet pull



$$t_{//} = |\vec{t} \cdot \hat{n}_{//}|$$
$$t_\perp = |\vec{t} \cdot \hat{n}_\perp|$$

NLL resummation

- the new variables $t_{//}$ and $t_{\perp}$ are IRC safe: we can combine fixed-order and resummed prediction in the standard way

- their resummation is relatively straightforward

- it closely follows the formalism develop for analogous projections of Q_T i.e. a_T (and ϕ^*)

Banfi, Dasgupta and Duran Delgado (2010)

$$\frac{1}{\sigma_0}\frac{d\sigma}{dt_{||(\perp)}} = \frac{2}{\pi}\int_0^\infty db\,\cos(bt_{||(\perp)})\exp\left[Lf_1(\lambda)+f_2(\lambda)\right]S_{ng}(\lambda)$$

- real that resummed spectrum for the pull magnitude has a similar from

$$\frac{1}{\sigma_0}\frac{d\sigma}{dt} = \int_0^\infty db\, b\, J_0(bt)\, \exp\left[Lf_1(\lambda)+f_2(\lambda)\right]S_{ng}(\lambda)$$

Towards phenomenology

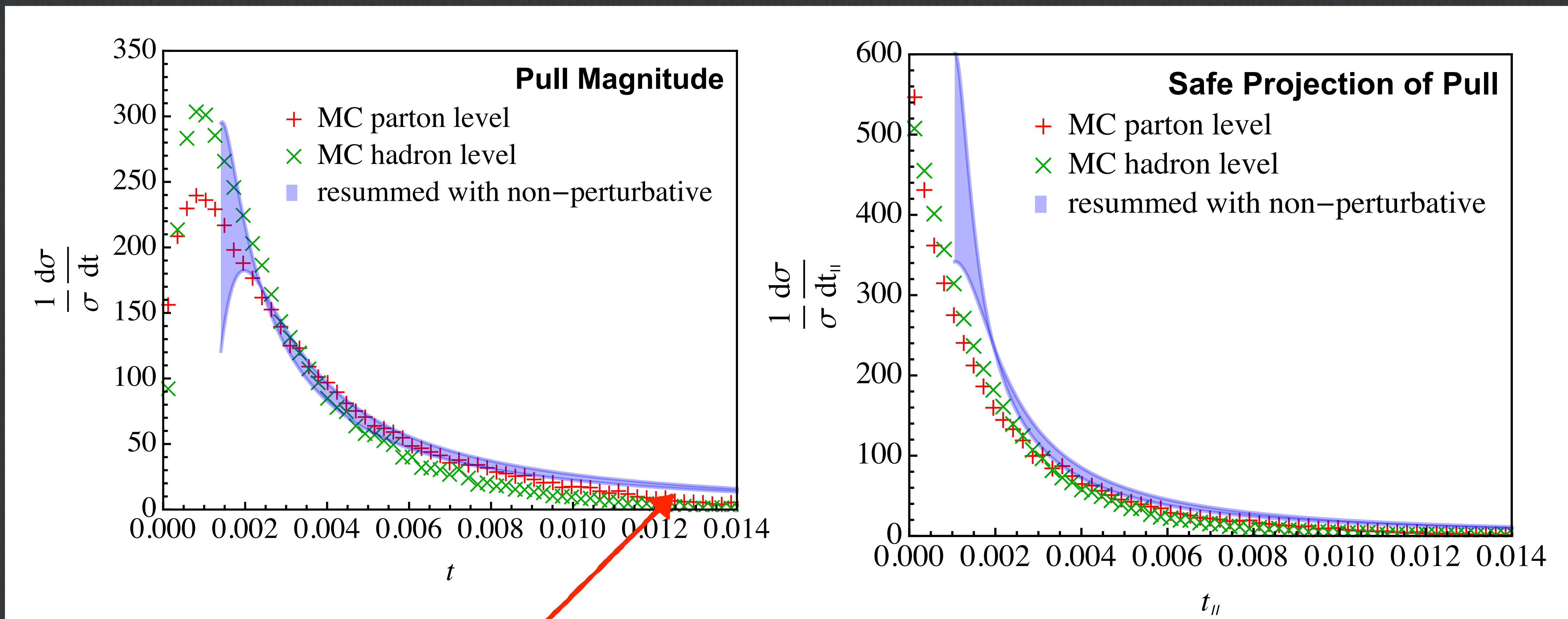
- in order achieve full NLL resummation we include
  - soft radiation at wide angle (through an expansion in powers of the jet radius)
  - non-global logarithms
- notice that soft radiation is crucial (this is what we want to probe) but it does depend on the jet environment
- we have to specify the process and the event selection, e.g.

