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Theory for FCC (ee) in Austria

Simon Plätzer
Institute of Physics, NAWI — University of Graz
Particle Physics — University of Vienna

At the
Austrian FCC Meeting
Vienna/Online | 11 October 2021

Austrian HEP Theory for FCC

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- Non-perturbative physics
- Electroweak Physics
- Dark Matter & BSM
- Phenomenology
- Monte Carlo event generators


Axel Maas


Simon Plätzer


Suchita Kulkarni

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- Effective Field Theories
- Precision QCD predictions
- Top Quark physics
- Electroweak physics


Andre Hoang


Massimiliano Procura

Close interaction within each other, and with experimental efforts at HEPHY.

Event Generators & Phenomenology

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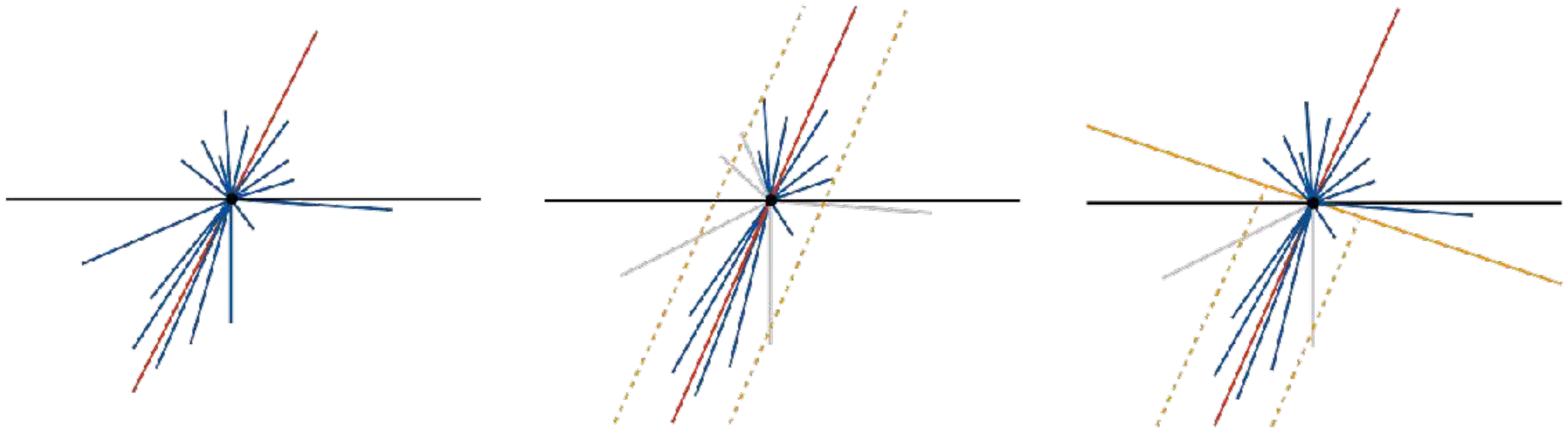
[Herwig collaboration – Eur.Phys.J. C76 (2016) 665]

Automated NLO QCD matching and multi jet merging, simulation of BSM processes.
Parton shower development, hadronization, multi-parton interactions.



NLO with matching

NLL with coherent branching
Issues in dipole showers

Issues in coherent branching
LL with dipole showers

Understand, decide and improve on shower accuracy to harness NNLO calculations.

[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]

Constrain phenomenological models from analytic input.

[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]

Focus for LHC phenomenology: VBS/VBF, top physics, multi-jet final states.
Mid-term goal: Apply QCD expertise to electroweak phenomena at high energies.

Simulations for Resummation

CVolver library implements numerical evolution in colour space.

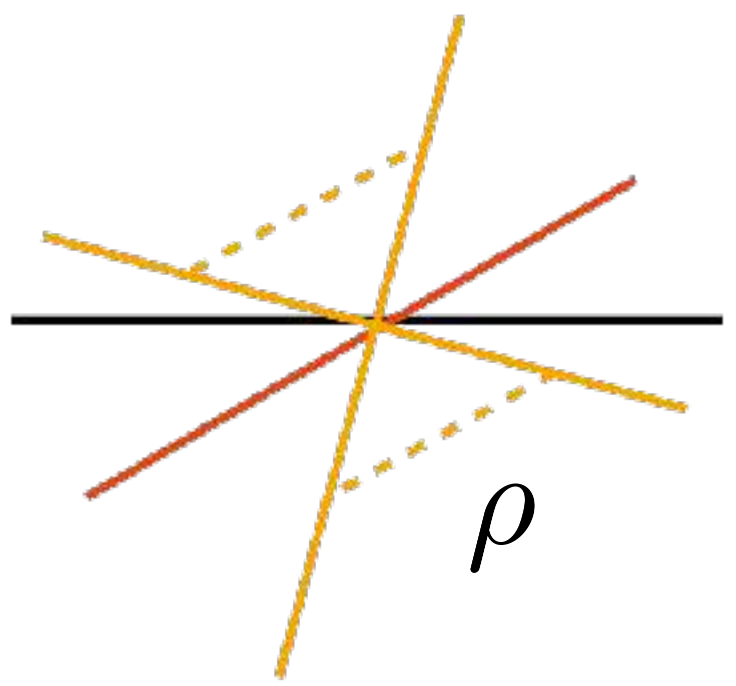
origins in [Plätzer – EPJ C 74 (2014) 2907]

CVolver

Monte Carlo algorithm at amplitude level: **new paradigm** for event generators and flexible resummation of QCD observables.

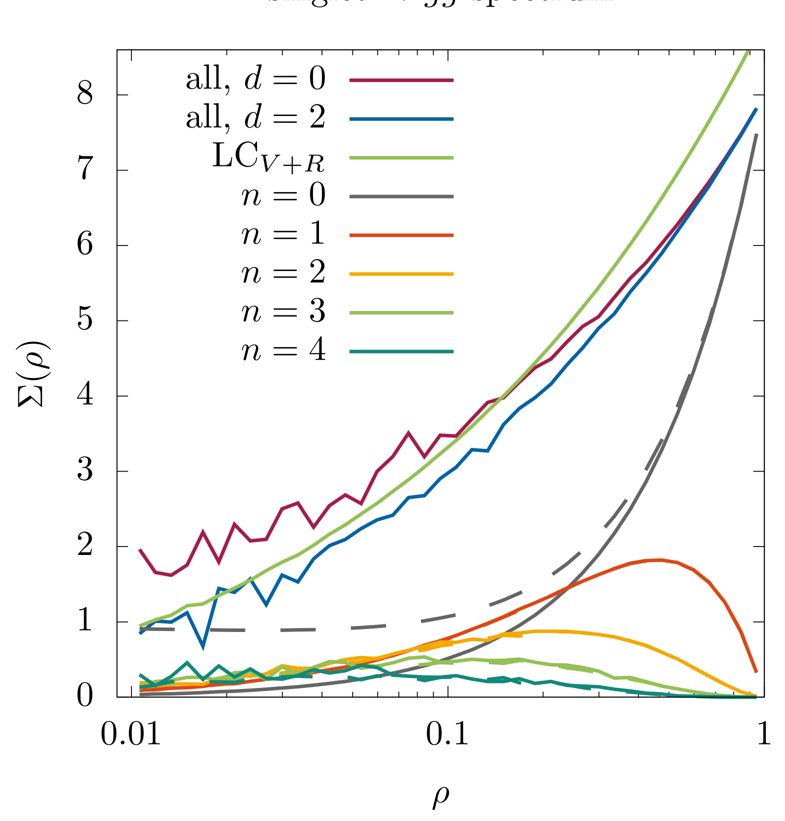
[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]

Resummation of non-global logarithms at full colour:

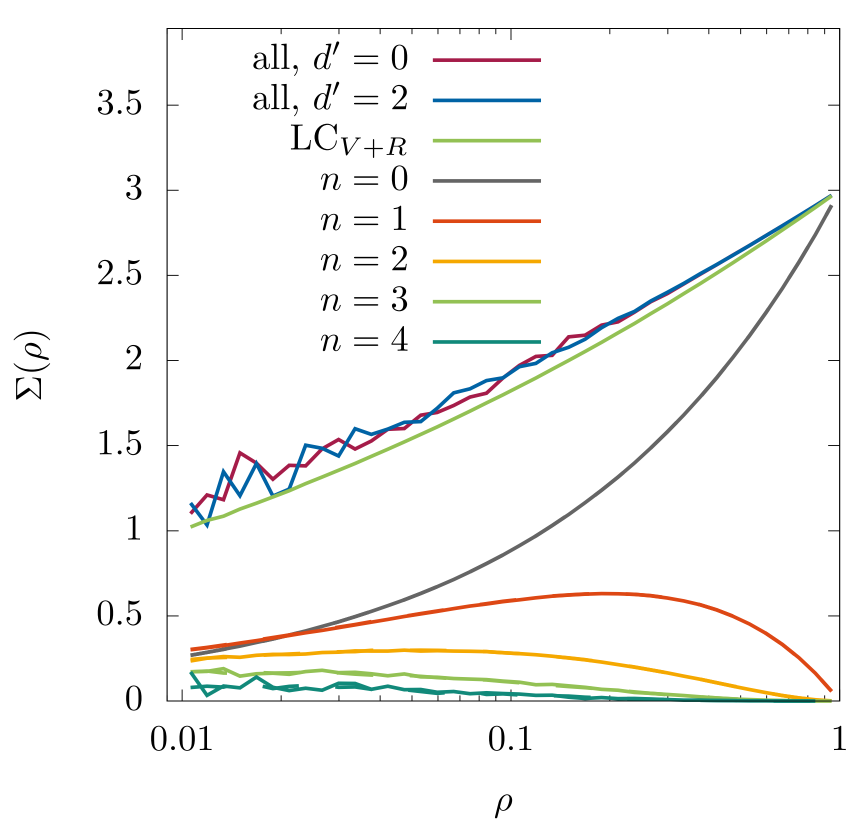


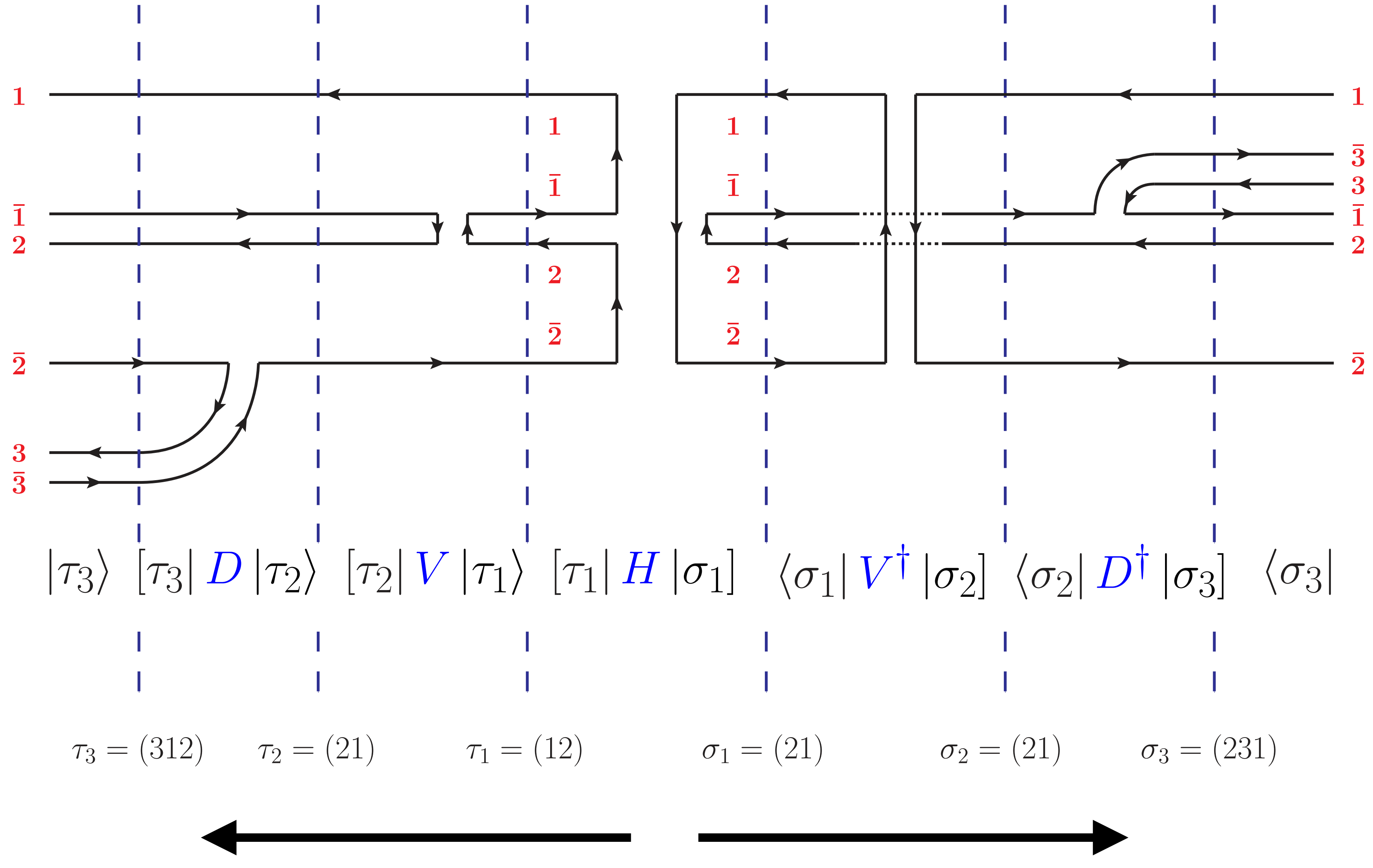
$$\Sigma(\rho) = \sum_n \int \mathrm{d}\sigma(\{p_i\}) \prod_i \theta_{\rm in}(\rho - E_i)$$

H to gg



Z to qq





amplitude

conjugate amplitude

Electroweak Physics

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Non-perturbative gauge-invariance requires additional substructure to left-handed leptons

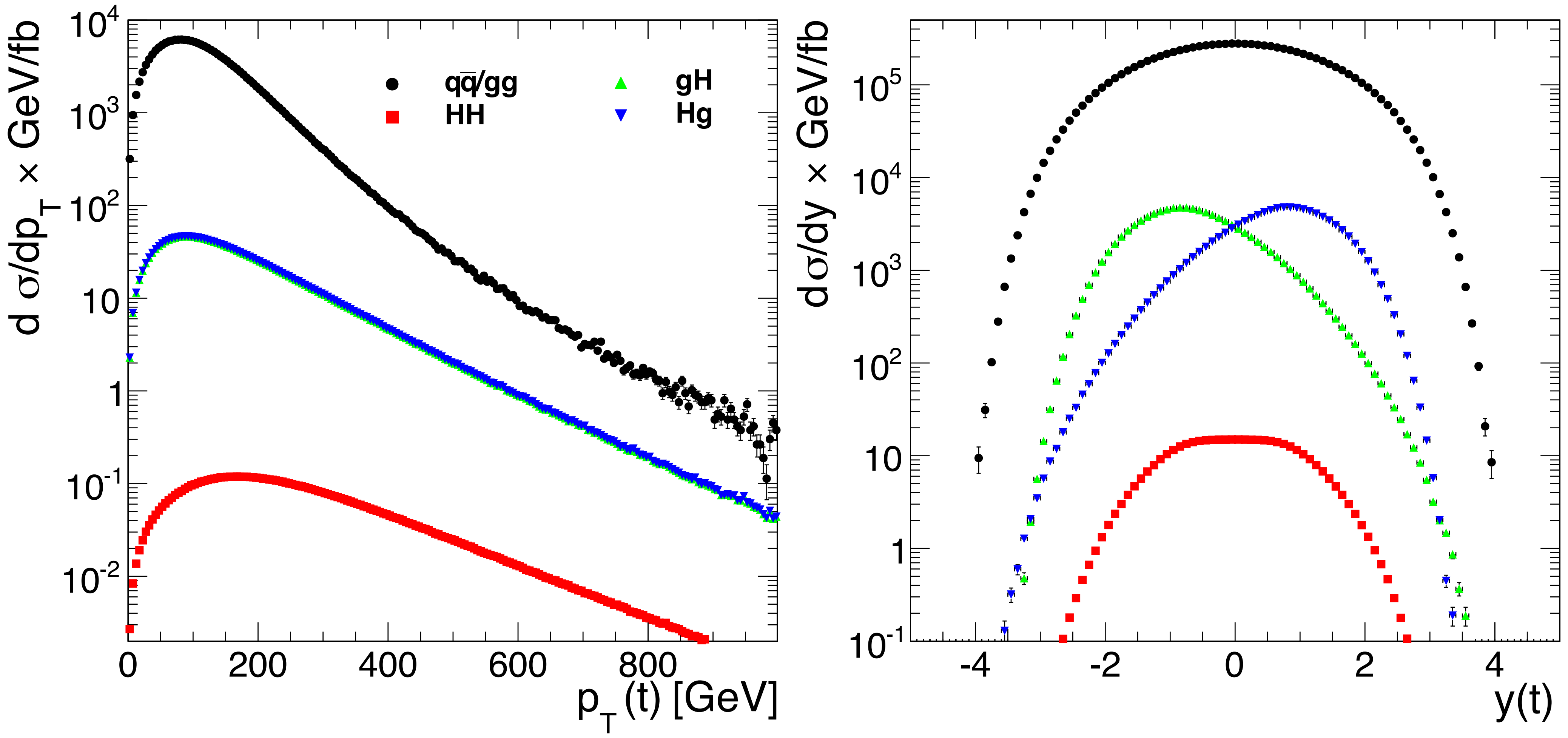
[Frohlich et al. — Nucl. Phys. B190 (1981) 553]

- Supported in lattice simulations [V. Afferrante et al. — 2011.02301
- Can be addressed in augmented perturbation theory [Maas — 1712.04721] [Egger et al. —1701.02881]
- At 1 TeV unpolarized e+e- to tbar t the impact is of the same order as NLO QCD effects
- Via restoration of the Bloch-Nordsieck theorem

Effects also in pp: Possible Higgs component in the proton.