$$pp \to H(\to b\bar{b}) + Z(\to l^+ l^-)$$

and measure the pull between the b (sub)jets

NLL results

- we find decent agreement between NLL and parton-shower results
- NP contributions are sizeable but they are parametrically power-corrections (the power of IRC safety!)

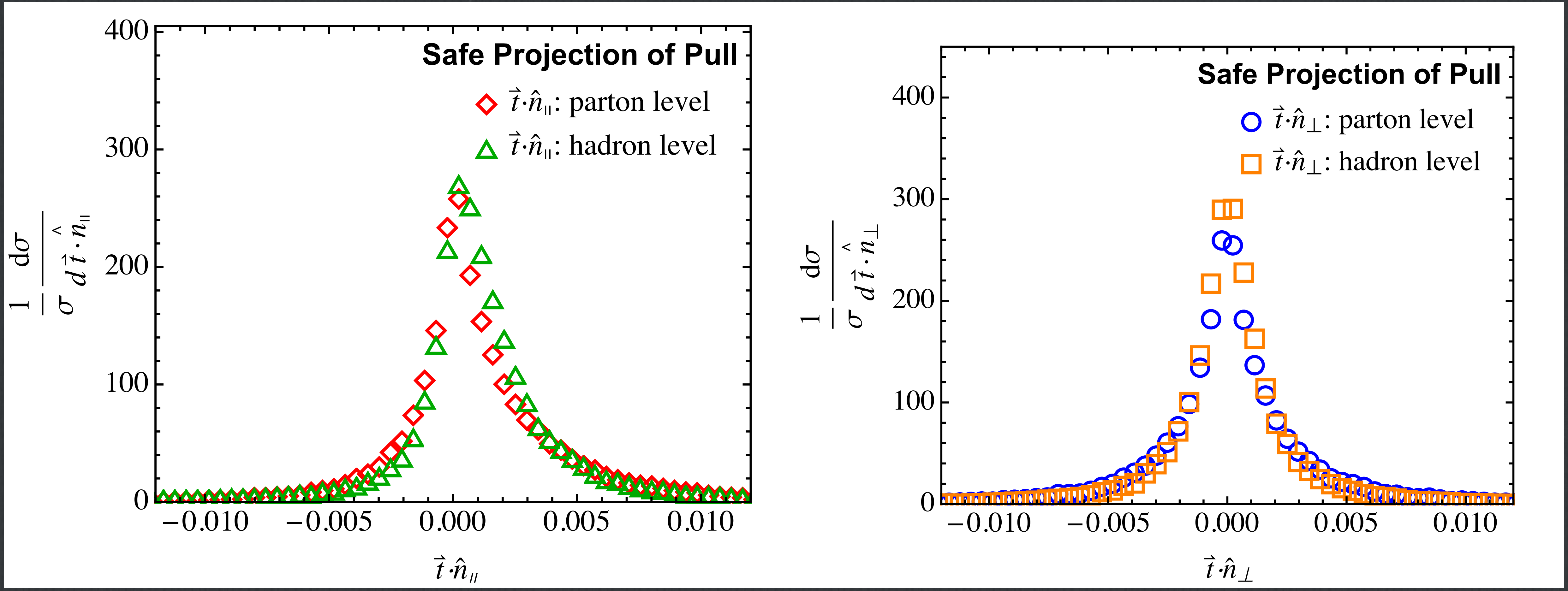


no matching yet

$$p_{tot} = p_{np} \overrightarrow{\otimes} p_{pert}$$

Asymmetric distributions

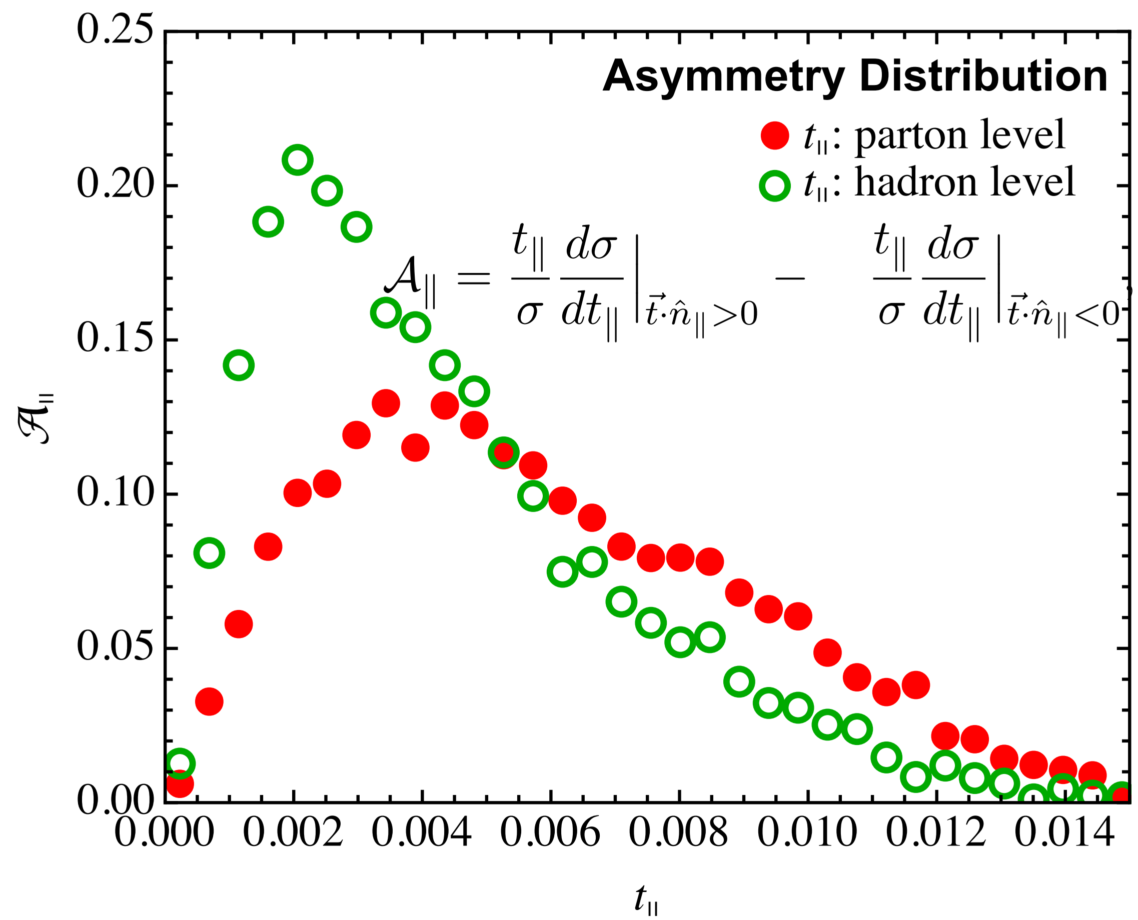
- we have defined projections to be positive-definite
- nice all-order properties but some important information is lost

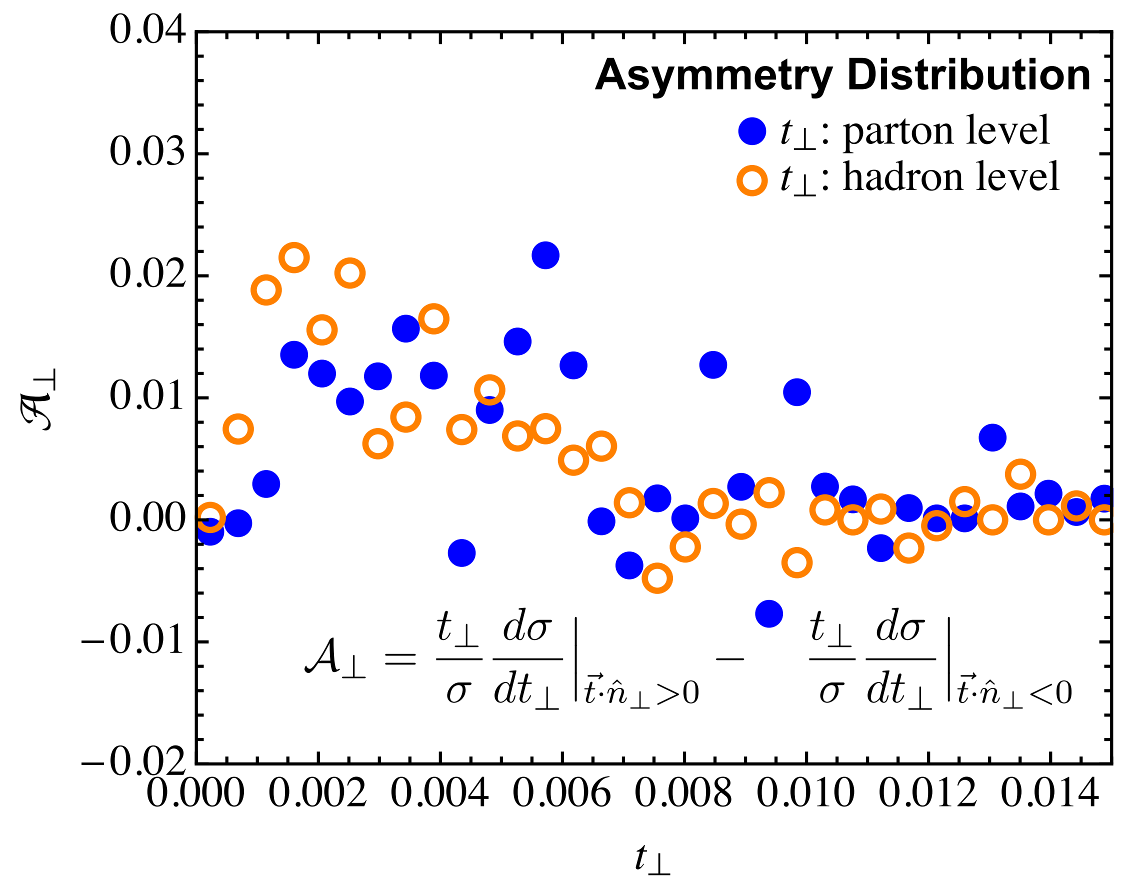


- radiation pattern is markedly asymmetric in the parallel direction

Asymmetries

- we define asymmetry distributions that expose these properties
- MC simulations are encouraging: it would be interesting to achieve resummation as well
- very sensitive to sub-leading colour effects