[Fernbach, Lechner, Maas, Plätzer, Schöfbeck — arXiv:2002.01688]

$$\langle p(x)p(y)X(z_1,\ldots)\rangle = v^2\,\langle (qqq)(y)(qqq)(x)X(z_1,\ldots)\rangle$$
$$+v\,\langle (qqq)(x)H(x)(qqq)(y)X(z_1,\ldots) + x \leftrightarrow y\rangle$$
$$+\langle (qqq)(x)H(x)(qqq)(y)H(y)X(z_1,\ldots)\rangle$$



Uni Graz — HEPHY — UniVie

Long Lived Particles: Heavy Neutral Leptons

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- Currently activities focused on sensitivity of FCC for BSM parameter space
- Topic of interest: lifetime frontier, in particular studies of heavy neutral leptons
- Both FCC-ee and FCC-hh options being explored
- FCC-ee: Collaboration with Uni Uppsala, joint master student supervised
  - Main job, first implementation of HNL framework in FCC-ee software
  - Machinery of sample generation and validation in place
  - Aim: understand necessary vertex resolution etc for constraining HNL scenarios
  - Also involved in snowmass FCC-ee LLP white paper as a theory expert
- FCC-hh: ongoing studies about non-minimal HNL production mechanisms and reach for B-L scenarios
  - Collaborators: W. Liu, F. Deppisch
- Future plans: Integration of several BSM scenarios in FCC software
- Close collaboration with experimentalists working on FCC physics case
- Joint students together with U. Uppsala extending collaborations initiated

Top Quark Physics

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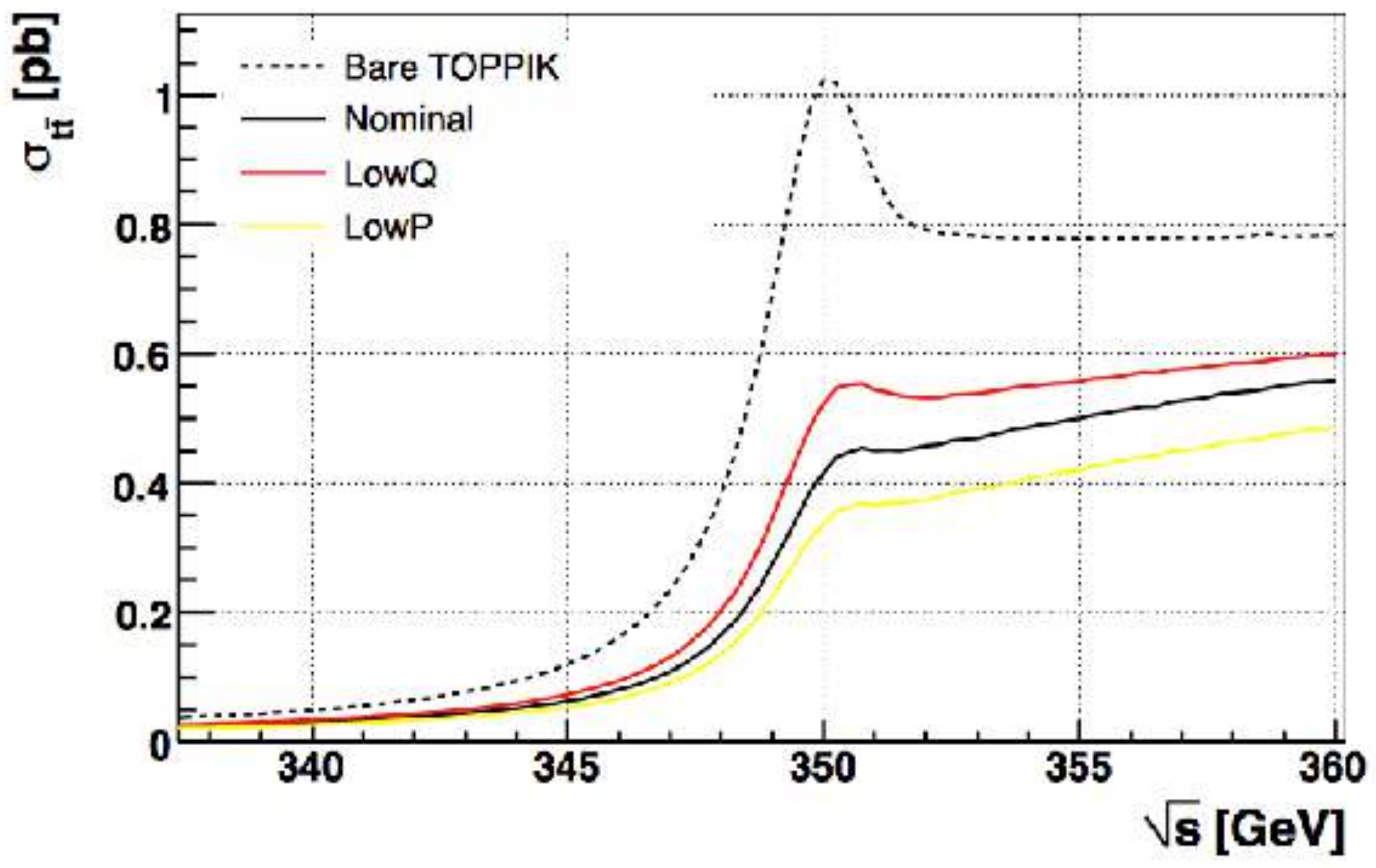
$\sigma(e+e- \to t\bar{t}+X)$ at $E_{cm} \approx 2m_t$



Principle: m_t from $\sigma_{tt}(m_t)$

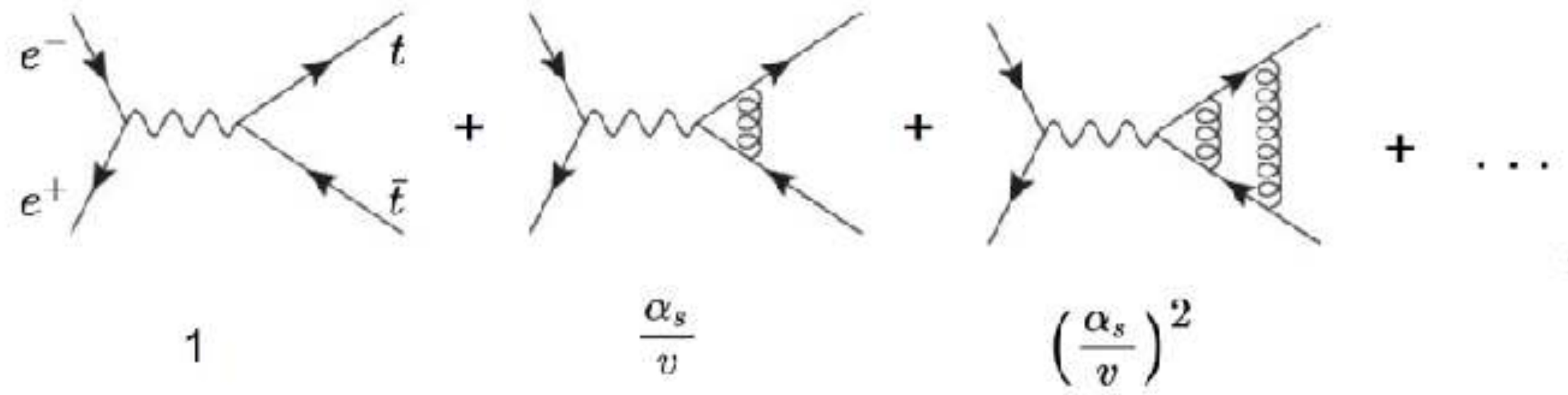
Advantages:

- count number of $t\bar{t}$ events
- color singlet state ← Crucial difference to top pairs at LHC
- background is non-resonant
- physics well understood (renormalons, summations)

➢ Top decay protects from non-pert effects

[Hoang, Stahlhofen et al. — 2013 …]

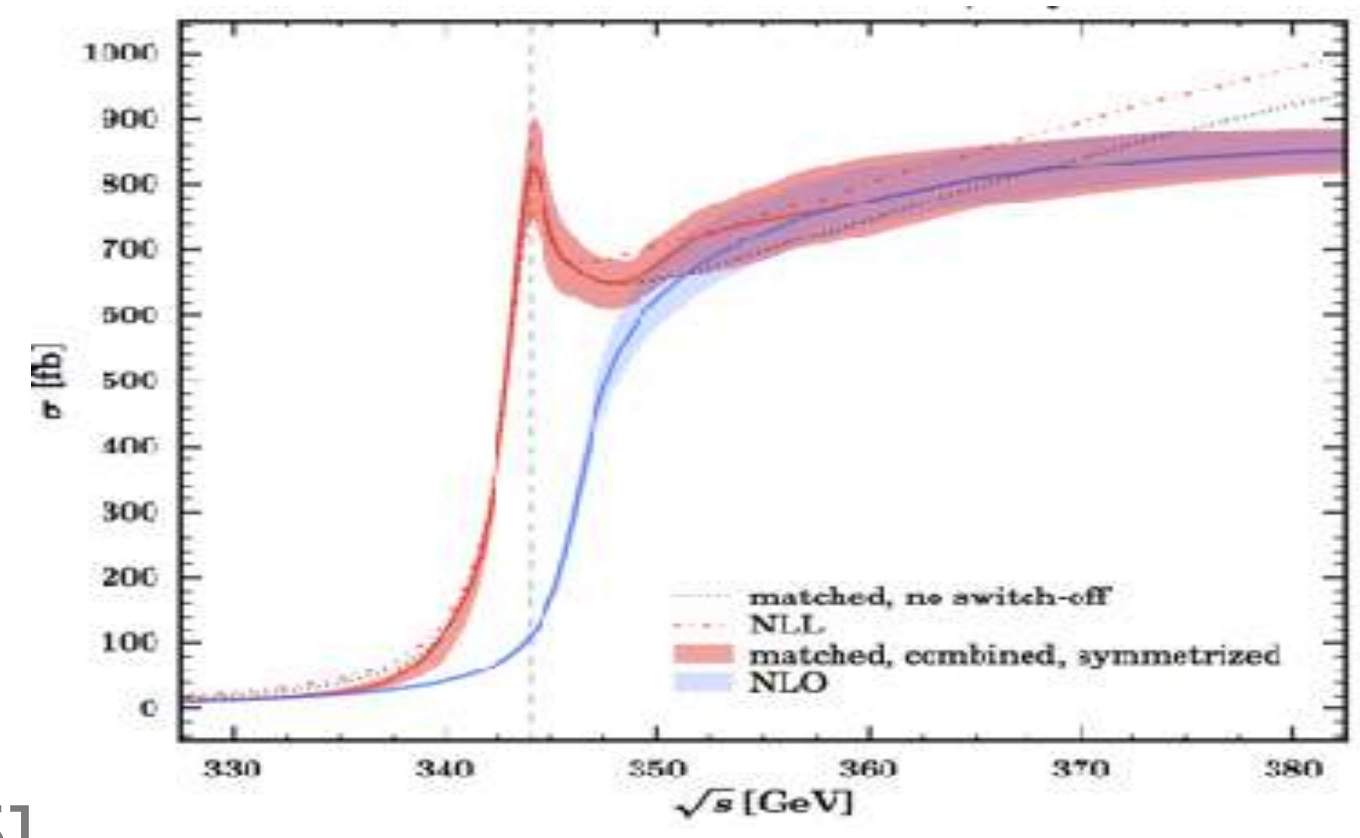
Top production at threshold:



- Coulomb resummations
- Finite Width effects are leading order
- NRQCD effective field theory counting (α_S~v)

Goal: Top mass in well-defined scheme with uncertainties ~ 50 MeV

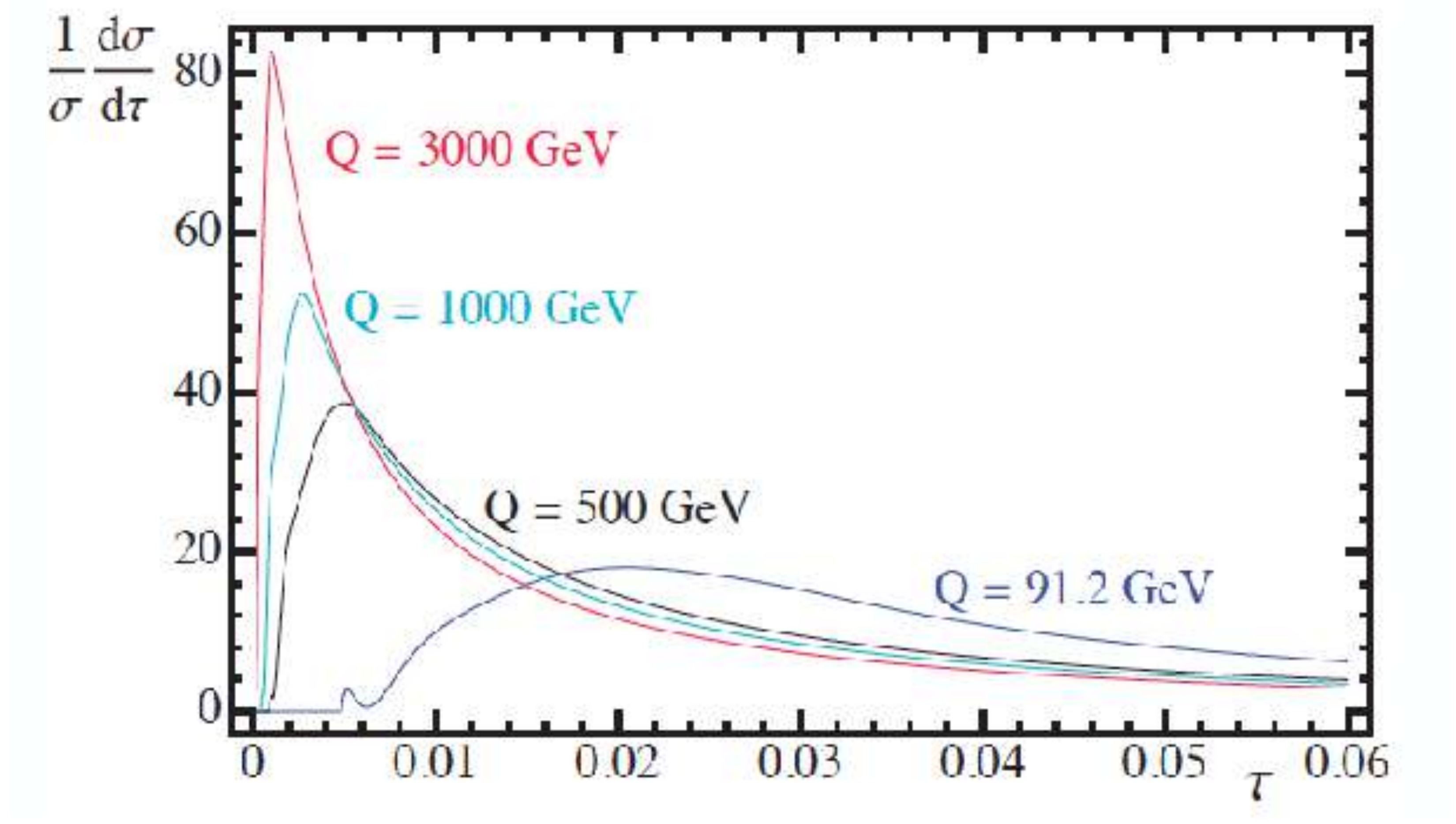
Can one use the radiative return?