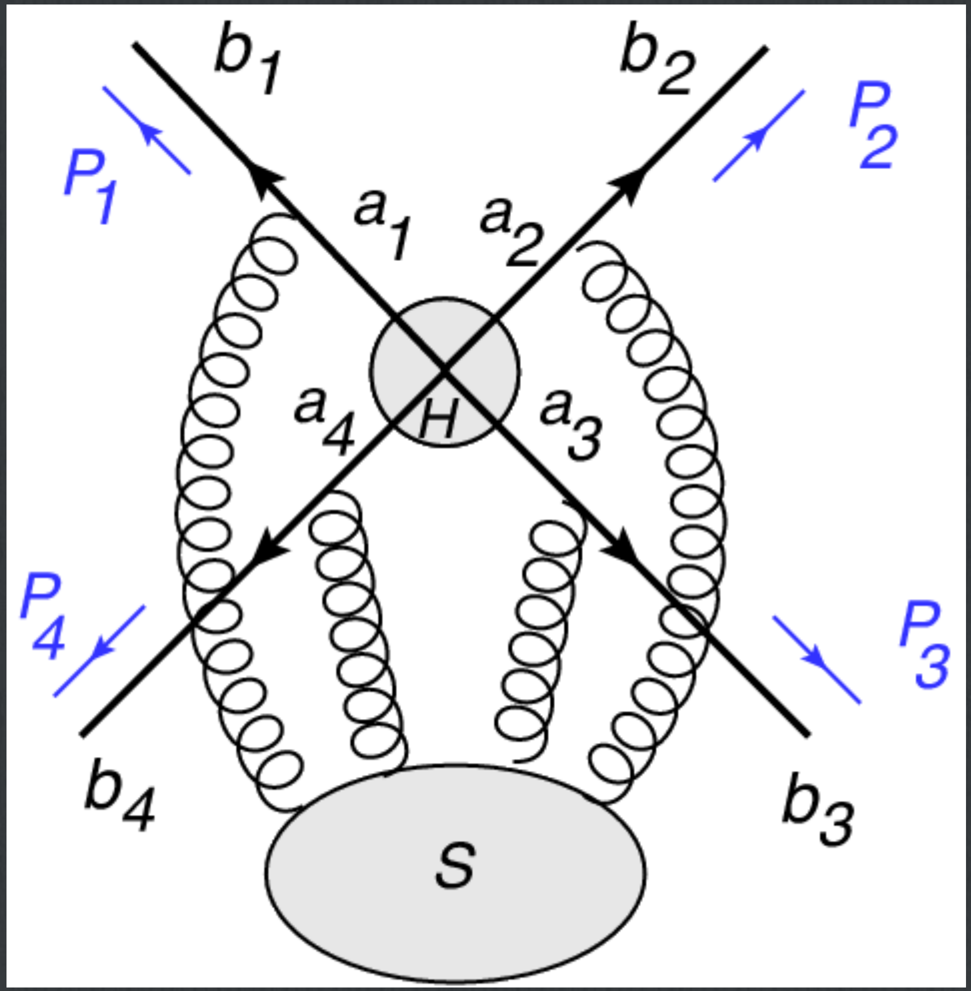




What can event generators do for analytic resummation?

- Automation has always been a stinging point for resummation. A few exceptions:
  - in the early 2000's Banfi, Salam and Zanderighi developed the CASEAR framework to perform NLL resummation for event shapes (more recently pushed to NNLL in ARES). However no public code available.
  - SoftSERVE: is C/C++ program to evaluate bare soft functions for wide classes of observables in SCET developed by Bell and collaborators.
  - SCETlib is a C++ package for numerical calculations in QCD and SCET developed by Tackmann and collaborators (soon to become public).