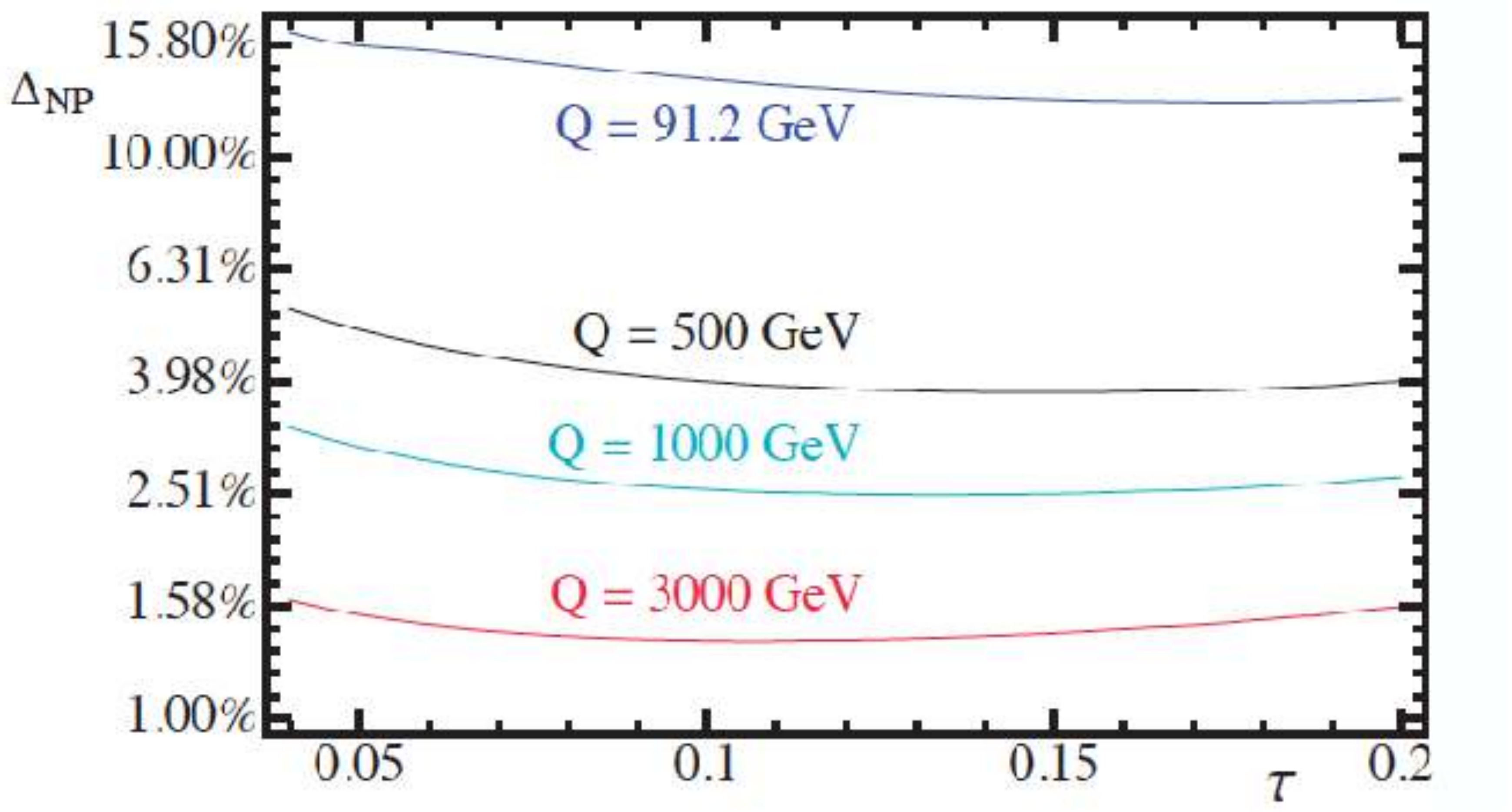


[Boronat, Fullana, Juster, Gomis, Vos, Hoang, Widl, Mateu — Phys.Lett.B 804 (2020) 135]

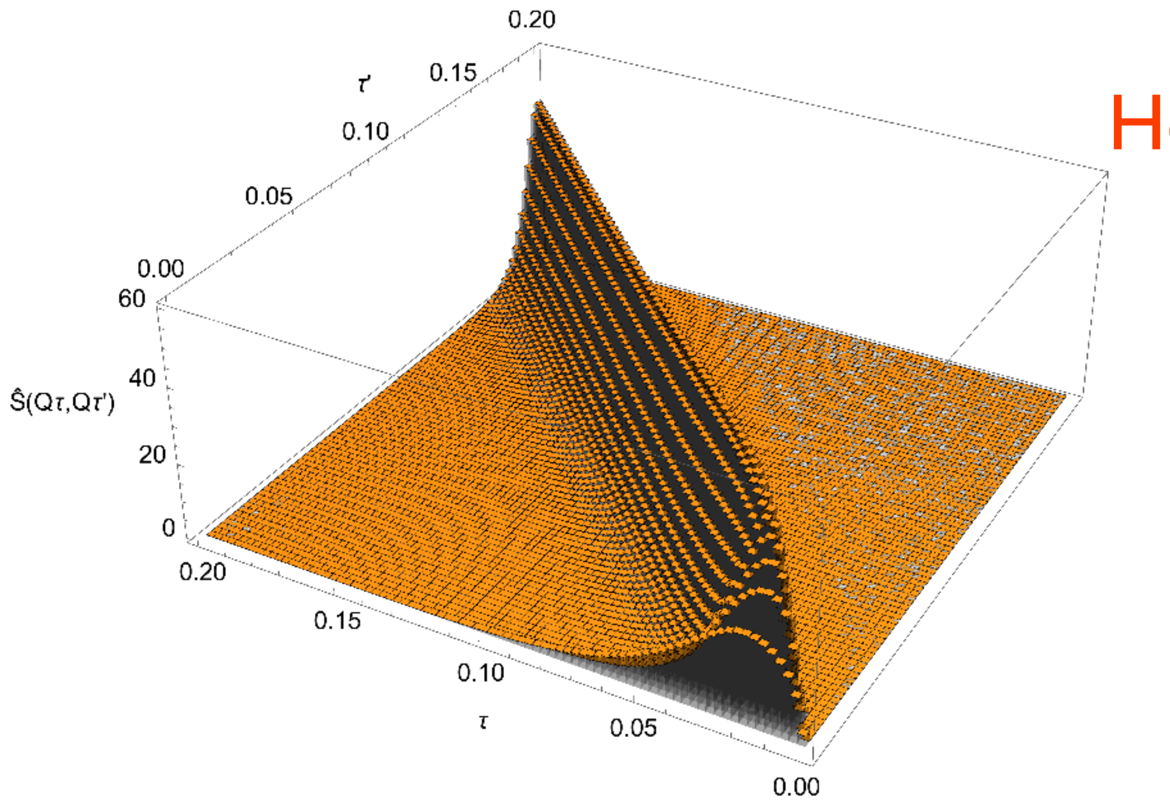
Strong Coupling Determination

- High precision analysis needed
- Non-perturbative effects decrease at large Q, but still important
- Need to understand gamma/gamma backgrounds

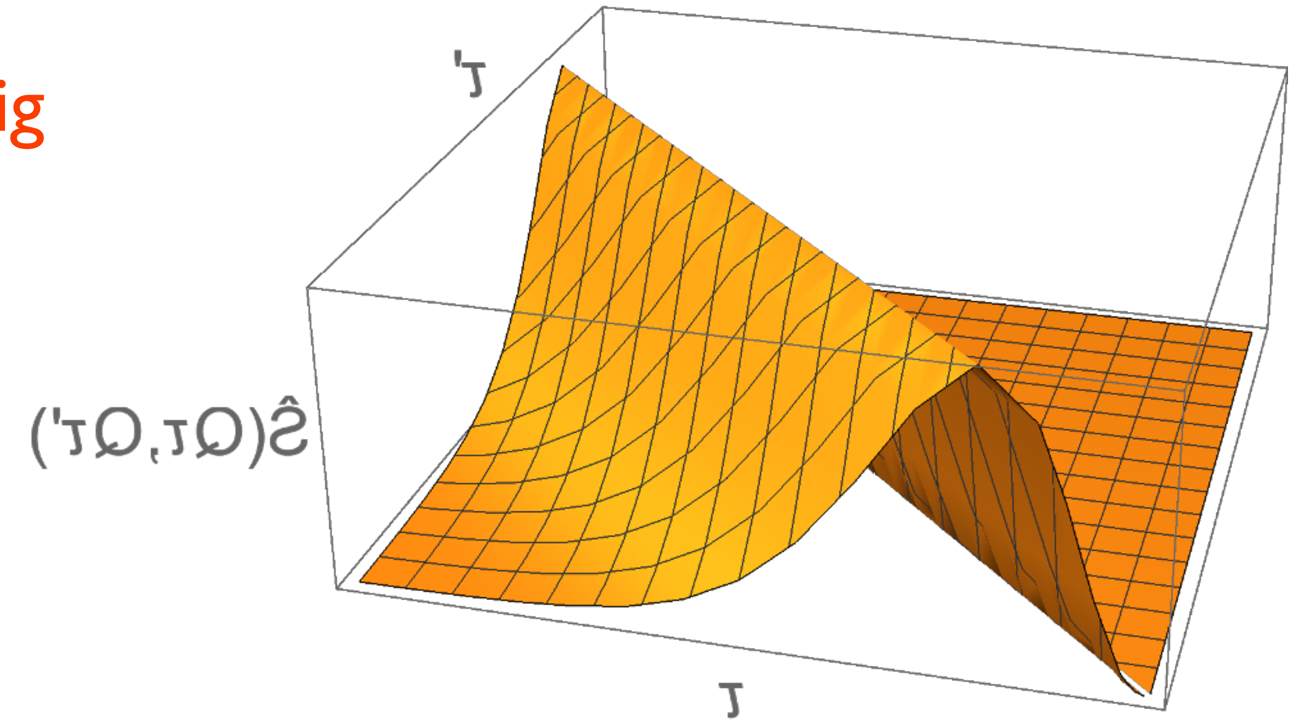




Complemented by exploring hadronization models and hadronization corrections



Herwig



analytic

[Hoang, Plätzer, Samitz — in progress]

Uni Graz — Uni Wien

Summary

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Focused on theory activities towards FCC-ee:
But of course we are deeply involved in LHC physics, as well as upcoming ep physics at the EIC.

Methods span a large toolset:

- Fixed-order corrections
- Effective field theories and resummation
- Event generators and simulation
- Non-perturbative methods

Physics scope:

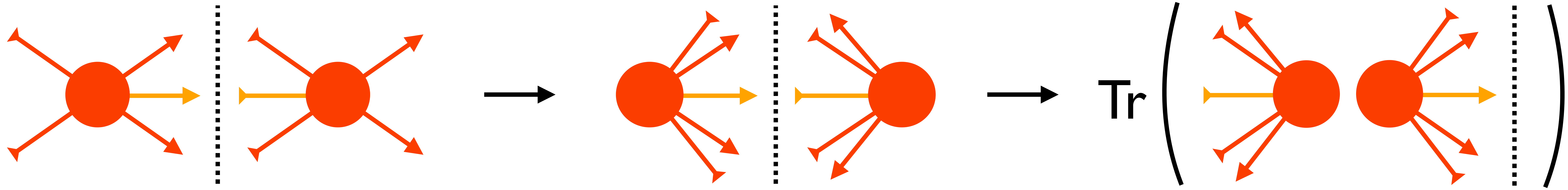
- Top and Higgs properties
- BSM scenarios and dark matter
- Electroweak physics and VBS
- Precision QCD

Interrelated interests in Austrian theory community:

- QED and electroweak radiation at high energies, non-trivial Standard Model effects
- Unstable particles, precise description of QCD dynamics and the quest for fundamental parameters
- Develop baseline and platform, and simulate BSM effects on all energy scales

Thank you!

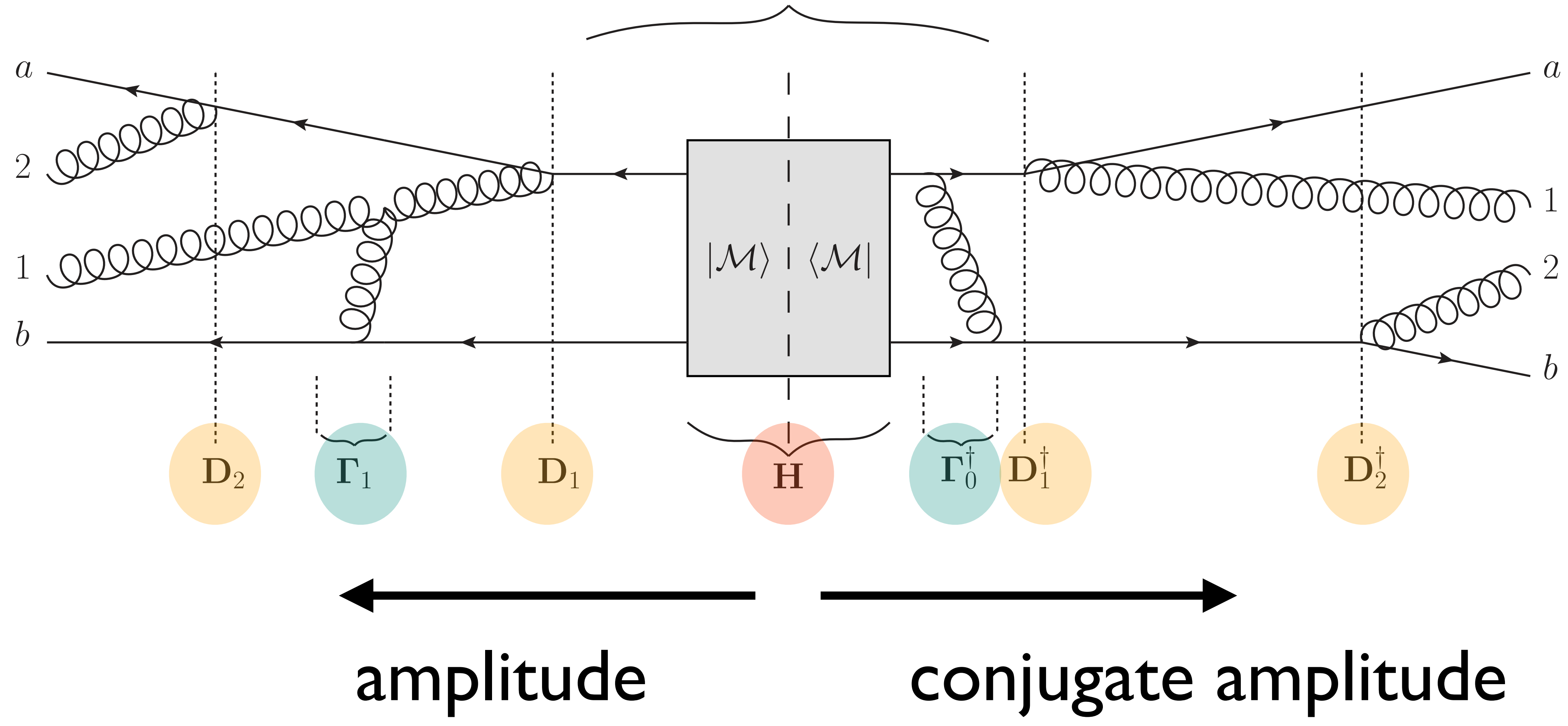
Cross Sections and Amplitudes



$$\mathbf{A}_n(q) = \int_q^Q \frac{\mathrm{d}k}{k}\, \mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}(k')}\, \mathbf{D}_n(k)\, \mathbf{A}_{n-1}(k)\, \mathbf{D}_n^\dagger(k)\, \overline{\mathrm{P}}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}^\dagger(k')}$$

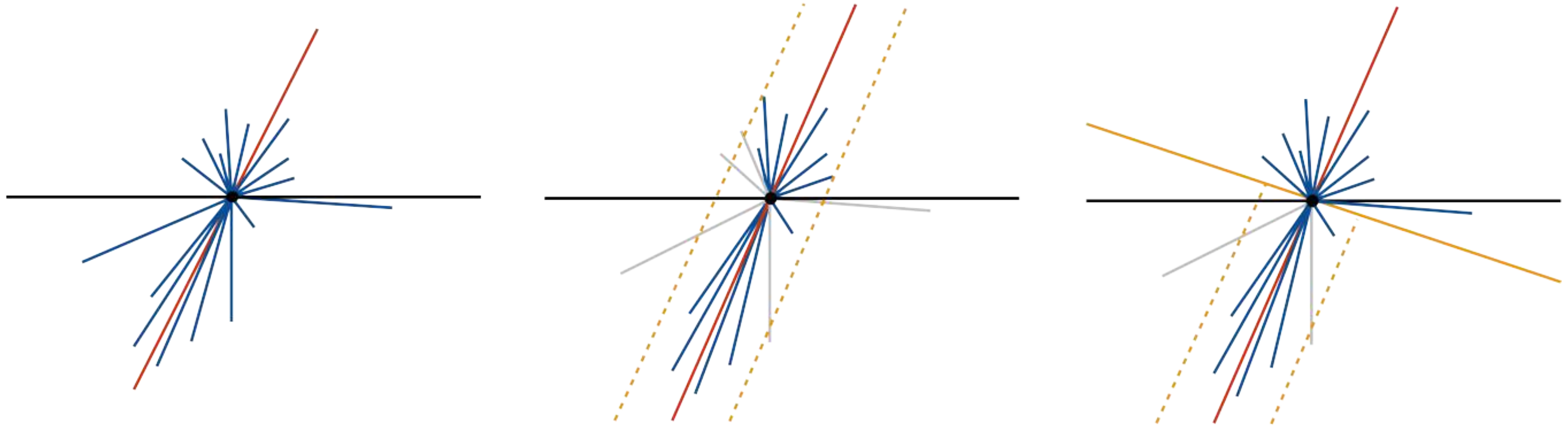
Markovian algorithm at the amplitude level:
Iterate gluon exchanges and emission.

Different histories in amplitude and conjugate amplitude needed to include interference.