Dealing with colour



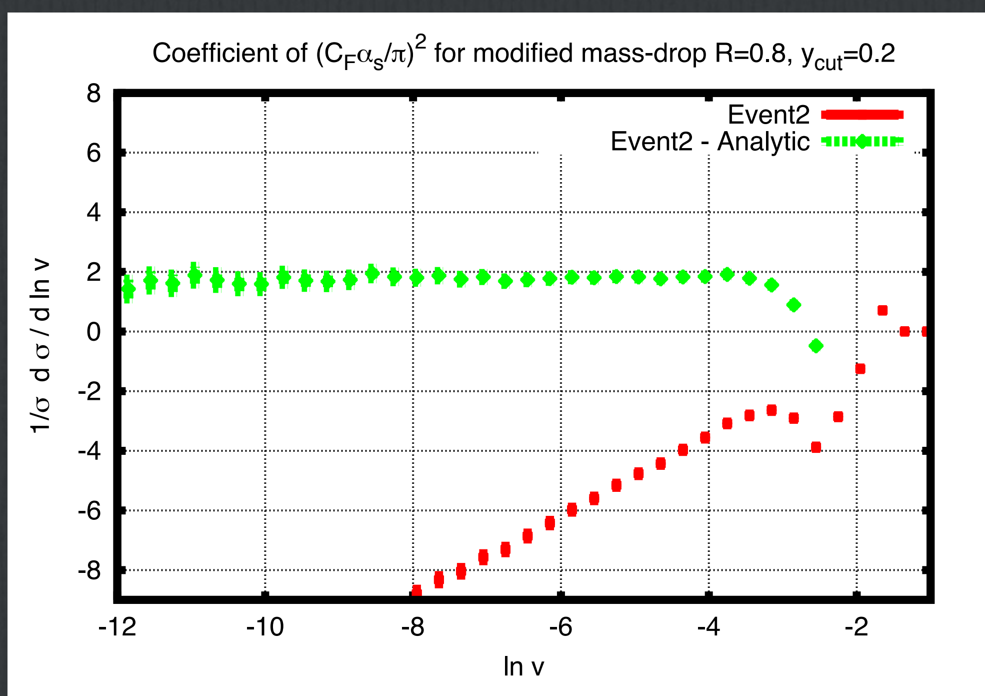
$$S(t) = \langle \mathscr{B} \,|\, e^{-t\,\Gamma^\dagger} e^{-t\,\Gamma} \,|\, \mathscr{B} \rangle$$

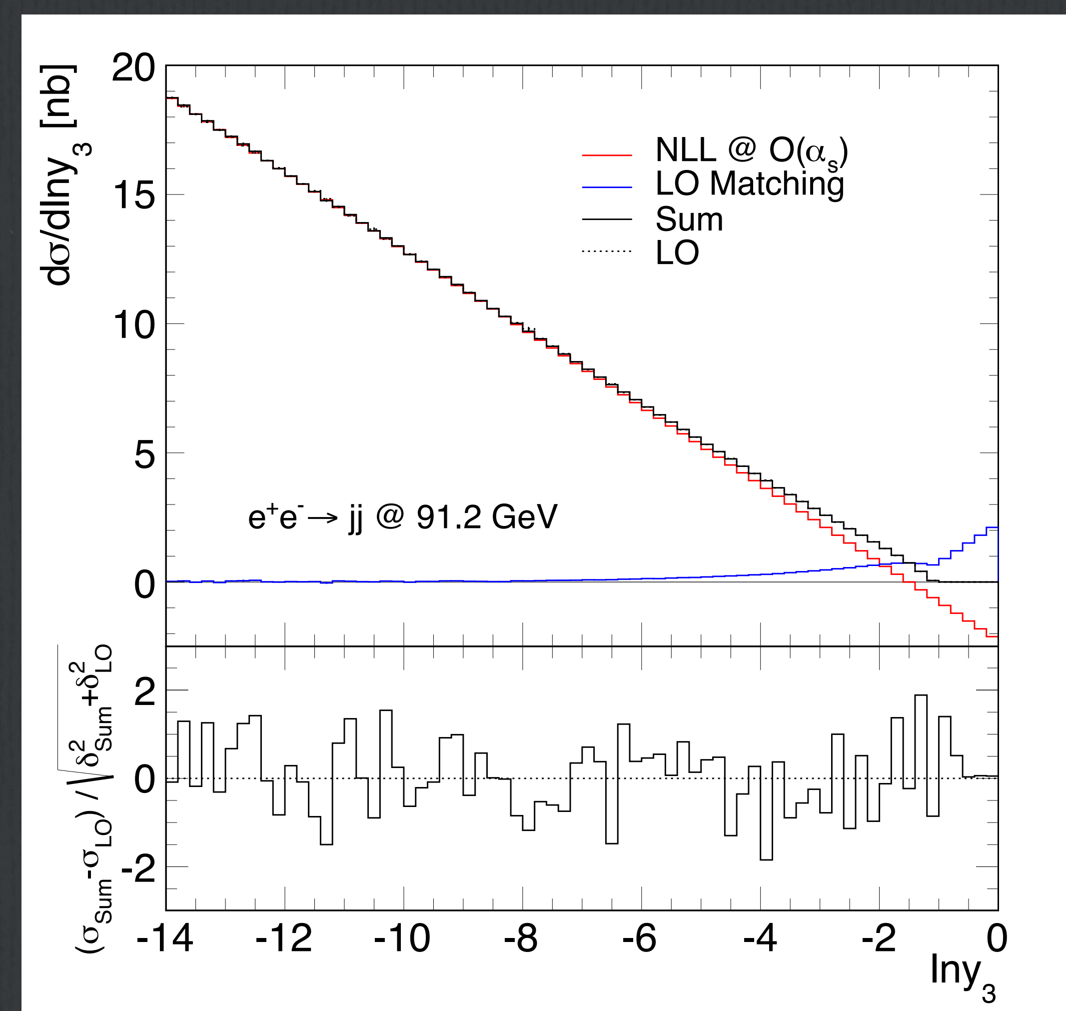
$$= \mathrm{tr}\left[cH e^{-t\,\Gamma^\dagger} e^{-t\,\Gamma} \right]$$