[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145]

New Insights into Existing Parton Showers



NLO with matching

NLL with coherent branching
Issues in dipole showers

Issues in coherent branching
LL with dipole showers

Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n\ \text{jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl}\ \alpha_s^k(Q)\ \ln^l \frac{1}{\tau}$$

New Insights into Existing Parton Showers

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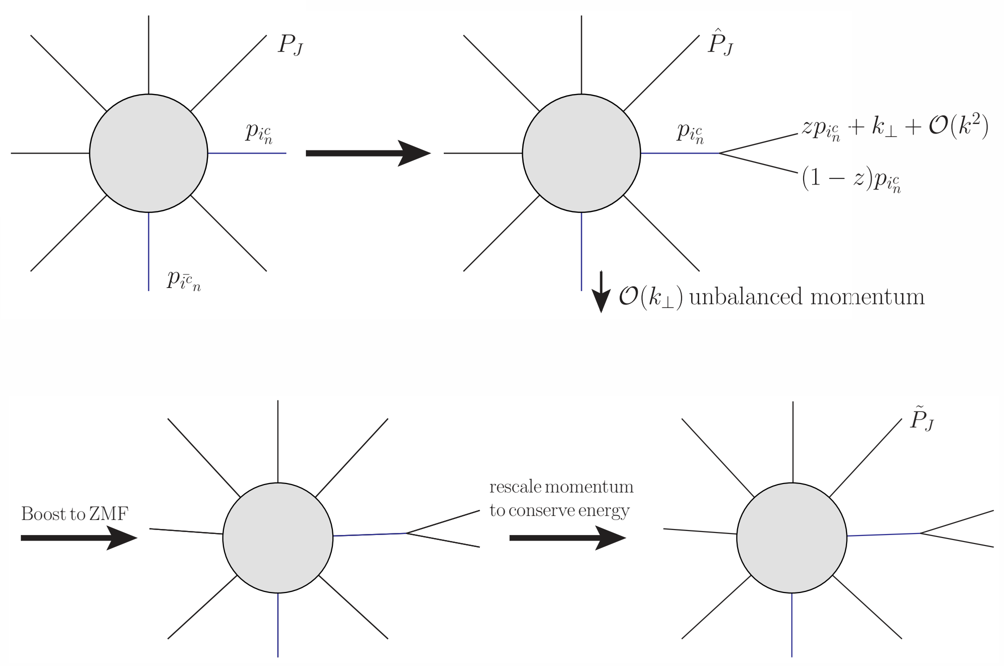
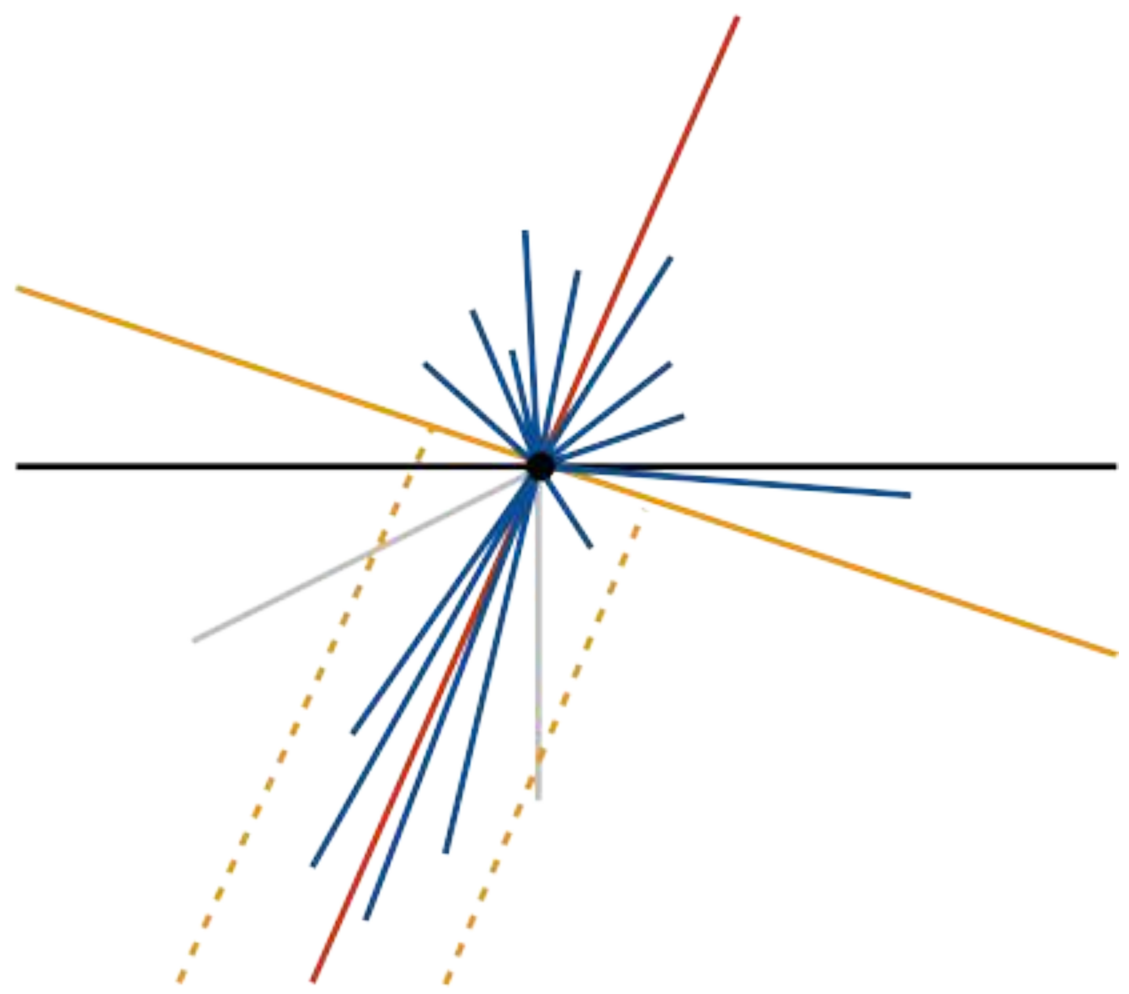
$$\frac{p_{i_n} \cdot p_{j_n}}{p_{i_n} \cdot q_n \; p_{j_n} \cdot q_n} \longrightarrow$$

$$\frac{p_{i_n} \cdot p_{j_n}}{p_{i_n} \cdot q_n \; p_{j_n} \cdot q_n} - \frac{T \cdot p_{j_n}}{T \cdot q_n}\frac{1}{p_{j_n} \cdot q_n} + \frac{T \cdot p_{i_n}}{T \cdot q_n}\frac{1}{p_{i_n} \cdot q_n}$$



[Dasgupta, Dreyer, Hamilton, Monni, Salam —PRL 125 (2020) 5]
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]



Dipole showers reproducing coherent branching: NLL & NLC global, LL & LC non-global

Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \; \alpha_s^k(Q) \; \ln^l \frac{1}{\tau}$$

Hadronization & Colour Reconnection

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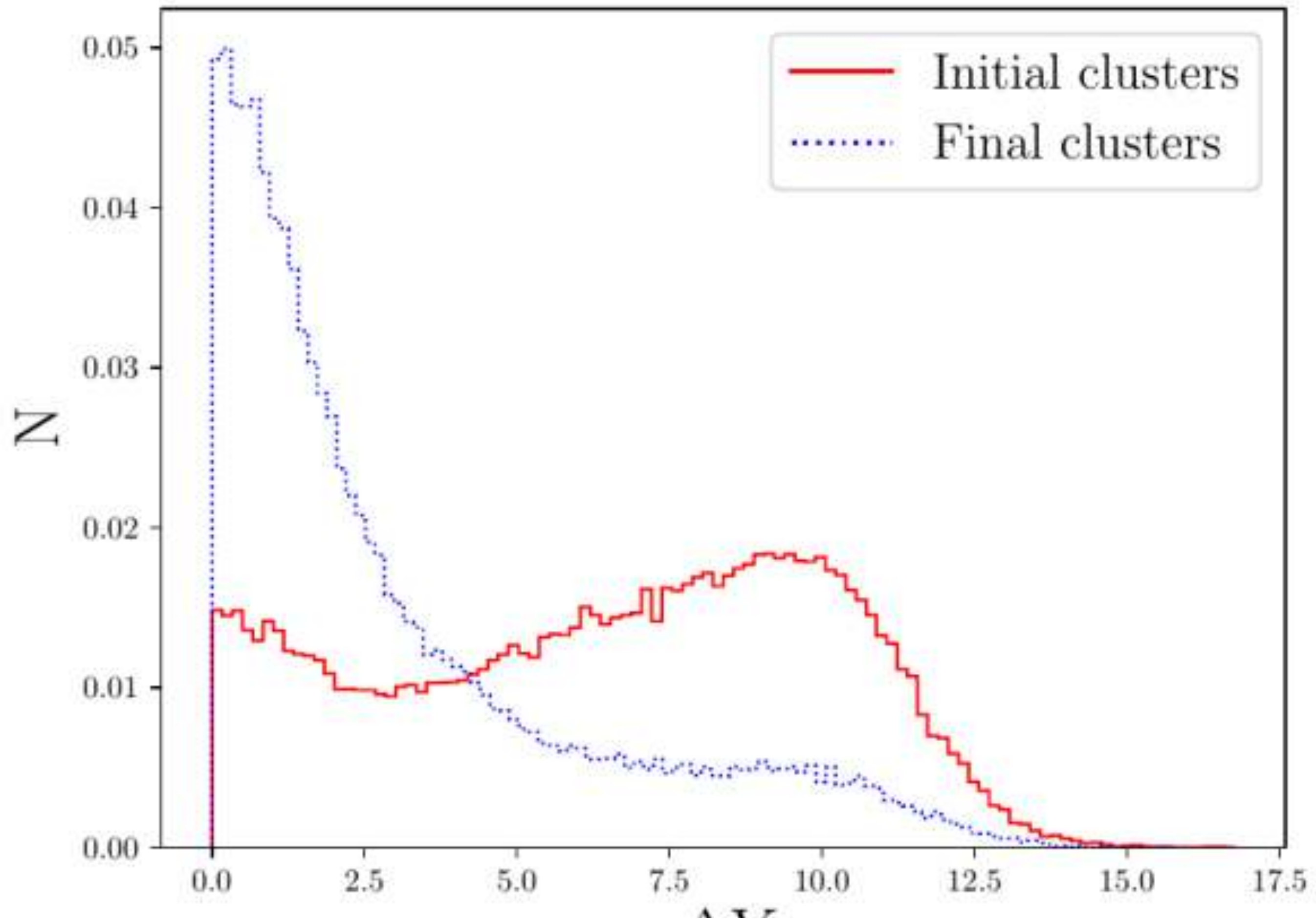
Approach colour reconnection from colour evolution: perturbative component?

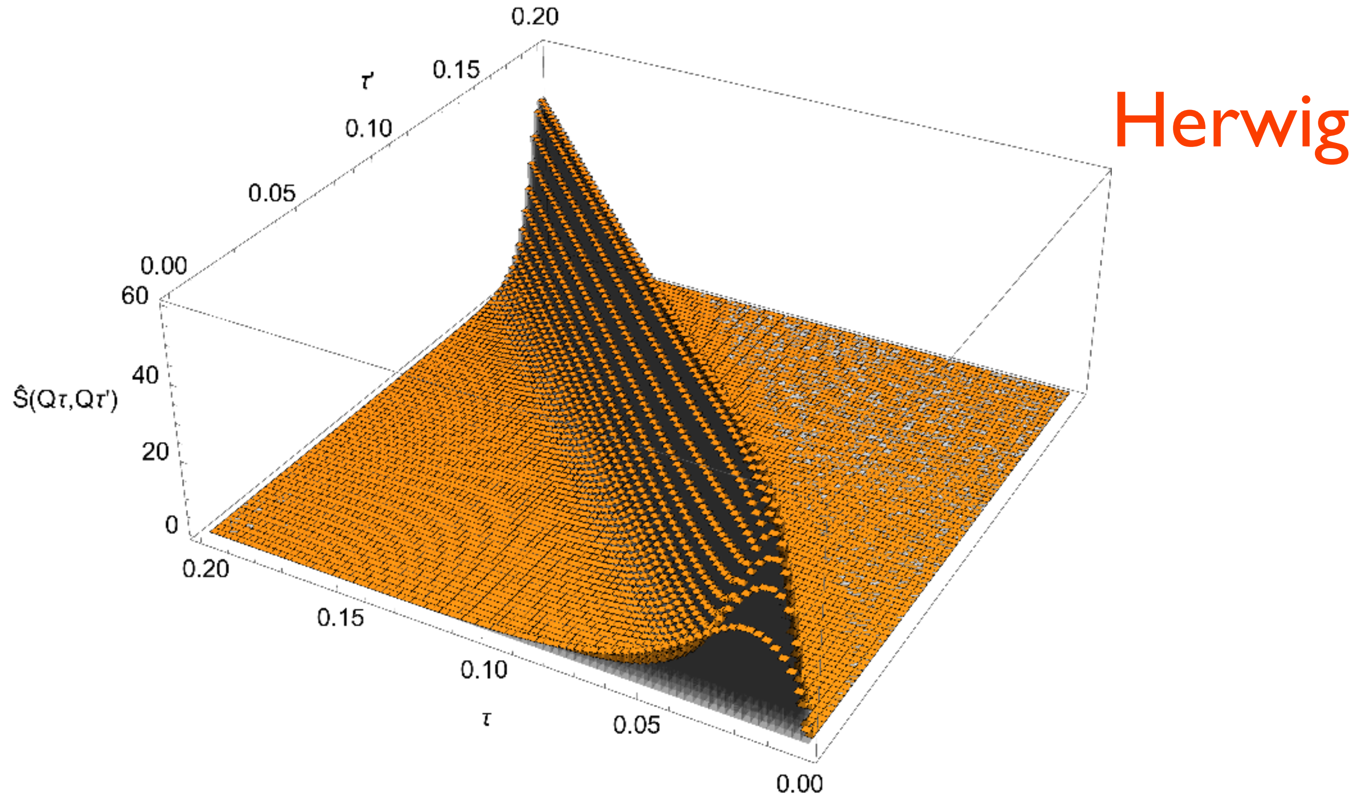
$$\mathcal{A}_{\tau\to\sigma} = \langle\sigma|\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right)|\tau\rangle$$

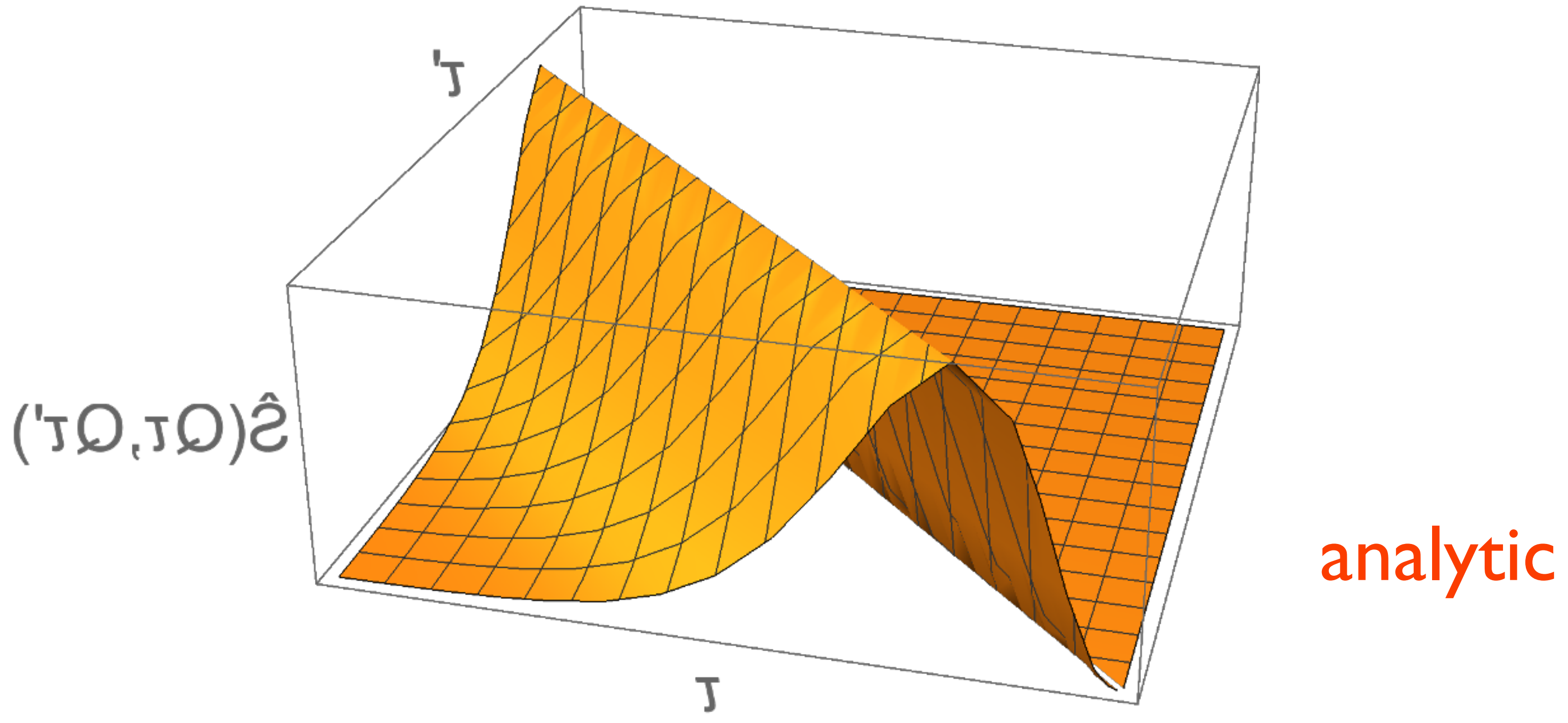
$$P_{\tau\to\sigma} = \frac{|\mathcal{A}_{\tau\to\sigma}|^2}{\sum_\rho |\mathcal{A}_{\tau\to\rho}|^2}$$



Strong support for geometric models from perturbative evolution.

Confronting hadronization models with analytic power correction models





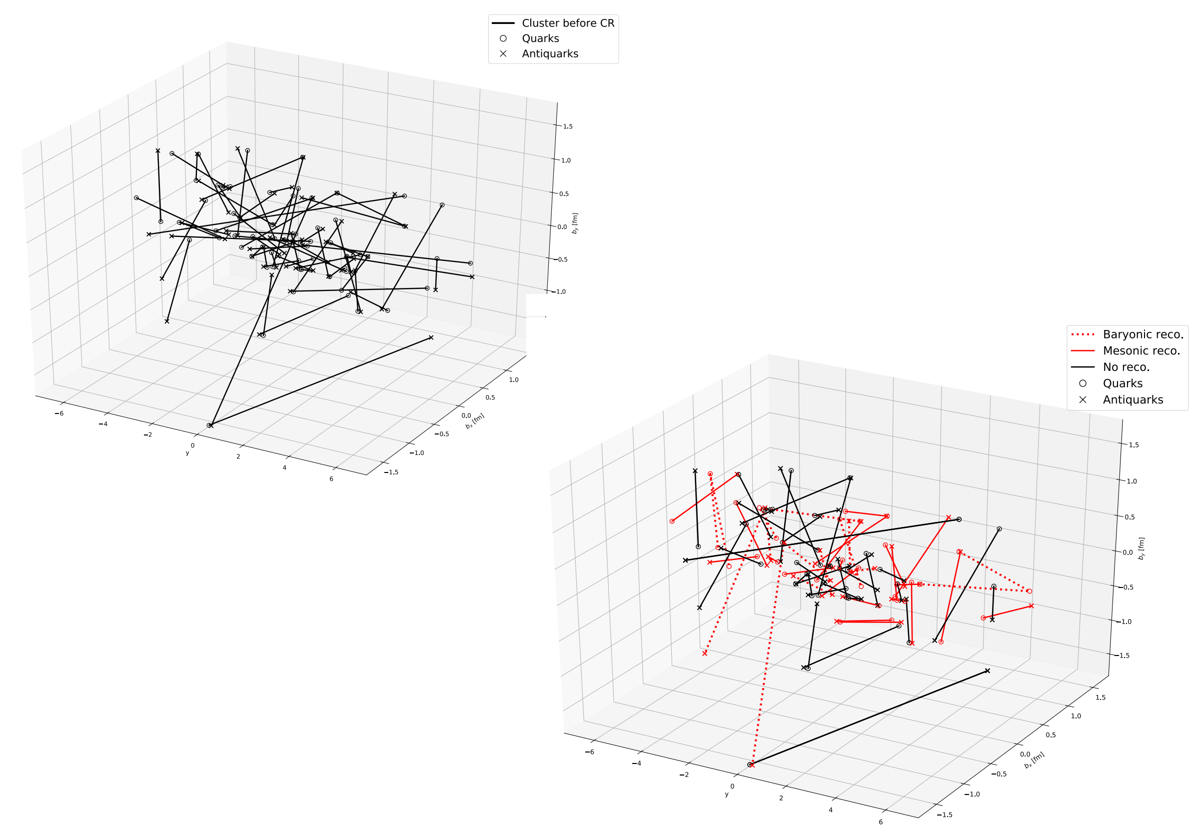
[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

[Hoang, Plätzer, Samitz — in progress]

Immediate links to ALICE physics

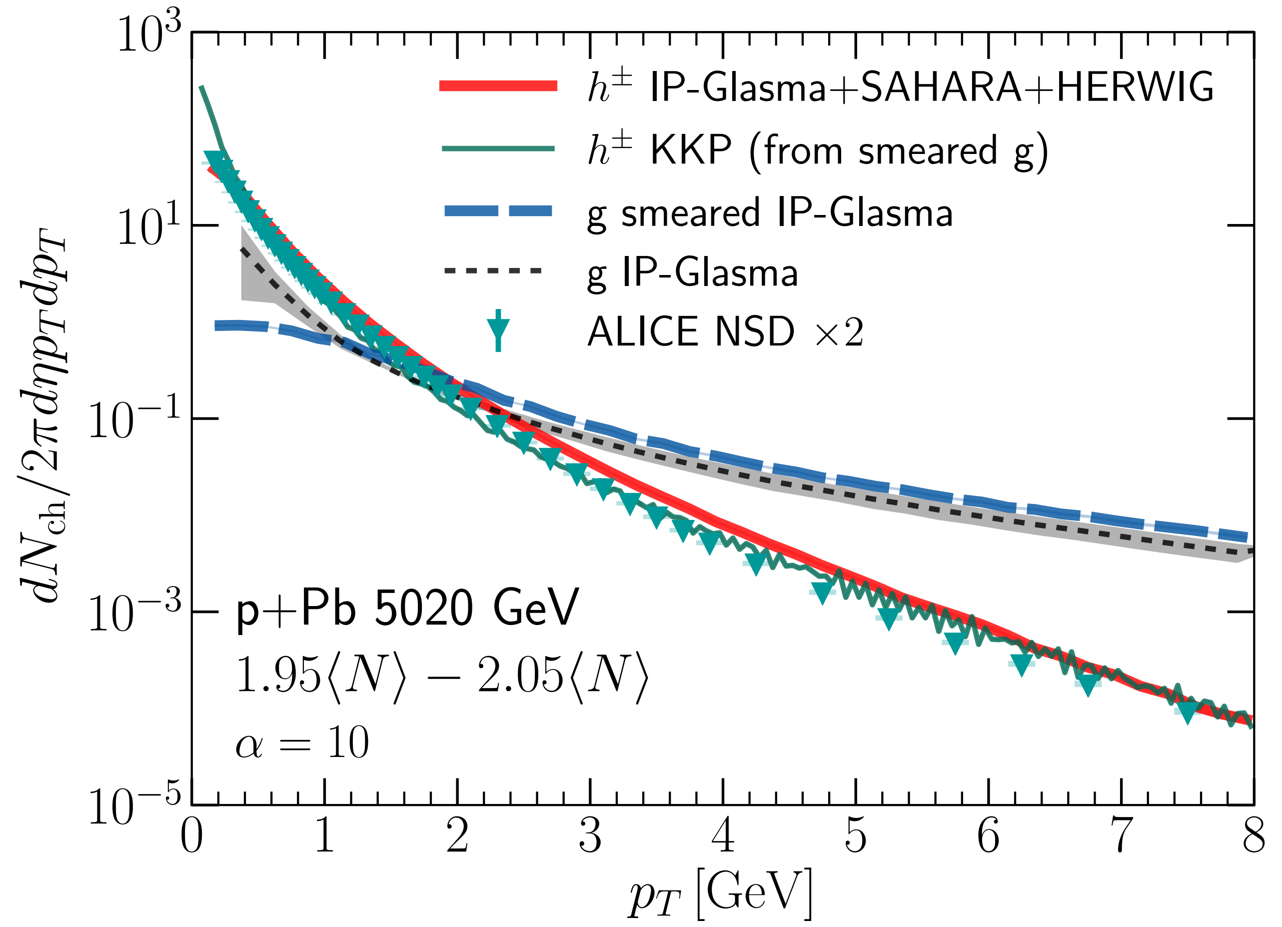
Improvements and application of event generators to **EIC physics and pA/AA** at the LHC.

Spacetime information and steps towards microscopic models.



[Bellm, Duncan, Gieseke, Myska, Siodmok – EPJ C79 (2019) 1003]

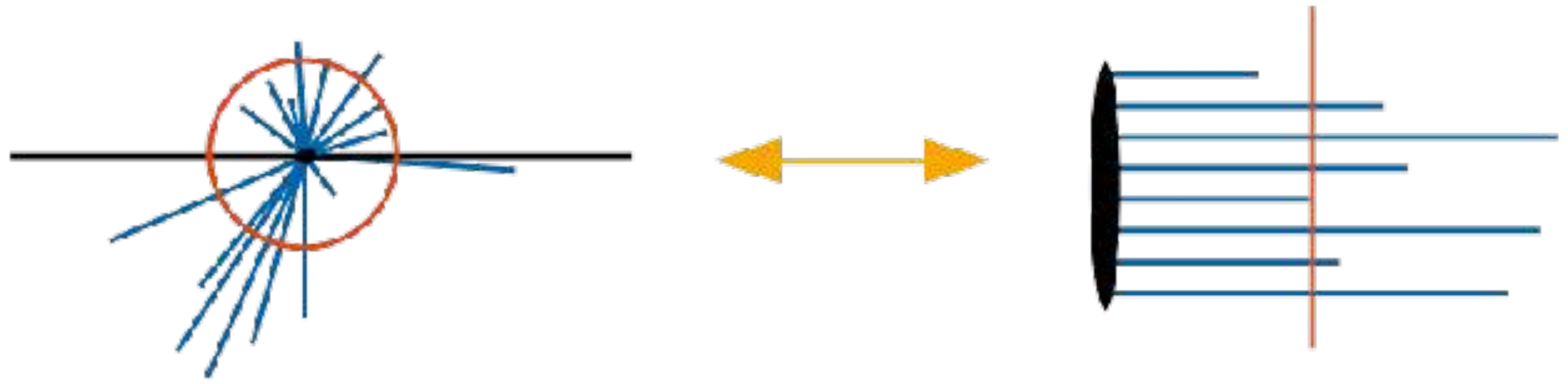
IP-Glasma interfaced to Herwig



[Greif, Greiner, Plätzer, Schenke, Schlichting - Phys. Rev. D. 103 (2021) 5]

Structure of (initial state) evolution and link to hadronization.

[Plätzer, Ruffa — JHEP 06 (2021) 007]
[Plätzer, Kirchgaesser, Ruffa , … in progress]



$$\sigma[u] = \sum_{n,m} \int \int \mathrm{Tr}\,[\mathbf{A}_n \mathbf{S}_{nm}]\, \mathrm{d}\phi(q_1, ..., q_n)\ u(P_1, ..., P_m) \mathrm{d}\phi(P_1, ..., P_m)$$

Immediate links to ALICE physics

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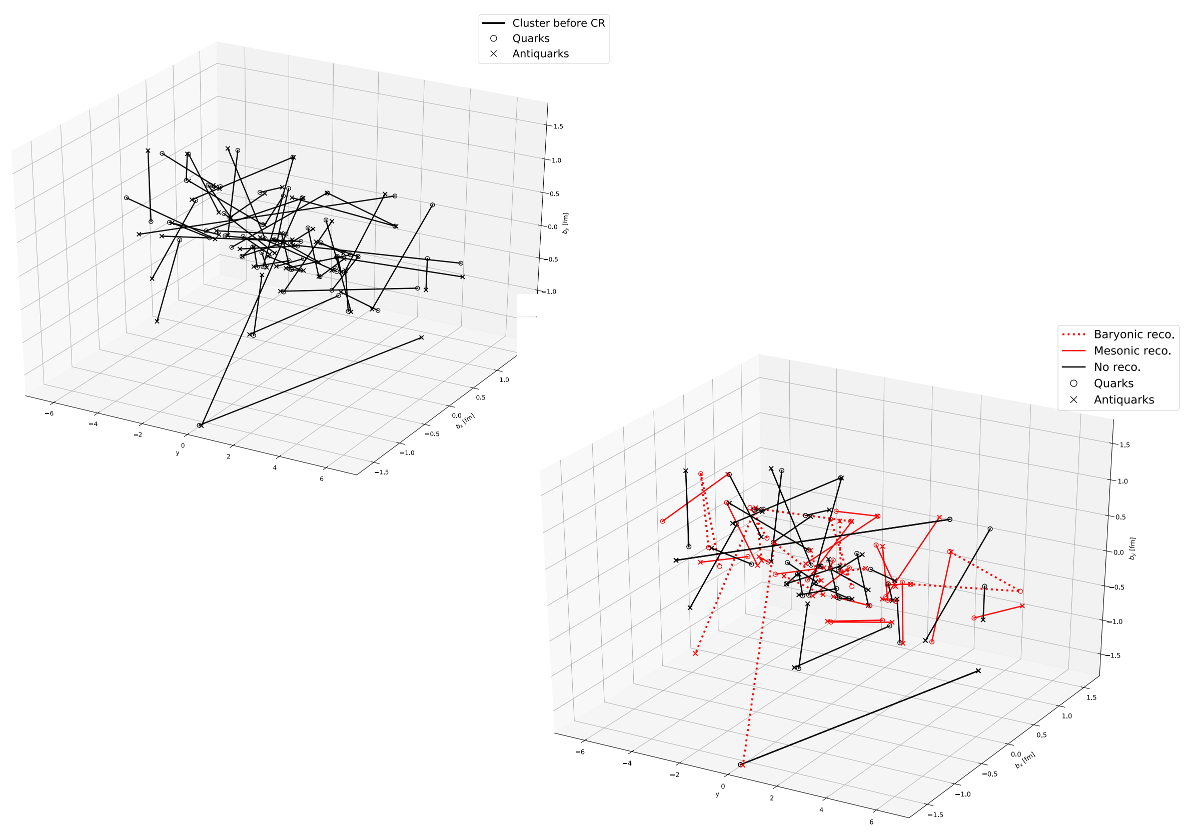
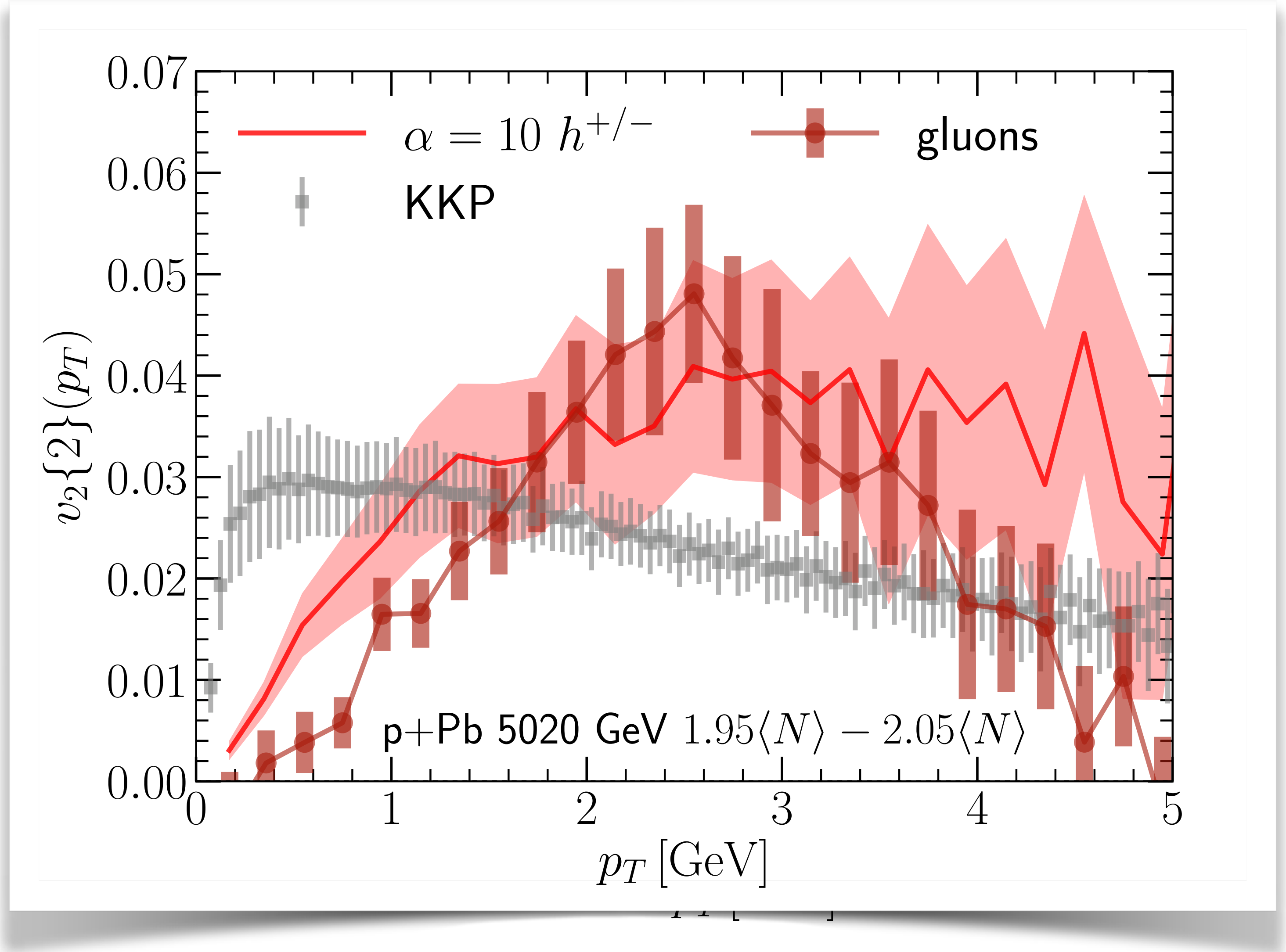
Spacetime information and steps towards microscopic models.