- large colour matrices most-easily handled by matrix-element generators like Comix
- method developed as a sherpa plugin in arXiv:1411.7325
- recently applied to resummation of multi-jet resolution parameters arXiv:1912.09396

Local-subtraction matching

- another painful task one usually faces is matching the resummation to fixed-order
- usually one matches distributions, which implies running fixed-order codes in region of phase-space where they're not supposed to work





- in the same 2014 paper, we devised a local matching scheme, where subtracted fixed-order events are generated. Extend this NNLO?

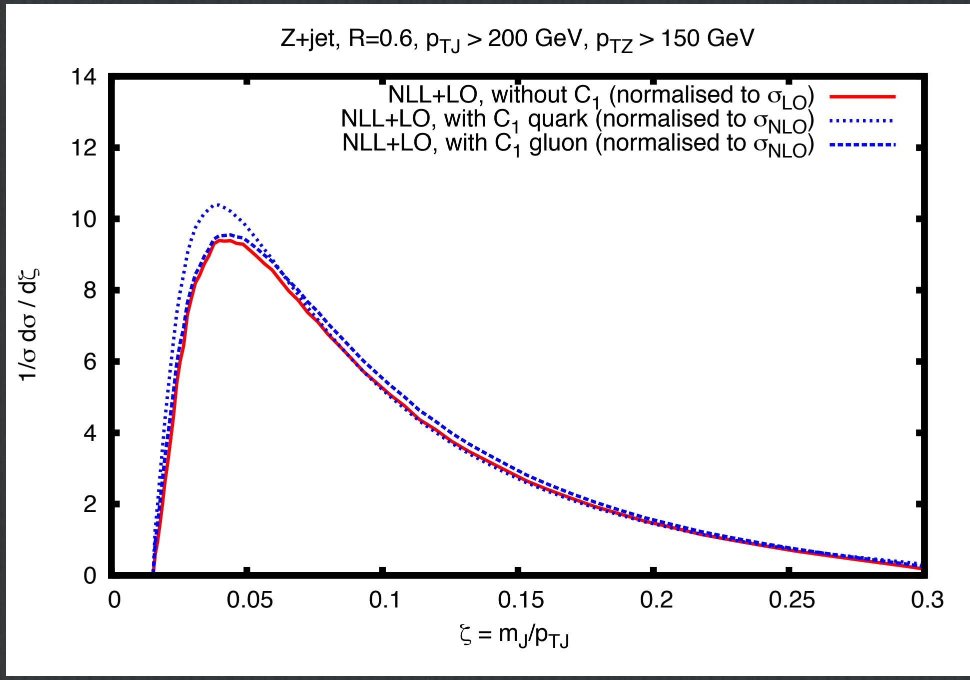
Tracing flavour

- Matrix-element generators can also be used to extract contributions to the resummation, if we can trace flavour information