[Bellm, Duncan, Gieseke, Myska, Siodmok – EPJ C79 (2019) 1003]

IP-Glasma interfaced to Herwig



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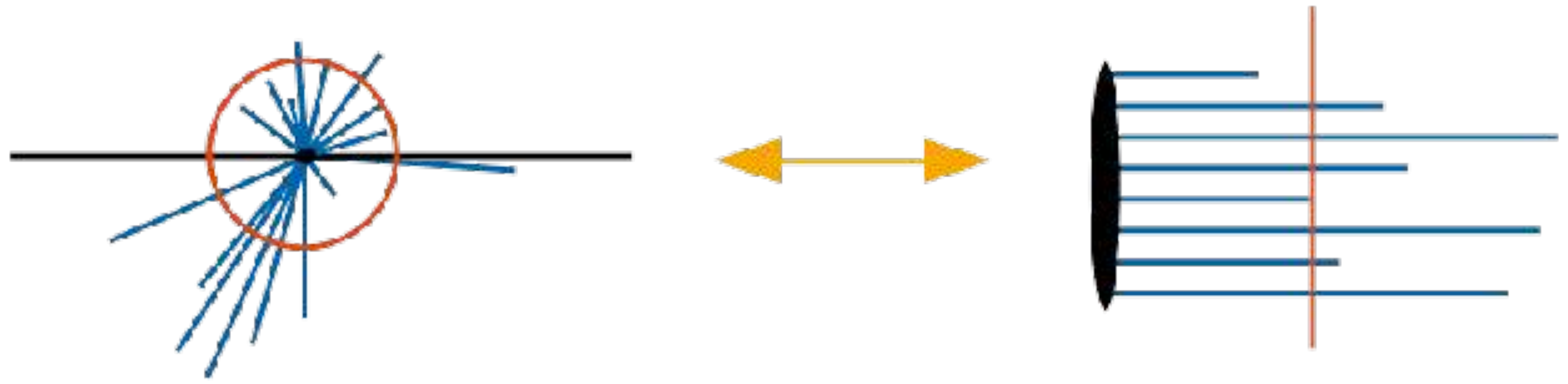

$$\sigma[u] = \sum_{n,m} \int \int \mathrm{Tr}\,[\mathbf{A}_n \mathbf{S}_{nm}]\, \mathrm{d}\phi(q_1, ..., q_n)\ u(P_1, ..., P_m) \mathrm{d}\phi(P_1, ..., P_m)$$

Instanton induced processes

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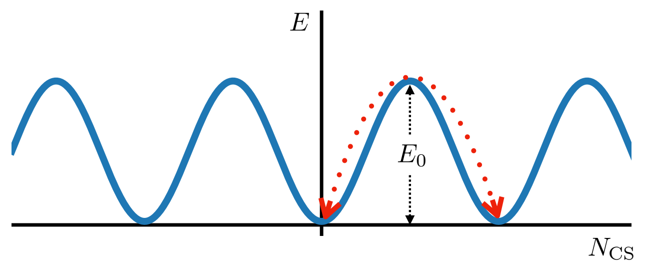
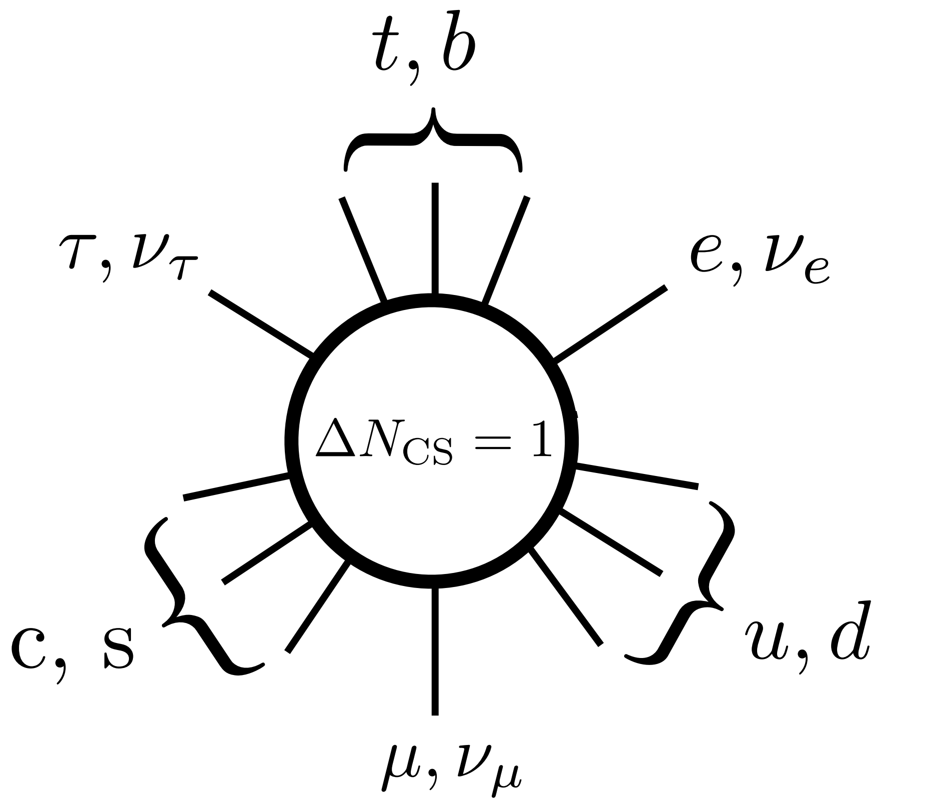
Framework for "blob" type processes and non-trivial vacua.
E.g. electroweak sphalerons

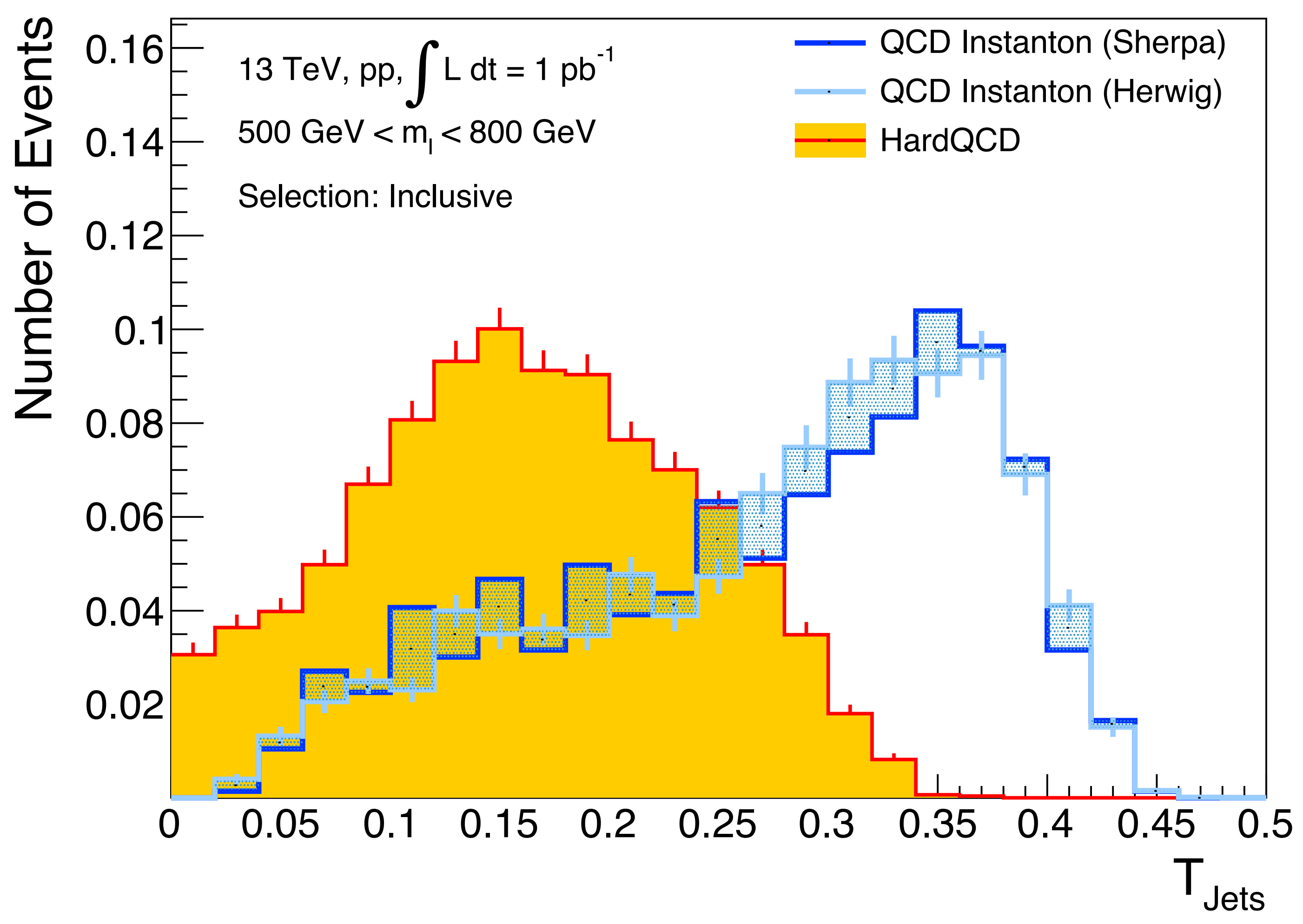


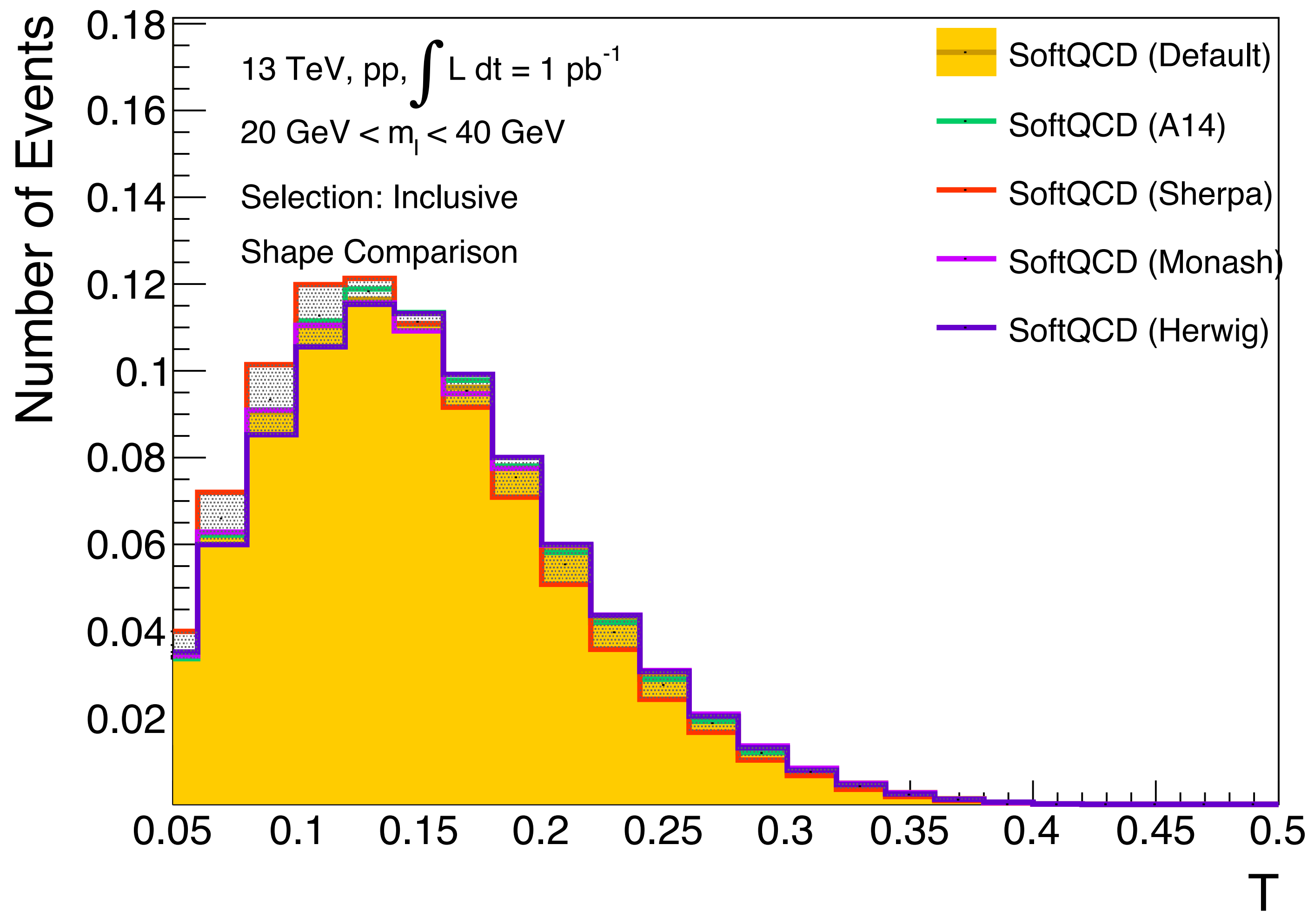


[Papaefstathiou, Plätzer, Sakurai — JHEP 1912 (2019) 017]

$$q + q \to 7\bar{q} + 3\bar{\ell} + n_B W/Z/\gamma/H.$$

Generalize to QCD instantons:
"Soft bombs" — possibly hidden/drowned in MPI?





$$g + g \to n_g g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf}).$$

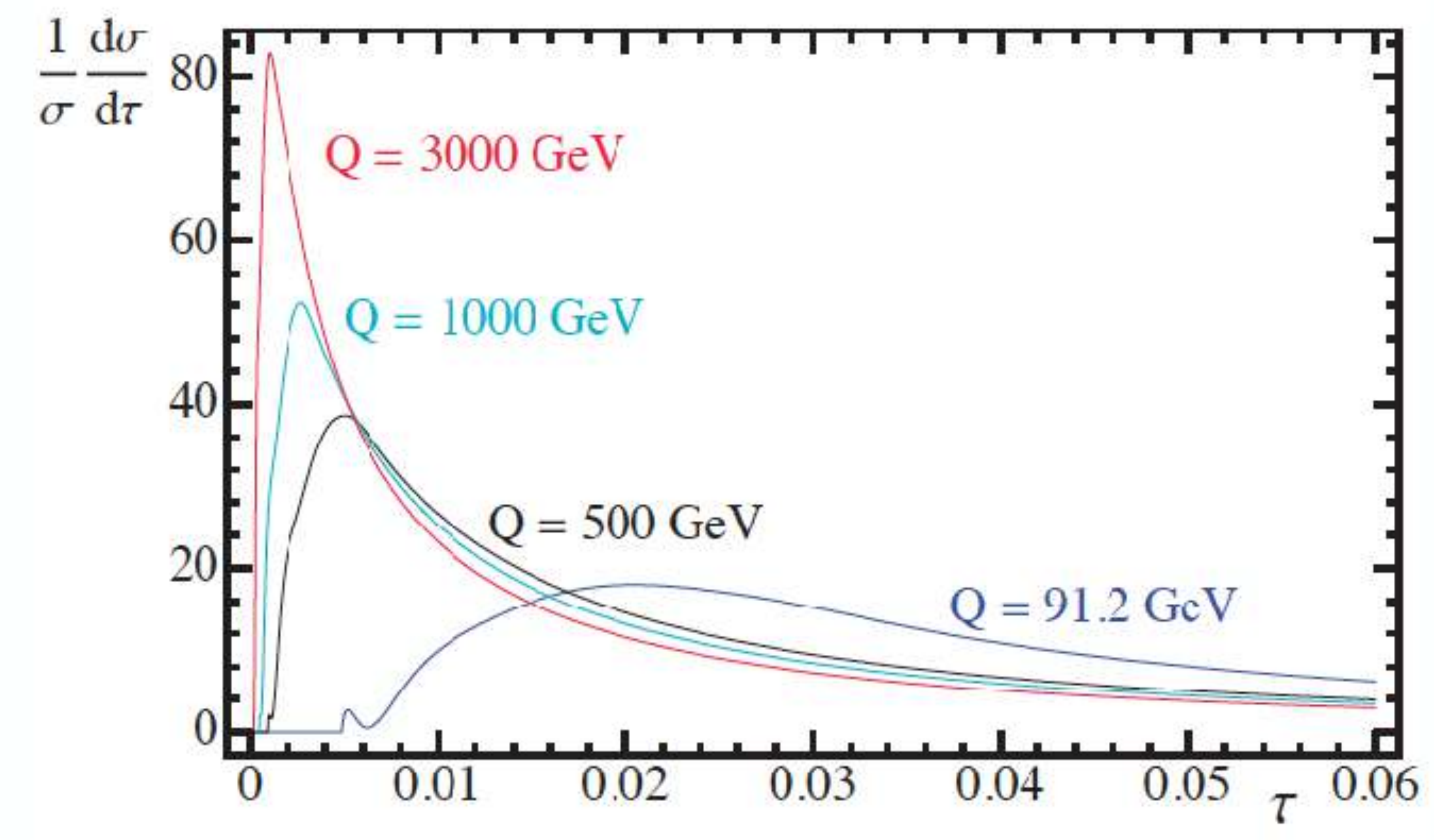
Need to understand colour structure and further details of showering and hadronization.

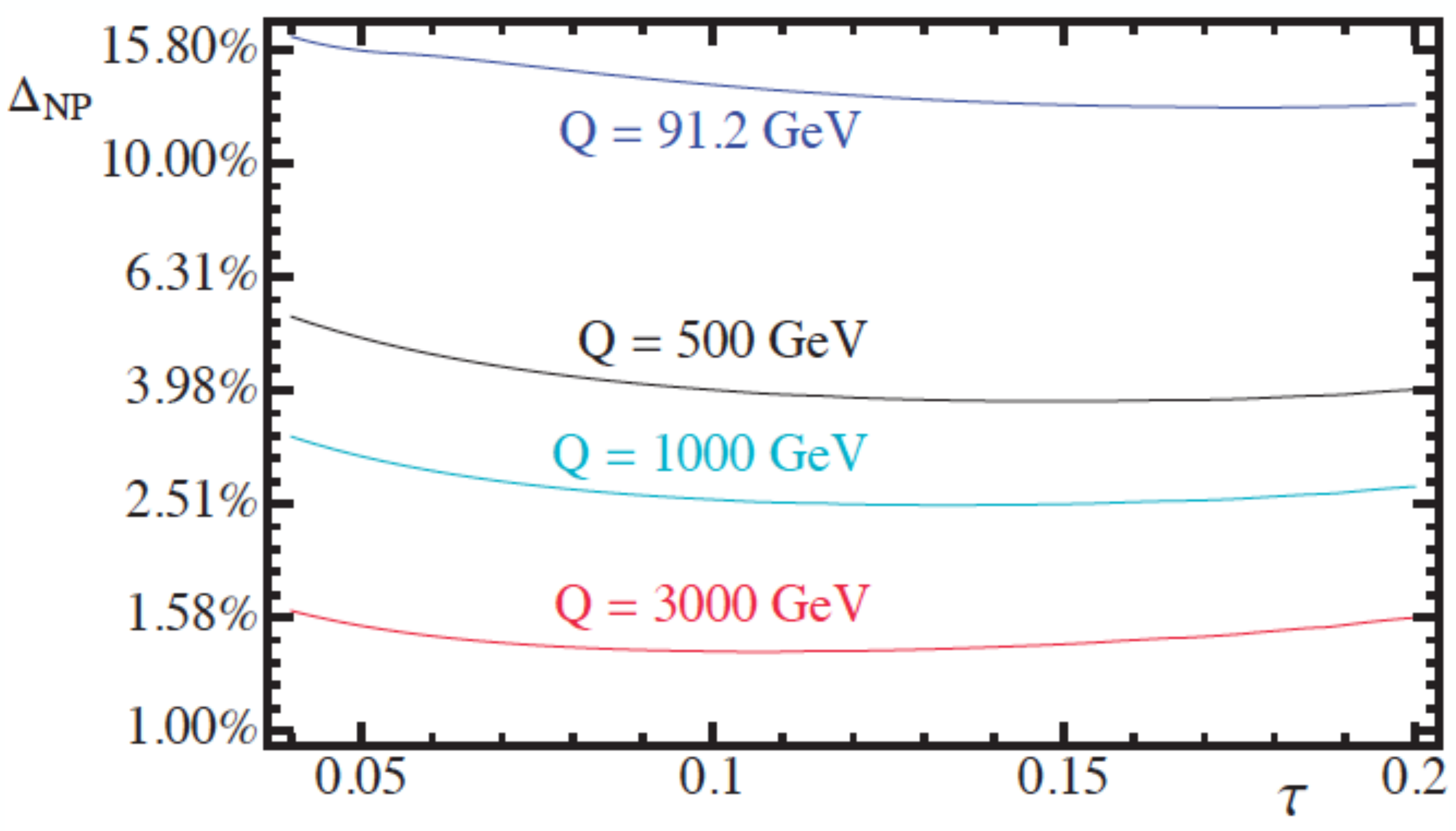
[Amoroso — based on Instanton simulation in Herwig 7]
[Papaefstathiou, Plätzer — unpublished]

[Cormier, Jin, Kirchgaesser, Papaefstathiou, Plätzer — in progress]

e^+e^- Event Shapes and the Strong Coupling

What would a precise measurement of event shapes at higher Q values contribute?





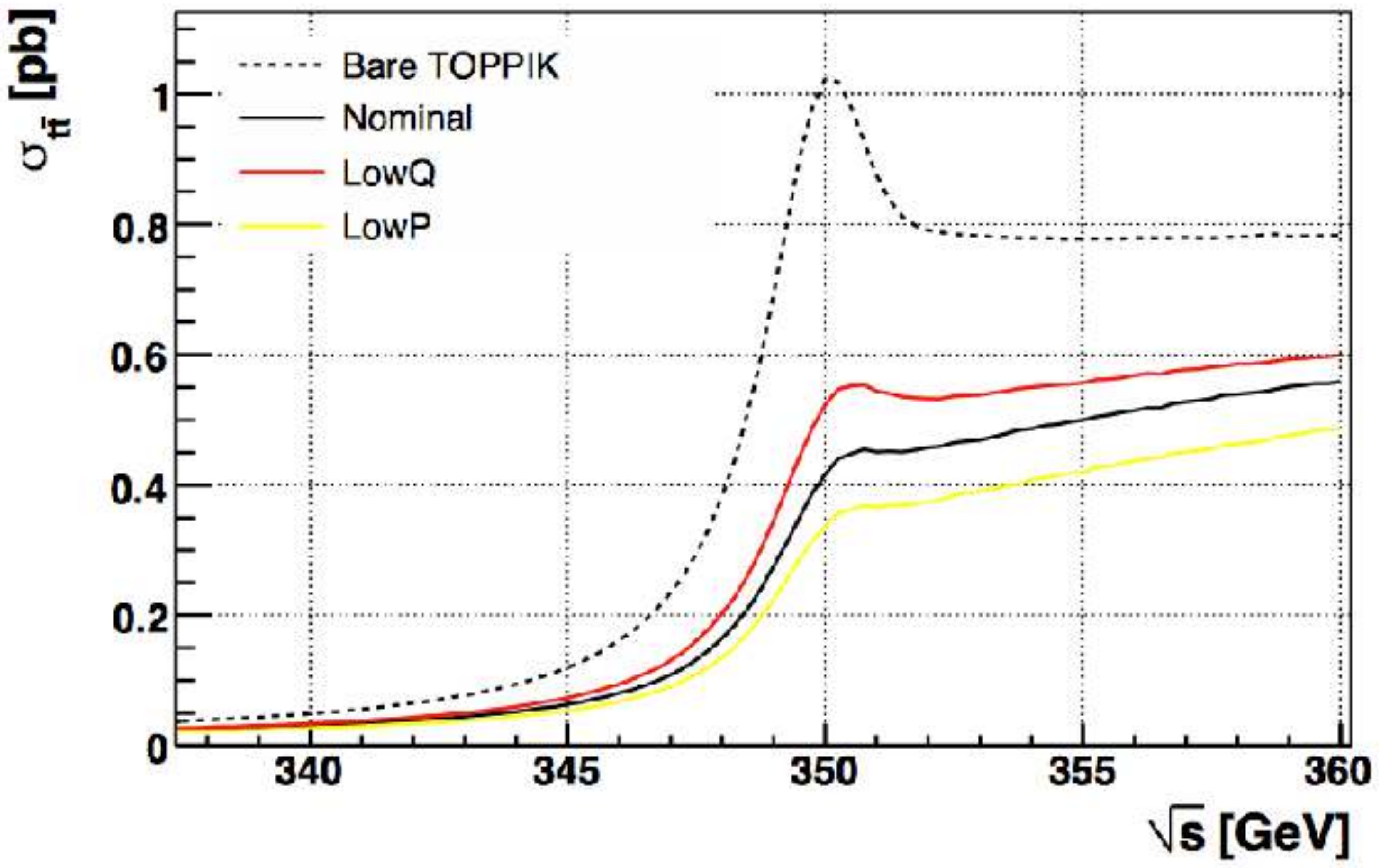
- Event accumulate in very small region at small values.
- High precision needed.
- Background tricky (γγ)
- Theory very well known and further improvements expected

- Non-perturbative effects decrease with Q
- At some point smaller than experimental uncertainty and negligible !!
- Difficult at very large Q, but very important for confirmations of lower-E measurements.

Top Threshold

Top pair total inclusive cross section:

$$\sigma(e+e- \rightarrow t\bar{t}+X) \text{ at } E_{cm} \approx 2m_t$$



Principle: m_t from $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood (renormalons, summations)

Crucial difference to top pairs at LHC

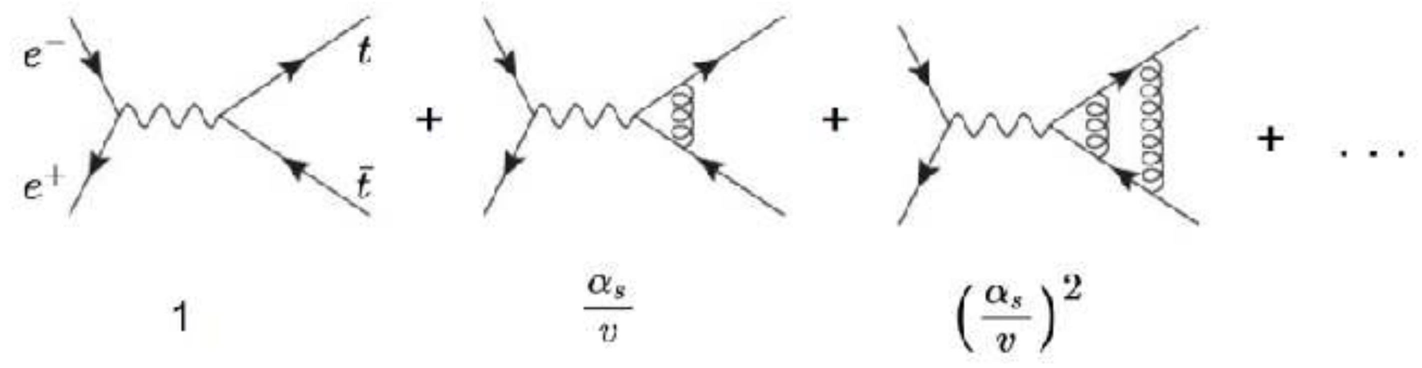
➢ Top decay protects from non-pert effects

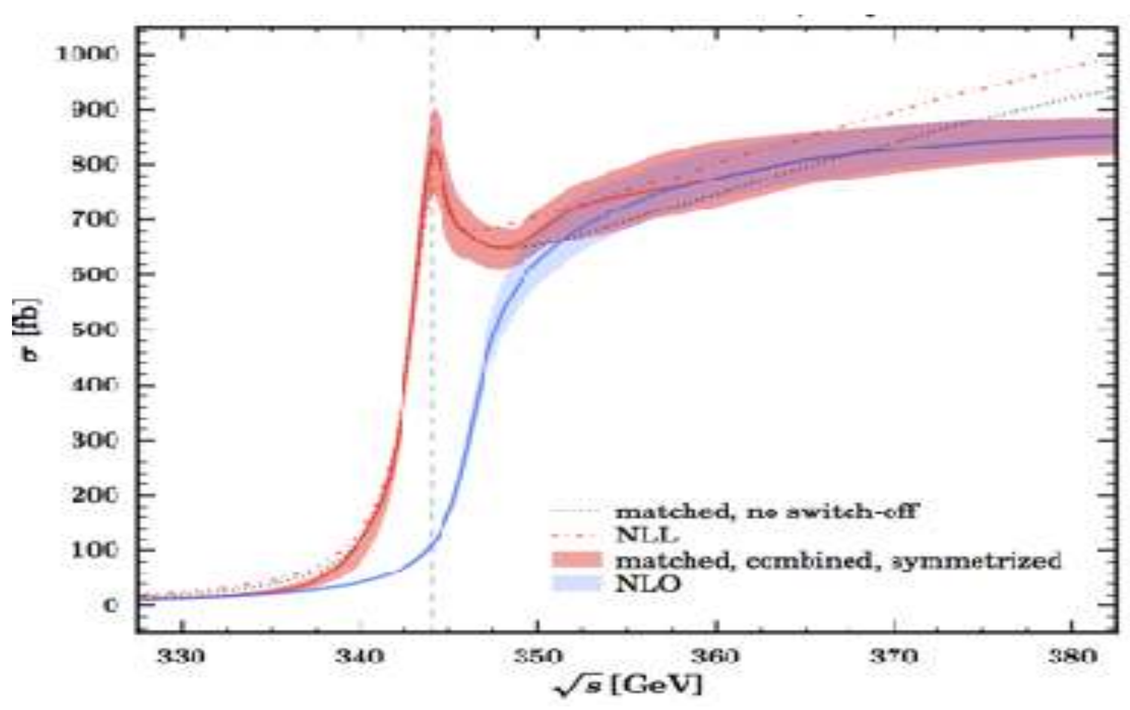
- Remnant of a topionium resonance ("postronium of QCD"): $R_{bind} = m_t \alpha_S \sim 30$ GeV
- Crucial to control e+e- luminosity spectrum
- Binding energy about twice the top quark width: $E_{\text{bind}} \approx \frac{\alpha_s^2 m_t}{2} \approx 2\Gamma_t$
- Can be calculated in pQCD at NNNLO/NNLL (nonrelativistic expansion):

$\longrightarrow$ **Top mass in well-defined scheme with uncertainties ~ 50 MeV**

Top Threshold

- Coulomb resummations
- Finite Width effects are leading order
- NRQCD effective field theory counting ($\alpha_S \sim v$)





- Total cross section at NNLO (FO in $\alpha_S \sim v$) — AHH, Beneke, Melnikov, Nagano, Ota, Penin, Pivovarov, Signer, Smirnov, Sumion, Teubner, Yakovlev, Yekhovsky '01
- Total cross section NNLO+NNLL (sum $\ln(\alpha_S) \sim \ln(v)$) — AHH, Stahlhofen, '13
- Total cross section NNNLO — Beneke, Kiyo, Marquard, Piclum, Steinhauser '13

- Non-resonant EW effects NNLL — AHH, Reisser, Ruiz-Femenia '04, '10
- Non-resonant EW effects $\text{NNNLO}_{\text{partial}}$ — Beneke, Maier, Rauh, Ruiz-Femenia '17,

- Top p_t 3-momentum distribution NNLO — AHH, Teubner '00
- Full differential: only NLO+LL !! — Chokoufe, AHH, Kilian, Reuter, Stahlhofen, Teubner, Weiss'17
- No MC generator exists!

Future aims: Fully differential at NNLO/NNLL $\longrightarrow$ Many non-trivial new issues!

MC event generator with top threshold

Associated Top Threshold Physics

tt + γ:

Boronat, Fullana, Juster, Gomis, Vos, AHH, Widl, Mateu '19

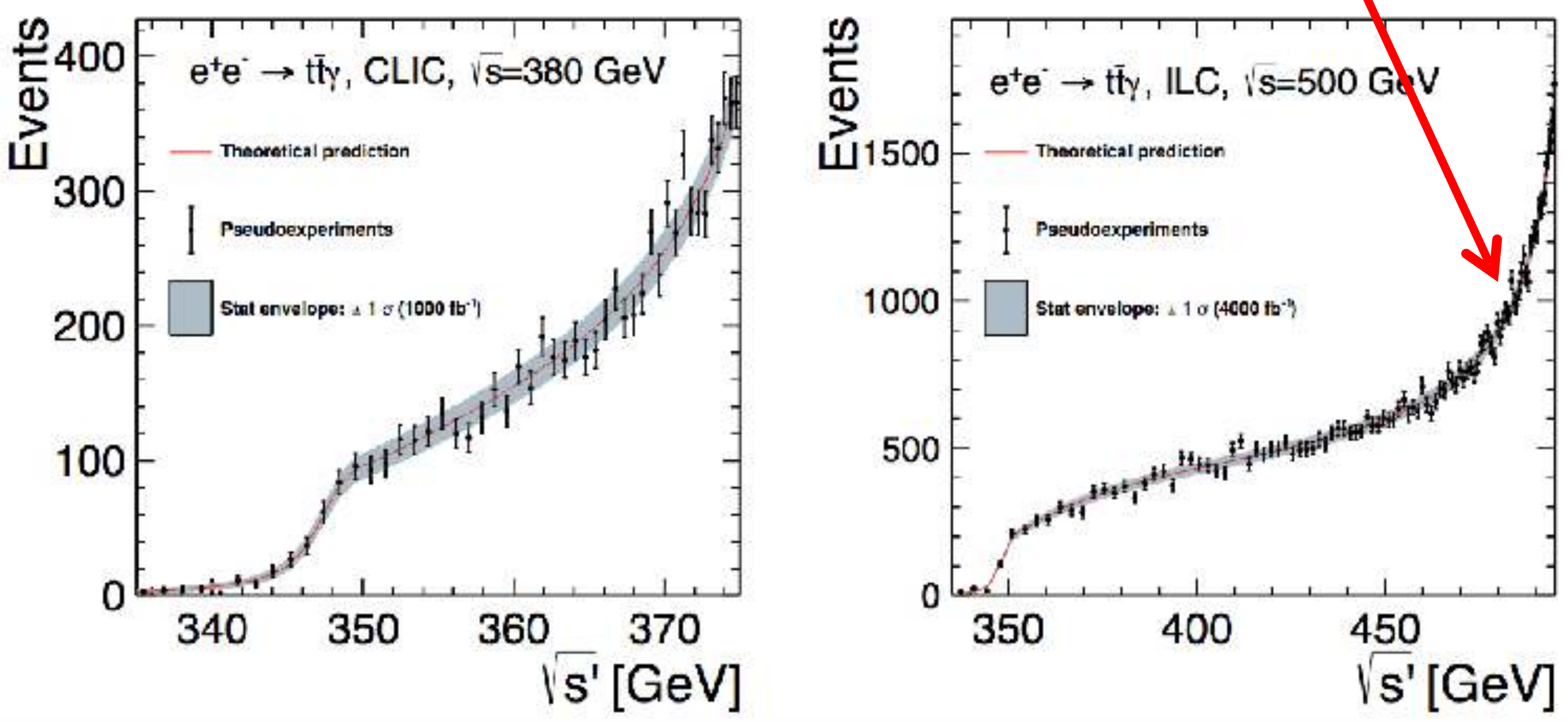
- Radiative return to the tt threshold allows for top threshold top mass measurements at higher energies.