- consider for instance jet-observables like the jet mass

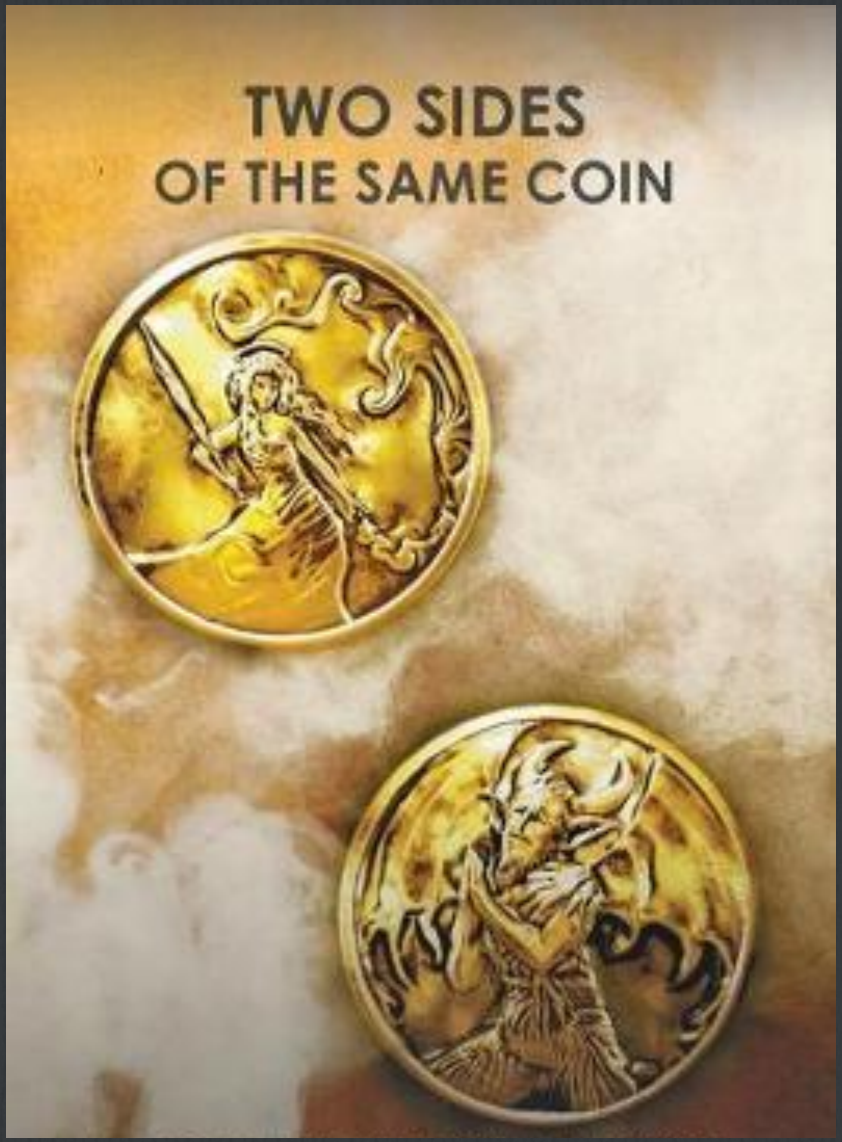
$$\frac{d\sigma}{dm_j^2} = \sigma_q^{(0)}(1 + \alpha_s C_q^{(1)} + \ldots)e^{-S_q}$$

$$+\sigma_g^{(0)}(1 + \alpha_s C_g^{(1)} + \ldots)\, e^{-S_g}$$



- the constants C_i are needed for NLL’ accuracy
- this has not been done yet, but it would be extremely useful!

Conclusions



it all depends on how valuable the coin is…

THANK YOU VERY MUCH!