$$\frac{d\sigma_{t\bar{t}\gamma}}{d\cos\theta\, d\sqrt{s'}} = 2\, g(x,\theta) \sqrt{\frac{1-2x}{s}}\, \frac{\alpha_{em}}{\pi}\, \sigma_{t\bar{t}}(s')$$

$$x = \frac{E_\gamma}{\sqrt{s}}\,,$$

$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

ISR enhancement

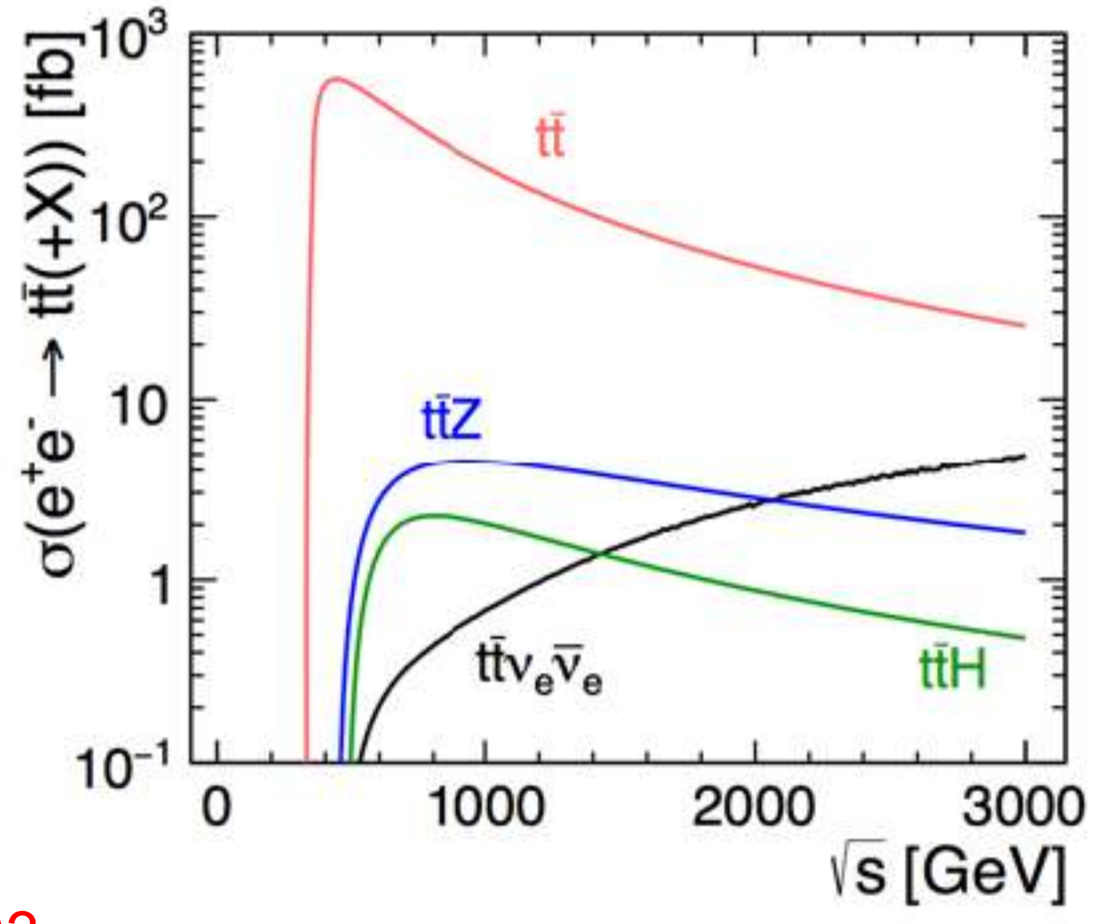


- Matched threshold (NNLL+NNLO)-continuum (NNNLO) cross section
- Realistic simulation experimental analysis
- Statistics dominated

cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

Associated Top Threshold Physics

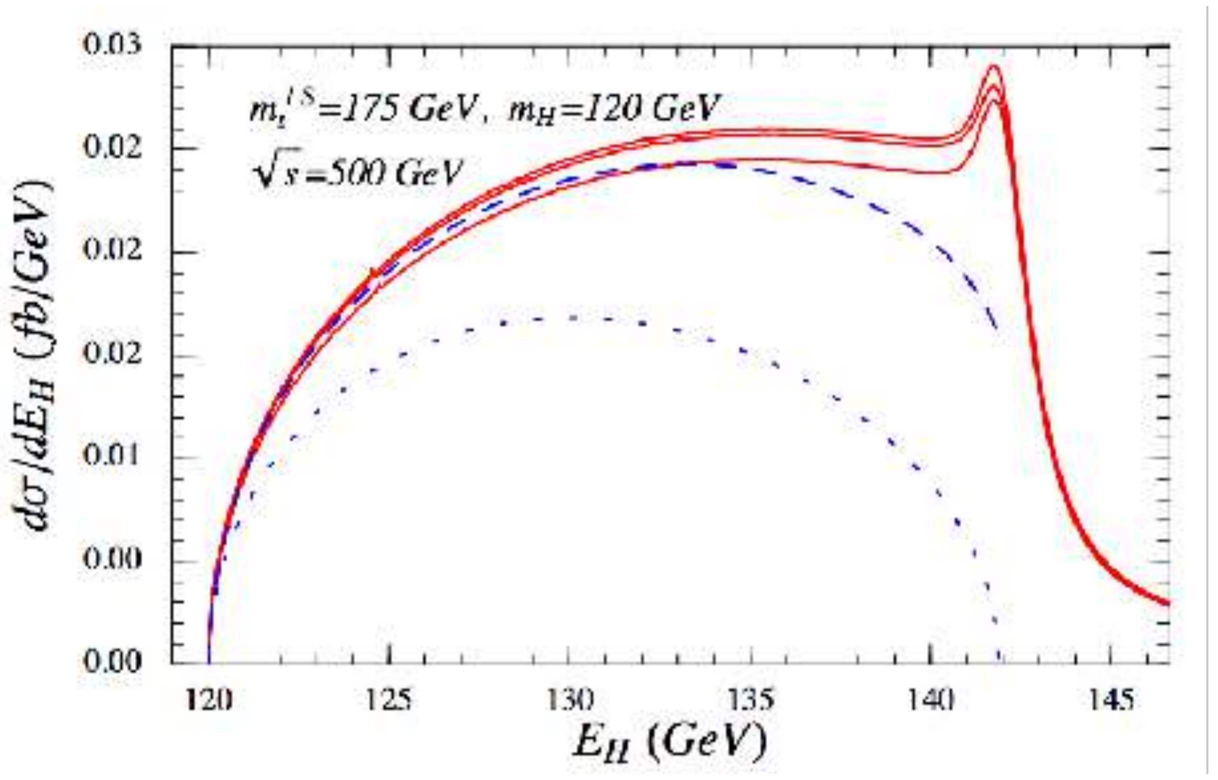
- A future e^+e^- collider with many associated ttbar thresholds
- Technology exists to extend ttbar threshold machinery to them, but much less event

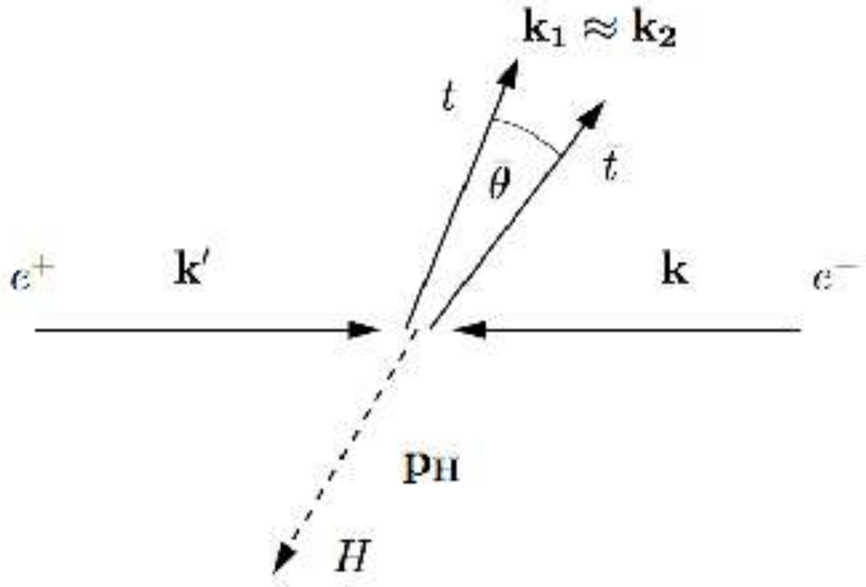


tt + H: (very similar for tt+Z)

- NLO QCD — Dawson, Reina '17,
- NLO EW corrections — Dener, etal,, Belanger, etal. You, etal '03,
- NLL threshold — Farrell, AHH '05

- Kinematic threshold enhancement reaching far into the continuum region for associated tt production, enhances cross section



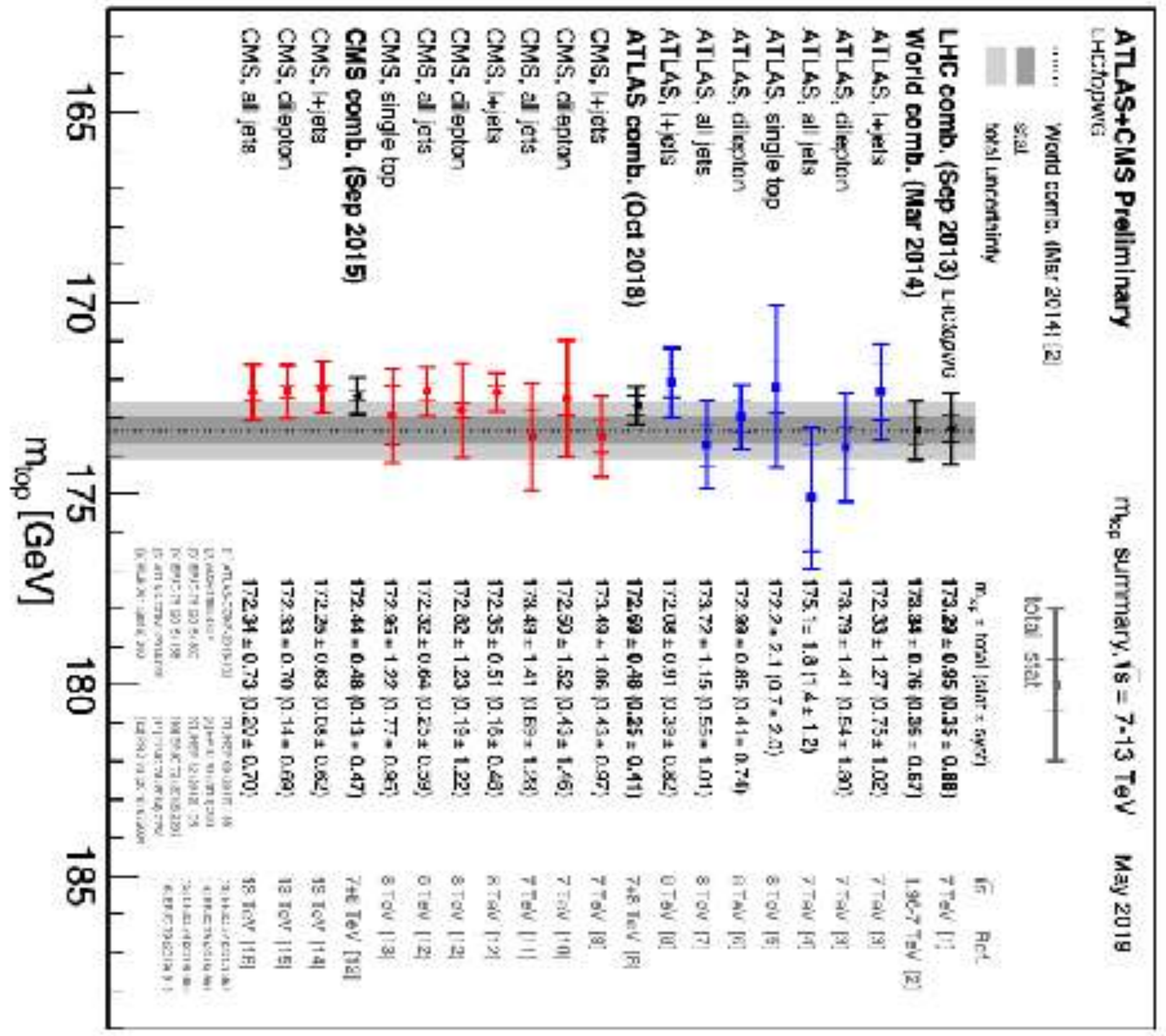


$\sqrt{s}$ [GeV]	m_H [GeV]	σ(Born) [fb]	$\sigma(\alpha_s)$ [fb]	σ(NLL) [fb]	$\frac{\sigma(\text{NLL})}{\sigma(\text{Born})}$	$\frac{\sigma(\text{NLL})}{\sigma(\alpha_s)}$	$\frac{\sigma(\text{NLL})_{\lvert\beta\rvert<0.2}}{\sigma(\alpha_s)_{\beta<0.2}}$
500	120	0.151	0.263	0.357(20)	2.362	1.359	1.78

Farrell, AHH '05

Top Mass from Direct Reconstruction

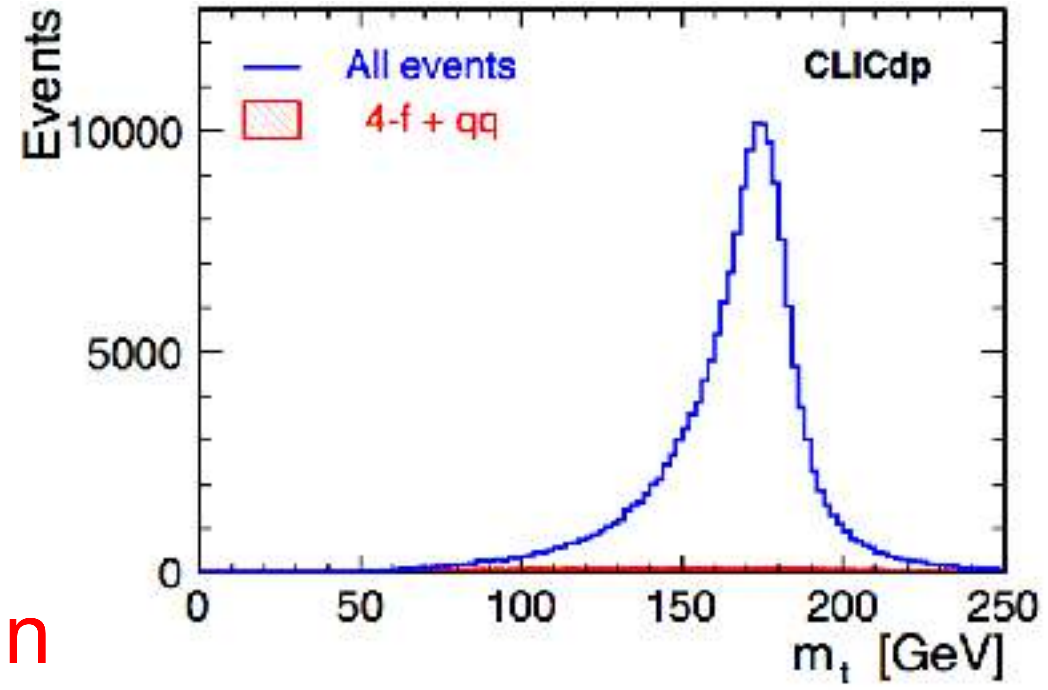
- Direct mass measurements (template or matrix element fits) are the moste precise method to determine the top mass at the LHC
- Variables ($M_{\text{lepton+b-jet}}$, m^{reco}) cannot be described by FO computation and are described completely by parton shower and hadronization dynamics in Monte-Carlo generators.
- Because MC have limited (observable dependent) precision the measured top mass m_t^{MC} cannot be a priori assigned to a particular mass scheme.



- Aim: Full factorized analytic calculation of template fit observable ($M_{\text{lepton+b-jet}}$) feasible for e^+e^- collisions. Problem easier than for the LHC.

- CLIC simulation study: m_t^{reco} template fit E_{cm}= 380 GeV

$(\Delta m_t^{MC})^{\text{stat}} \sim$ 30 MeV $(\Delta m_t^{MC})^{\text{syst}} \sim$ 50 MeV



Abramowicz etal. '18

Substantial theoretical insight concerning QCD can be gained in connection top threshold measurements.

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